European Co-operation in the Field of Scientific and
Technical Research

COST 345

Procedures Required for Assessing Highway Structures

Joint report of Working Groups 2 and 3: methods used in European States to inspect and assess the condition of highway structures

European Commission
Directorate General Transport

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Executive summary

The movement of people and goods has a pivotal role in any society. For example, within the EU the current annual expenditure on the transport industry is around €1000 Billion, or more than 10 per cent of the Gross Domestic Product, and the industry employs more than 10 Million people (EC, 2001).

The highway network is the most important part of the land-based transport infrastructure in Europe. Bridges, buried structures (such as tunnels and culverts) and earth retaining walls make up a substantial proportion of the fixed assets of this network. The stock of such structures has been accumulating over the years: some in-service structures predate the 20th Century. Such structures are vital elements of the highway network, particularly on primary routes where failure can have severe economic and political consequences, and the imposition of weight and/or speed restrictions or lane closures can generate serious traffic delay costs.

The realisation that material and financial resources are finite and limited is encouraging greater emphasis on the conservation of the existing stock of structures in a serviceable condition. And a reliable, integrated system of inspection, assessment and maintenance is required to ensure the safety of the public at large, and the efficient allocation and expenditure of resources to the upkeep of the stock.

It was against this backdrop that COST Action 345 was undertaken to define the *procedures required for the assessment of highway structures*. The term 'procedures' covers (a) physical methods - such as visual examination and testing, (b) methods of analysis - both qualitative and quantitative, and (c) construction practices for maintenance and refurbishment. These cover more or less, respectively, inspection, assessment and remedial works.

Working Group 2 was set up to examine the procedures used to inspect highway structures, whilst Working Group 3 was to cover the methods used to assess the condition of such structures. The Groups were to summarise current practice, recommend improvements to current practice and identify research needs. In the event, for clarity and practicality, Working Groups 2 and 3 produced a unified report.

The fundamental reason for undertaking inspections is to check that structures are, and remain, fit for purpose. Inspections are therefore undertaken to:

- detect the presence of defects
- determine the cause, extent and rate of deterioration
- provide information for assessing stability and serviceability
- provide information for evaluating the cost-effectiveness of various remedial measures.

An inspection should provide information on (a) the location, severity and extent of defects, (b) the causes of these defects - and the associated deterioration processes, and (c) the impact of the defects on the serviceability and safety of the structure. This report describes the more common types of defect found on highway structures.

Failure to identify a defect or the misdiagnosis of a defect cannot be rectified, other than by chance, by subsequent analysis or compensated by remedial works, no matter how well either of these is completed. Thus the quality of an inspection is a crucial part of an asset management system. An inspector should, therefore, be provided with (a) standard inspection report forms, (b) information on the structure under inspection, (c) a catalogue of defects, and (d) training: the effectiveness of all these sources of information should be reviewed periodically.

Various inspection regimes have been implemented within Europe. There is a good deal of commonality between the regimes, but there are differences in the definition of a structure, details of the inspection procedures, and the intervals between inspections. Current practice should be reviewed to determine where improvements can be made: particular attention should be given to the integration of the inspection process within the bridge management system, the utility of standard report forms, and the identification of factors that pose the greatest risk to the safe use of a structure (including basic assumptions made in design). Furthermore, within the EU there is a wide diversity in the requirements for inspectors regarding their formal education, training and experience. It would seem necessary to introduce a certification scheme for inspectors at a national level but, given the similarities in the bridge management systems used across the EU, there would be merit in adopting a pan-European approach.

Tests are often used to supplement visual inspections, and details of the more commonly used tests are provided in the report. It is concluded that (a) there would be benefit in producing guidelines on the application and interpretation of NDT methods, and (b) research should be directed at improving NDT equipment and the capture and analysis of data from such tests. Within the EU, the policies regarding the load testing of bridges vary widely: in some States such tests are undertaken as a matter of course whilst in others they are permitted only for research and development purposes. It would seem necessary to investigate this divergence of opinion through a more detailed review of the advantages and limitations of loading tests; this should cover cost-effectiveness, selection of the applied load level, instrumentation and data collection and analysis.

Some aspects of the behaviour of an in-service structure can be monitored on a continuous (or effectively so) basis, and the data from such studies can help in the assessment of the stability and serviceability of a structure - particularly one that does not meet current performance requirements but shows little sign of distress. The data from such studies provide the basis of reference databases and can underpin whole life cost models. It would seem, however, that monitoring works are not undertaken widely (particularly over the longer term) and the consensus view was that they should be undertaken as a matter of routine. Long-term studies are required to track the initiation and propagation of defects and deterioration processes.

A Condition Assessment (CA) is undertaken to provide information on (a) the overall condition of a structure - or of its components and elements, and (b) the severity and extent of defects and damaged areas - and their effect on the stability and serviceability of the structure. Thus the objectives of a CA are to:

- identify deterioration processes
- rate the condition of a structure and/or its components or elements
- identify what further works are required, and the likely cost and timing of such works
- provide information for establishing the condition of the stock of structures, and for optimising future expenditure.

Many deterioration processes can be initiated and promoted by one or more factors, acting singly or in combination, and so it may be difficult to derive a simple explanation of the problem(s). But only when this has been done can the most appropriate treatment be identified, planned and executed. Furthermore, usually there are several options for treating a particular problem, and selection has to take into account the residual life of the structure, the likely cost-effectiveness of the treatment, and operational requirements during the works. Thus, completing a CA is not straightforward.

Within Europe, various qualitative and quantitative systems for deriving a condition rating for a bridge have been developed but they all, inevitably, require a large measure of engineering judgement. To help rationalise such judgement, mathematical methods based on, for example, probability, neural networks and fuzzy logic have been used in assessing the condition of deteriorated structures. Further work is required to investigate the potential of such methods for the routine assessment of structures. Because of the subjectivity of a structural assessment it is difficult to confirm its reliability and consistency, but it is clear that there is a need for some form of checking system. A certification scheme for assessors could be developed and introduced at a national level but there is merit in following a pan-European approach.

Because in a CA no account is taken of the in-service loads acting on a structure, the condition rating does not provide a direct measure of the level of safety or, therefore, of the priority for remedial works. The methods used to develop an adequacy rating or priority ranking for structures should be reviewed. For this, and other reasons, it would seem necessary to develop methods for establishing specific loading rules for highway bridges. Furthermore, in many States there are no assessment standards and in their absence the stability of an in-service highway structure will tend to be assessed according to the requirements of design codes for new structures. This will hardly ever be appropriate: the application of design codes will probably underestimate the stability of the structure, and may lead to unnecessary strengthening works. Work should be directed at producing a best practice guide to the assessment of structures; although this may be done on a national basis, again there is merit in considering the development of European-wide documents.

The current inspection and assessment procedures have been developed, almost exclusively, for highway bridges. It seems necessary to devise procedures for all types of major highway structures: although such procedures can be based on those developed for bridges they must take account of differences in the nature and type of defects and loading regimes.

Data management plays an important role in an asset management system. It is essential that the database is suitably structured to allow the input, retrieval and interrogation of the information obtained from inspections, tests, monitoring works, assessments and remedial works. There would seem to be benefit in establishing a register or log for each highway structure.

As stated above, the highway network is by far the most important element of the land-based transport system in the EU, and highway structures are essential components of this network. Several Billion Euros are spent annually on the maintenance, repair and renewal of these assets, and so even a relatively modest improvement in the management of these assets represents a substantial saving. One of driving forces behind the COST 345 Action was to identify where improvements in current practice could be made, and it is hoped that the findings of the Action, as provided in this report for example, will help such savings to be realised.

Chapter 1 Introduction

1.1 BACKGROUND

1.1.1 The importance of the land-based transportation system within the EU

The movement of people and goods has a pivotal role in any society. The importance of transportation was recognised in the Treaty of Rome by the provision for a common transport policy across the EU.

Within the EU, the current annual expenditure on the transport industry is around €1000 Billion, or more than 10 per cent of the Gross Domestic Product (GDP), and the industry employs more than 10 Million people (EC, 2001).

The highway system is currently the most important part of the land transport infrastructure in the EU: its value is so large that it almost defies quantification. In 1998 some 92.7% of passenger kilometres travelled were by road as well as 73.7% of the tonne kilometres of goods traffic (EC, 2000). And while the proportion of passenger travel carried by road has remained relatively static over the years the proportion of goods traffic has increased dramatically since 1970 when it was 47.9%. In absolute terms, in 1998 goods traffic and passenger travel by road were, respectively, 3 and 2.2 times their 1970 levels: see Figure 1-1. Over this 28-year period, in the remainder of Europe the increase in goods traffic was similar to the above whilst car ownership has increased about 11 fold. It is clear that the highway infrastructure will have a considerable role to play in the social and economic life of Europe for many years to come.

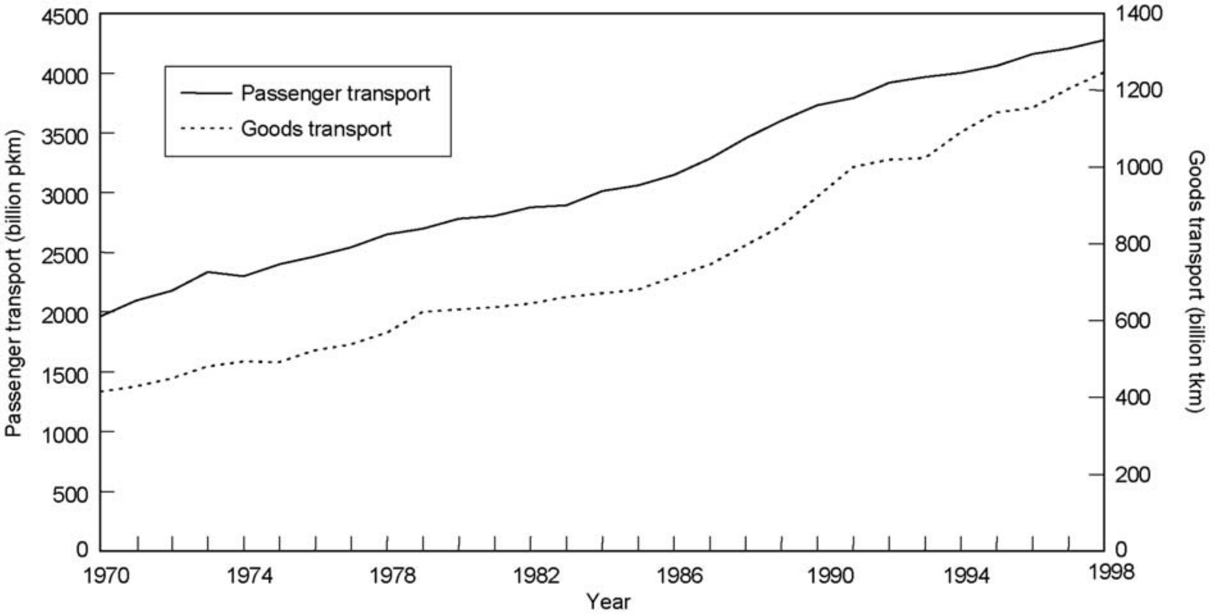

Figure 1-1 Evolution of passenger and goods transport on roads 1970-1998 (European Commission, 2000)

The highway infrastructure is hierarchical. The primary routes, an increasing number of which are multi-lane high speed roads, form the backbone of a national highway network but they only represent about 5% by length of the entire network. Secondary roads link these routes to the tertiary or local road network which, apart from localised trouble spots, is in general lightly trafficked (particularly outside peak hours) and makes up about 75-85% of the road network.

1.1.2 Highway structures

Bridges, buried structures (such as tunnels and culverts) and earth retaining walls make up a substantial proportion of the fixed assets of the land-based transportation network of Europe. The stock of such structures has been accumulating over the years: some in-service structures predate the 20th Century, with some masonry arch bridges dating back to Roman times.

Such structures are vital elements in the road network. The closure of a bridge or tunnel severs the highway on which it is located; failure of a retaining structure is often less dramatic but traffic is impeded and the public is put at some risk. The consequences of such incidents are related to the location of the unserviceable structure. For primary roads the resulting detours can have severe economic and political consequences; for example, the fires in the Mont Blanc and St Gotthard Tunnels (Bettelini, 2002; Tunnels and Tunnelling International, 2001). On the other hand the closure of a lightly trafficked local road inconveniencing at most a few hundred travellers will have little impact either economically or politically, and provided such incidents are not too numerous they can be overlooked at a national and even a regional level.

More commonly, defective structures on the highway result in the imposition of weight and/or speed restrictions and/or lane closures. Again the repercussions are greatest on national roads and least on local roads where, being less dramatic, their impact on the general public is reduced as is their political importance. However their economic consequences can still be serious with the heavier goods vehicles often being forced to make considerable detours and in some cases being completely excluded from some areas.

There can be and often is a fundamental dichotomy between the short-termism of political institutions and the long-term requirements of a highway system where the pavement needs resurfacing or reconstructing every 10-40 years and the structures on it are designed for a 50-100 year life-span or more. This mismatch is most apparent during periods of budgetary restraint although the World Bank (1994) is clear that an ill-advised cut in maintenance expenditure at such times ‘is a false economy’. Lack of funds for maintenance invariably results in unnecessary deterioration of, and possibly some damage to, the highway infrastructure that is usually more expensive to rectify at a later date.

The increasing realisation that material and financial resources are finite and limited is encouraging greater emphasis on the conservation of the existing stock of highway structures in a serviceable condition. That said, whilst considerable effort has been put into the development of specifications and standards for the design of new structures, comparatively little has been done on the development of documents covering the assessment of existing structures. In the absence of specific documents covering assessment there will be a tendency to assess the serviceability and stability of in-service structures using the rules given in design documents. But such an approach may be inapplicable; and even where it can be followed it is likely to underestimate the stability of an existing structure. In some cases it could lead to the unnecessary replacement or strengthening of existing structures with all the attendant costs of traffic delays. What is required is a system of assessment within which longevity and structural condition are qualitatively or quantitatively balanced against the required factor or margin of safety deemed to be required: it inevitably involves some form of risk assessment.

A reliable integrated system of inspection, assessment and maintenance is required to ensure the safety of the public at large, and also the efficient allocation of resources to the upkeep of the highway network.

1.2 COST 345

It was against the backdrop of the foregoing that COST Action 345 was undertaken to define the procedures required for the assessment of highway structures: the Action was supported by the European Commission and involved experts from 16 European States. Note that the term ‘procedures’ in the title covers (a) physical methods, such as visual examination and testing, (b) methods of analysis, both qualitative and quantitative, and (c) construction practices for maintenance and refurbishment. These cover more or less, respectively, inspection, assessment and remedial works. The Action covered all types of highway structure and so encompassed bridges, buried structures (such as culverts and tunnels), and earth retaining structures, but low-value structures (such as street furniture) and very long span bridges were excluded.

The main objective was to describe current European practice on the inspection, assessment, maintenance and repair of the stock of in-service highway structures. Secondary objectives were to:

- collect information on the stock of highway structures, including current expenditure levels
- define the requirements for future work
- identify the types of structure that are not amenable to simple inspection, analysis or repair.

The development and application of reliable inspection, assessment, maintenance and repair procedures for the European highway network could ensure the continued high performance of the network and, potentially, could save billions of Euros in construction, maintenance and traffic delay costs.

The end-users of the results of this Action include International, National and Local Government highway organisations and agencies, construction companies and the technical and scientific world. At International and National levels, the data collected as part of this study could influence matters of policy regarding safety and the administration and operation of highways. Such data will also be of interest to different parts of these institutions for decision-making in the areas of transport policy, legislation, research and development.

At a regional or local level, engineers charged with the upkeep of a section of highway infrastructure will benefit from the availability of information on methods of inspection, assessment and analysis, and from improved whole life cost models. Together these could improve the efficiency of operations, provide more reliable predictions of expenditure, and assist in the planning and execution of inspection and maintenance works. The information will also be of benefit to road operators and contractors concerned with such works.

1.2.1 Work programme

The programme of work was undertaken by seven Working Groups as follows:

Working Group 1 Inventory

Working Group 2	Inspection
Working Group 3	Condition assessment
Working Group 4	Numerical techniques
Working Group 5	Safety and serviceability
Working Group 6	Remedial measures
Working Group 7	Final report

Figure 1-2 shows an outline of the work programme for Working Groups 2 and 3, and how it interaction with the work of the other Working Groups.

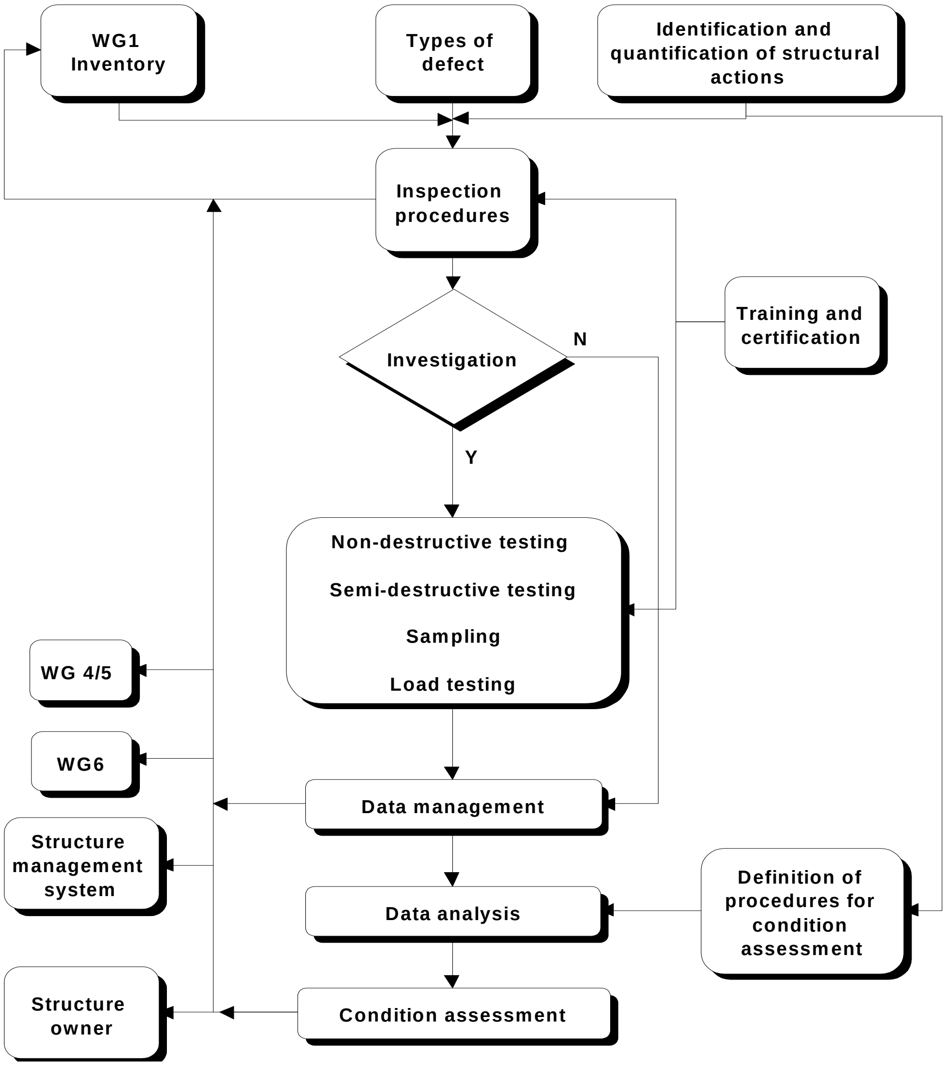

Figure 1-2 Outline work programme of Working Groups 2 and 3

1.2.2 Working Groups 2 and 3

Working Group 2 examined the procedures used to inspect highway structures, whilst Working Group 3 examined the methods used to establish a condition assessment of such structures. The Groups did not cover the assessment of the load-carrying capacity of structures (this was covered by Working Groups 4 and 5) nor earthworks.

The Working Groups were to report on these particular subjects, and also to recommend improvements to current procedures and provide suggestions for further research. In the event, for clarity and practicality, Working Groups 2 and 3 produced a unified report.

Details of the membership of Working Groups 2 and 3 are provided in Annex I, whilst further details of the COST Action are provided in the Appendix of the Annex I.

1.3 INSPECTION AND ASSESSMENT

1.3.1 Objectives

The condition of a structure varies with time according to the details of its design, construction, maintenance, and in-service conditions. Structures deteriorate for a variety of reasons, such as:

- inadequacies in design, detailing or construction
- poor planning and/or execution of maintenance works
- shortage of funds to complete regular routine maintenance works
- poor planning and/or execution of structural alterations
- in-service environmental conditions, which can change with time
- ageing processes
- accidental loading and vandalism
- increases in the volume of traffic
- changes in the mix of traffic
- increases in vehicle weights and speeds.

The basic purposes for undertaking inspections are to check that structures (a) are, and remain, fit for purpose - that is, they have no obvious defects that may affect the safety of the public, and (b) are deteriorating at an acceptably low rate - for example, consistent with achieving their intended in-service life. Inspections are therefore undertaken to:

- detect the presence of defects
- determine the cause, extent and rate of deterioration
- provide information for assessing stability and serviceability
- provide information for evaluating the cost-effectiveness of various remedial[1] measures.

Thus an inspection should provide information on (a) the location, severity and extent of any observed defects, (b) the causes of these defects - and the associated deterioration processes, and (c) the impact of the defects on the serviceability and safety of the structure. These data form the basis for identifying appropriate remedial works (where deemed necessary) and for deriving cost estimates for such works.

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[1] Herein, the term ‘remedial measures’ includes rehabilitation, periodic maintenance, routine maintenance, repair and renewal works.

The information from a suite of inspections can be collated to determine the overall condition of the stock of structures they cover.

1.3.2 Role in an asset management system

The position and importance of inspections in a bridge management system can be judged from Figure 1-3; this is taken from the OECD (1992) report on Bridge Management.

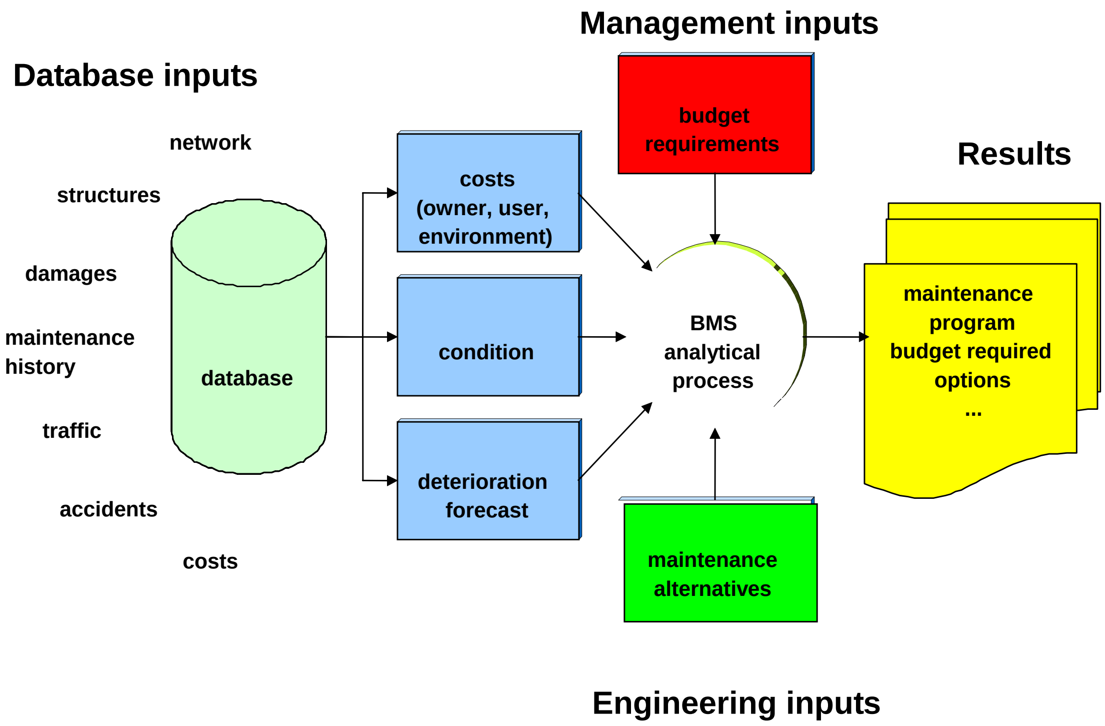

Figure 1-3 Outline of a bridge management system, from OECD (1992)

The figure shows how the results of inspections are drawn into a comprehensive database containing information on a stock of bridges (for example, on its condition, rate of deterioration, and maintenance expenditure) from which a maintenance strategy can be derived. In advanced systems the information is manipulated to rank and prioritise structures for maintenance, and to develop and compare various options for remedial works. A similar approach could be adopted for other types of highway structure.

The results of an inspection are used to derive a qualitative and/or quantitative rating of the serviceability and/or stability of the structure, and therefore provide input to the design of any remedial works. Failure to identify a defect or the misdiagnosis of a defect cannot be rectified, other than by chance, by subsequent analysis or compensated by remedial works, no matter how well either of these is completed. Thus the quality of an inspection is crucial to an asset management system.

1.4 STRUCTURE OF REPORT

Before undertaking an inspection it is necessary to identify (and in some cases quantify) the actions to which highway structures are subjected, and the types of defect that occur on them. An action is defined in the Structural Eurocodes (EN 1990: 2002) as:

a) Set of forces (loads) applied to the structure (direct action);

b) Set of imposed deformations or accelerations caused for example, by temperature changes, moisture variation, uneven settlement or earthquakes (indirect action).'

Defects are covered, respectively, in Chapters 2 and 3 of this report.

Inspections may involve some or all of the following, and with varying degrees:

- visual examination of the structure
- physical tests (laboratory and/or field)
- use of access equipment and traffic management works
- risk assessment for road users and inspectors
- risk assessment of the structure during field inspections and tests
- reporting the findings.

Various inspection regimes have been implemented within Europe. There is a good deal of commonality in the regimes, but the main differences between them are in the definition of a structure, details of the inspection procedures, and the intervals between successive inspections. Current inspection procedures used in some of the States participating in COST 345 are reviewed in Chapter 4.

Tests are often used to supplement visual inspections, and details of commonly used tests are provided in Chapter 5. These include (a) the determination of material properties, which requires samples to be taken from the structure, (b) intrusive tests, which may involve some minor damage to the structure, (c) non-destructive tests, (d) load testing, and (e) in-service monitoring.

It is clear from the foregoing that inspections can generate a huge amount of data. Chapter 6 addresses the problems of collecting, manipulating and analysing these data.

One of the objectives of an inspection is to provide the owner or delegated authority with a measure of the condition of a structure. There are a number of procedures for deriving a condition rating that describes the state of a structure or the various elements of a structure. Details of the various procedures are described in Chapter 7.

The reliability of the results derived from an inspection depends on the skill and experience of the inspector. The qualification and certification of those responsible for inspecting highway structures are considered in Chapter 8.

The sequence of the content of these Chapters is as follows:

- description of current position
- recommendations for future strategy
- identification of research needs.

Chapter 9 provides some concluding remarks.

Chapter 10 provides a consolidated list of references and a bibliography. Even a cursory review will show that there is a vast library of literature on the management of assets. Numerous papers on the subject have been published as part of the proceedings of conferences, symposiums and the like, and also in journals of learned societies such as ICE. Relevant reports have been produced by international organisations (such as CEB, FIP, IABSE, OECD, and PIARC) and by research organisations (such as BAST, LCPC, NCHRP and TRL), and standards have been produced by organisations such as AFNOR, ASTM, BSI, CEN, DIN and ISO, and by various national road associations, ministries and agencies (such as HA). Furthermore, a good deal of freely available and relevant information is available through the World Wide Web. Thus, for brevity and clarity, no attempt has been made to provide an exhaustive database of papers and reports in Chapter 10: indeed, only key references are listed and, in the main, the bibliography reflects the personal sources of information of the various contributors to this report.

Additional technical detail is provided in various Annexes: a consolidated list of recommendations is provided in Annex VI.

Chapter 2 Identification and quantification of actions

2.1 INTRODUCTION

Highway structures are subjected to a wide variety of actions; for example, dead loads from self-weight and earth pressures, and live loads generated by traffic, wind, and perhaps also seismic events. It is necessary to quantify the relevant actions so that the stability and serviceability of a structure can be checked using one or more of the various numerical methods of analysis available. Nonetheless, the structural integrity and condition of a structure can also be assessed through an inspection.

Inspections provide an opportunity to:

- check the design assumptions underlying the quantification of some actions
- detect changes in use that could affect the stability or serviceability of a structure
- detect damage due, for example, to vehicle impact, ground movements and vandalism
- detect signs of structural distress due to overloading
- identify areas of material degradation
- provide a basis for determining structure-specific loads.

2.2 CURRENT POSITION

2.2.1 Verifying the inventory

Some inventories identify the code or standard used for the design of a structure along with the year of its issue. Where this information is unavailable, an inspector familiar with the development of such documents may be able to infer it from the age and origin of the structure.

The types of data used to determine the design values of the actions include:

- geometric information, such as the dimensions of the structural elements, the width of traffic lanes and the thickness of the pavement
- material properties, such as the strength and stiffness of the structural components - including any backfill and the foundation subsoil
- in-service environmental conditions, such as temperature range, wind, rainfall and depth of the water table
- calculation assumptions, such as joint fixity and the rigidity and stability of foundations
- calculation expedients, such as the values of the various partial factors
- calculation procedures, such as the method of analysis.

Some but not all of the above could, and therefore should, be checked through an inspection.

It is the case that as-built drawings are not always available or updated following the end of construction. The partition of the carriageway over a bridge into traffic lanes may be changed in service, but this may not be registered in an inventory; the same situation may arise with the thickness of the carriageway overlying a bridge or buried structure. (Such cases may be adequately covered by partial factors built into the design process.) Further information used in design, such as material properties and the (assumed) level of groundwater, could also be gathered during an inspection and incorporated into the inventory and related maintenance documents - but this is rarely done.

2.2.2 Changes in use

Inspections tend to focus on the detection of defects or damage and so changes in use by users or even the owners of the structure, or of adjacent infrastructure, may be overlooked. It will be appreciated that the performance of a highway structure can be affected by planned or unplanned activities outside its site boundaries. Similarly, the presence of a highway structure can affect an area outside its immediate confines. These activities may involve the excavation or stockpiling of soil and the demolition or construction of buildings, but they may not be noticed unless they infringe the site boundaries or have an immediate and obvious effect.

2.2.3 Identifying defects

Asset management systems require areas of damage and material deterioration to be identified, but in some systems emphasis is on estimating the cost of remedial works rather than identifying and remedying the cause of degradation. For example, a subroutine could be devised to calculate the cost of repairing spalling to the concrete soffit of a bridge, but this would not address the underlying problem of the bridge having a sub-standard clearance.

2.2.4 Site-specific loading

In 1991, the first versions of the Structural Eurocodes were issued in a ‘pre-standard’ form - as EuroNorm Vornorms or ENVs (ENV 1991-n.n): it is expected that by the end of 2003, a vote will be taken to convert the ENVs to EuroNorms (ENs). As may be anticipated the ENVs give details of the various actions and their combinations that should be considered in the design of highway structures: details of the actions covered by the ENVs are provided in Annex II. The ENVs do not, however, cover some site-specific or structure-specific actions, and so, for example, the Swiss road and rail authorities provide guidance on the actions due to rockfalls and avalanches to be considered in the design of protection galleries.

2.3 USE OF DESIGN CODES FOR ASSESSMENT

In assessing the stability of an in-service structure, the relevant actions could be quantified according to the standard or code(s) used for its design. However this would not satisfy the requirements of the owner or society at large because it would not take advantage of knowledge gained in the interim nor of changes in design practices, such as traffic loading. Such objectives could be overcome by applying up-to-date design codes to assess stability but this would undoubtedly lead to unnecessary widespread and substantial strengthening works.

The following describes briefly how some States involved in COST 345 deal with the assessment of in-service structures.

2.3.1 Czech Republic

The code for assessing both new and old structures is CSN 73 6221 ‘Inspections of road bridges’ but there is no specific code covering the strengthening of bridges that have insufficient load-bearing capacity: the choice and detailing of strengthening works are left to the designer. A road authority can impose restrictions on vehicle weight, and this option is commonly applied to sub-standard bridges on regional roads.

2.3.2 Poland

Values of the actions to be used when assessing in-service bridges are defined in ‘Instructions on current [basic; detailed] examination of bridge structures located on non-urban public roads.’ - DP.-T.16 [17; 18] M, which was issued in 1990. In theory, the instructions only apply to structures on the national road network, which is about 5% of the total network, but in practice they are applied to the entire network. However the assessment of load-carrying capacity is not covered by the above documents and existing bridges are strengthened, where necessary, according to the design code for new bridges.

2.3.3 Slovenia

There are no standards or guidelines for assessing in-service highway structures, but research into the assessment of existing bridges has been undertaken. A few bridges have been assessed using a method based on the actual dimensions of the structure, material properties (obtained from a detailed investigation), and a traffic-loading model derived from weigh-in-motion data.

2.3.4 Spain

There is no standard or guideline for assessing in-service structures that do not meet the requirements of current design codes.

2.3.5 Switzerland

The procedures that can be applied where a structure does not comply with design codes are described in a guide (SIA 462). This allows the values of the partial factors for the actions to be reduced where supplementary safety measures are taken. As with all the Swiss codes, the guide allows the use of more refined methods where they can be justified by new developments or adequately supported by theory or experimental data. Thus reliability methods can be applied: in which case the reliability index β is calibrated against the requirements of deterministic codes.

2.3.6 United Kingdom

A set of codes for assessing structures forms part of the Design Manual for Roads and Bridges (DMRB). The procedures comprise five levels of assessment of increasing sophistication. The first level requires a site inspection and uses a basic load model, codified resistance models and a simple analysis to produce a reasonably conservative assessment. If this is unsatisfactory, the analysis and site data are refined successively - eventually working up to a full reliability analysis for just a few cases. The load model and codified resistance models have been developed for assessment and therefore avoid over-conservative assumptions and requirements. Without this provision, some in-service structures would be assessed wrongly as being unsafe.

2.4 FUTURE STRATEGY

2.4.1 Systematic classification of hazards

A better understanding of the actions that should be taken into account when designing and assessing structures requires the systematic identification of hazards. In each of the categories listed in Table 2-1 increasing action and or decreasing resistance can lead to failure: only the actions are considered in the following. The table provides a checklist based on the origin of the hazard to show which actions may be relevant in a particular case.

Table 2-1 Checklist of actions

Hazards due to the structure: *those that result from or are increased by the presence of the structure*	**Hazards due to use**: *those that result from the intended, excessive or improper use of the structure*	**Hazards due to the environment**: *those that would occur without the structure*
Self weight - due to structural and non-structural elements	Imposed loads - such as bearing pressures on foundations	Earthquakes
Wind forces	Static and dynamic traffic loads	Storms/gales/snowdrifts
Water pressure	Starting and braking forces*	Rockfalls, landslides, mudflows and the like
Wave forces	Nosing forces*	Flooding
Ice drifts	Impact loads from collisions	Fires - grass and forest
Lateral earth pressures	Fire	Climate change
Effects of temperature	Explosion	Avalanches and ice falls
Frictional forces	Vandalism	Groundwater
Retaining spring forces: for example, bridge piers that are deformed horizontally by the superstructure (through temperature, creep, shrinkage), generate forces that may predominate at fixed bearings.	Application of de-icing salts Poor or inappropriate maintenance and repair	Weathering Air and water pollution Marine conditions

* applies particularly to railway structures

2.4.2 Identifying discrepancies between in-service conditions and design assumptions

An inventory should list important design assumptions and an inspector should be able, and be required, to check that these are not violated in service.

Through an inspection the following may be observed:

- surcharging behind an abutment, wing wall or retaining wall - which will increase the disturbing earth pressure (a surcharge may be obscured by vegetation)
- a blocked drainage system - this could generate a rise in the groundwater level and hence increase water pressures

- placement of a new pavement without the complete removal of the original - thereby increasing the dead load (this may only come to light during a site visit - it may not be recorded in an inventory)
- installation of new utility apparatus, street furniture and the like, such as pipes, poles, signs, lighting columns and safety barriers
- removal of vehicle weight or speed restrictions, or the failure to observe posted restrictions
- changes in the number and width of carriageway lanes
- excavations in front of retaining walls and bridge abutments or adjacent to buried structures - such works can destabilize these types of structure
- the growth of vegetation in cracks - this can lead to the deterioration of surfaces

2.4.3 Detecting signs of overloading

Damage, deformation and/or material deterioration is clear evidence that the condition of a structure has degraded in service, but it may also indicate that a structure has been overloaded at some time or other. For example,

- noticeable deflection and buckling usually signify overloading
- scratching on the soffit of a superstructure or on a bridge support is likely to be due to vehicle impact.

2.4.4 Site-specific loading

Codes cannot be expected to cover all possible circumstances.

The results of an inspection should allow an engineer to judge whether the conditions at the structure are covered by a particular code and, if so, how the requirements of that code should be applied.

Examples of conditions that are more favourable than assumed in design are:

- the presence of rock rather than soil
- the joints of a rock mass having a favourable rather than an unfavourable inclination
- limited access or low traffic flow such that the design traffic loads cannot be applied.

Examples of site conditions that are less favourable than assumed are:

- rock formations with joints having an unfavourable inclination
- the presence of boulders in a soil matrix rather than the existence of rockhead
- a greater depth of weathered rock
- environmental conditions, such as extreme temperature variations.

2.4.5 Remediation

Whenever possible, the underlying physical mechanisms and associated structural actions should be determined for all types of deterioration found during an inspection. It is bad practice to simply repair defects that are found: the cause of any defect should be identified and assessed because the need to eliminate its source may well affect the design and execution of the remedial works. Thus it is unreasonable to repair a crack before its origin has been determined: cracks due to overloading will reopen after repair, and filling cracks produced by thermal actions may lead to more extensive damage to the structure.

2.5 RECOMMENDATIONS

Recommendation 1 Key design assumptions should be defined in the inventory of the asset management system. Where possible, the system should require these assumptions to be checked by an inspector.

Recommendation 2 A best practice guide for assessing highway structures should be established. Such a guide may lead to the development of national assessment codes in States where they do not already exist, but it would seem more productive to develop European-wide documents covering the assessment of highway structures.

Recommendation 3 Specific loading rules for assessing in-service structures should be devised. The first priority is the development of a new code for traffic loading that takes account of local conditions, remaining service life, and supplementary safety measures such as monitoring and controlling traffic flows. There is benefit in considering a European-wide approach to the development of such codes.

Recommendation 4 Information on actions that have been investigated in some depth should be disseminated and compared. Relevant documents should be translated into English.

Chapter 3 Types of defect

3.1 GENERAL

The condition of a highway structure can be detrimentally affected by various factors. These may act singly or in combination to generate functional, load-carrying and long-term durability problems. A reliable appraisal of defects and their cause(s) is essential for assessing the condition of a structure, its load-carrying capacity, remaining service life, serviceability, and functionality as well as for the design of remedial works.

3.1.1 Design

Defects and premature deterioration can result from:

- Inadequacies in the design approach or material specifications.
- Inadequate detailing of particular parts of a structure. A number of examples follow. Short drain pipes under a bridge deck can lead to wetting and subsequent degradation of the concrete surface; similarly, subsurface tubes (acting to drain water collecting between the deck surfacing and waterproofing membrane) that end at the soffit of the deck can lead to degradation of the surrounding concrete. Inadequate protection to foundations in a riverbed can lead to scour, with fatal consequences. Inaccurate placement of reinforcement may result in excessive cracking and deflection and, in the extreme, to the rupture of a structural element. Inadequate concrete cover can reduce durability, which can in turn reduce load-carrying capacity, particularly where the structure is exposed to a harsh environment.

3.1.2 Materials

The use of sub-standard or inadequate materials can produce under-strength structures and increase expenditure on remedial works. Defects and deterioration may arise where:

- The properties of the materials are untested, unknown or not well understood at the time of construction. For example, the use of high alumina cement (HAC) in certain environments; reactive aggregates which can lead to alkali-silica reaction (ASR); aggregates containing sulfides; and additives such as calcium chloride.
- Poor quality control was exercised during construction. For example, the placing of sub-standard concrete; inadequate compaction; the use of reinforcing or structural steel that did not meet design requirements; and the use of metallic fasteners that promotes corrosion of the reinforcement.

3.1.3 Construction

Many problems of durability stem from poor construction practices.

One of the commonest problems met with concrete structures is inadequate cover to the reinforcement. The evidence of this may not be immediately evident but it will show itself with time through the corrosion of the reinforcement: an early sign is the appearance of the outline of the reinforcement mesh on the surface of the concrete: this print is produced by colour variations generated by vibration of the fresh concrete. Other defects at the construction stage include: honeycombing due to poor compaction or aggregate grading; cracking due to differential settlement of the falsework; and blow-holes due to air being trapped against the shutter.

A structure can be damaged by the construction or rehabilitation of ancillary equipment and services - such as the installation of additional safety fences and the repair of utility apparatus respectively. For example, the soffit of a concrete box structure can be damaged by poor workmanship during installation of the parapets and safety fences on top of the structure: in some cases in the UK, the holding-down bolts to these ancillary structures have penetrated through the roof of the structure, thereby allowing the ingress of water. There are also examples in the UK where the installation or replacement of a utility service duct has damaged a masonry arch bridge.

3.1.4 Loading

Defects due to in-service loading can take many forms. Excessive deflection of a bridge deck can be generated by higher than anticipated live loads and through a reduction in the load-carrying capacity of the superstructure or substructure(s). Excessive deflections of prestressed superstructures can result from the use of prestressing reinforcement with a higher relaxation than assumed in design. Outward displacement of abutments or retaining walls may result from higher than anticipated lateral earth pressures (sometimes in combination with pore water pressures) or ground movements - due to the settlement of the foundations for example. Impact loads from vehicles, ships, or floating debris and ice can severely damage the supports and superstructure of bridges and other types of structure. Loading due to natural causes, such us flooding, earthquakes, landslides, rockfalls and fire can also damage structures: this damage may be evident many years after the event.

3.1.5 Environmental conditions

Environmental conditions, acting on a wide or micro-scale can promote structural instability as well as severe and chronic serviceability problems. Many types of defects and deterioration processes, such as ASR, exhibit characteristic visual patterns on the exposed surface of a structure: such patterns can give valuable information about defects themselves, including their nature and cause. The time at which traces become visible can vary from a few hours (for plastic shrinkage and settlement cracking of concrete) to several years (for cracking in concrete through long-term drying shrinkage and ASR; fatigue cracking in steel structures; rotting of timber structures; erosion of riverbanks and scour of foundations). For a reliable condition assessment to be made it is essential to have records on the initiation of defects and deterioration processes and their propagation with time. Such records seldom exist for older structures, but for new structures it is advisable that records are maintained from construction onwards.

Vandalism may be a problem, particularly with culverts and subways, and can including fire damage.

3.1.6 Categorisation

To track or assess the rate of deterioration of a structure, defects should be graded with respect to their nature, intensity and extent. Gradation should be in a manner that fits the type of damage, the cause of the damage, and the material forming the structural element. It is important that as much information as possible on those defects that affect the condition, functionality, durability and load-bearing capacity are included in the catalogue for the structure. Such catalogues are useful for training: they help inspectors make reliable judgements regarding defects and deterioration processes, the cause(s) of these processes and their likely rate of propagation, and on the selection of remedial works.

3.2 REVIEW OF DEFECTS

In the following the most commonly found defects on structural elements of highway structures are reviewed. Such defects can have a significant impact on the condition and assessment of a structure. Typical defects are illustrated on the separate file that forms Annex III of this report. Further information on defects is provided in the report of Working Group 6 which covers remedial works.

3.2.1 Terminology

It is necessary to define some terms prior to the review, and a few are reproduced below from CEB (1998).

Defect: A specific deficiency or inadequacy in the structure or its components that materially affect its ability to perform some aspect of its intended function either now or at some future time.

Damage: Physical disruption or change in the condition of a structure or its components, brought about external actions and influences, such that some aspect of either the current or future functionality of the structure or its components is impaired.

Degradation: A worsening of condition with time, usually resulting in damage.

Deterioration: A worsening of condition with time, which may result in a progressive reduction in the ability of the structure or its components to perform some aspect of their intended function.

However, the above terms are not definitive and so some tend to be used interchangeably.

3.2.2 Common defects

3.2.2.1 Erosion

Erosion is the wearing away of soil by water or, less commonly, wind.

Earthwork slopes are at risk of erosion by heavy rainfall, and damage takes the form of surface depressions - oriented mainly down the slope, and missing or damaged parts of drains.

Riverbanks and beds are also at risk of erosion from flowing water but this is normally termed scour; see 3.2.2.6 below.

3.2.2.2 Abrasion

Abrasion is the wearing away of a surface. It can be generated by a number of sources; the most common is the action of airborne or waterborne particles, but the collision of vehicles with the soffit and/or superstructure of bridges is not uncommon. Abrasion can occur along the inside of a culvert, and is commonly found in corrugated steel culverts that do not have some sort of protective pavement. It can also be generated under drainage pipes, which end at the surface of a wall, by the action of solid particles carried by the water. Similarly, it can be generated in tunnels by the leakage of water through joints and cracks; and also on substructures under expansion joints not provided with a watertight membrane, and where water drains over the abutment surface. Frictional forces due to ice formation or from moving ice can also abrade a surface. Abrasion damage can be seen on concrete, masonry and timber elements but, apart from corrugated steel buried culverts, it is rarely found on steel structures.

3.2.2.3 Deformation

Deformation is a blanket term covering a change in shape or alignment from the as-built position. For main structural elements, particular terms are reserved for characteristic deformations: thus deflection is a vertical movement of a superstructure, whilst lateral and rotational movements describe the deformation of supporting structures.

- *Buckling* is a permanent change in the alignment of an element due to compression forces: it is usually only observed in steel structures.
- *Mechanical damage* is a localised change in the shape of an element: this is usually generated by impact forces. In the extreme it shows as broken element(s).
- *Distortion* is usually associated with the deformation (sagging and warping) of masonry structures. But it can also be generated at bearings - particularly at elastomeric ones: at some bearings, torsional deformation around the vertical axis may be observed in addition to horizontal and vertical deformations.

Deformation can be generated by various mechanisms such as poor fabrication; faulty erection procedure; inadequate joints; the use of materials with inadequate strength or stiffness; the overlooking of torsional effects in design; missing or broken connectors between elements (such as rivets and bolts); and inadequate bracing or foundation support (see Figure 3-1). Deformation can also be generated by loading, such as due to self-weight, impact, temperature changes, and earth pressures.

Figure 3-1 Deformation of a superstructure due to undermining of a pier by scour

3.2.2.4 Deflections

Deflection of a superstructure can be generated by loading, creep movements, and material degradation. It can be tracked by periodic measurements of line and level. Visible signs of excessive deflection are sagging at the centreline of a bridge span, flexural cracking and ponding on the overlying pavement.

3.2.2.5 Movements

Excessive vertical movement of supporting structures (such as abutments, wing walls, retaining walls and piers) can be generated in various ways, such as through faults in the design or construction of their foundations (such as piles, pile caps, and strip foundations). Settlements can be uniform or differential: the latter generates far more serious problems than the former. The settlement of an approach slab to a bridge can increase the dynamic traffic loading on the bridge, and these loads can be transmitted to its supporting structures.

The joints between adjacent sections of a buried concrete box can fail due to relatively modest differential movements between the sections. In these cases, the joint sealant debonds from one face or it is missing altogether. The failure of a joint allows the passage of water into the structure - often in preference to the drainage routes provided. In some cases the concrete adjacent to a failed joint will become honeycombed, or spalling will occur (see 3.2.3.3 and 3.2.3.6 respectively). And some cast in situ concrete box structures will show signs of deterioration at the construction joint between the roof and side walls: see Figure 3-2.

Figure 3-2 Deterioration of the construction joint between the roof and side wall of a concrete box structure due to differential movement

Lateral movements can be generated by the settlement of the foundation; excessive earth pressure - see Figure 3-3; failures of earthworks adjacent to a structure; water pressures produced by inadequate or blocked drains; and by changes in the strength or degree of consolidation of the subsoil or backfill.

Rotational movement usually results from unsymmetrical settlement or lateral movements.

Specific types of movement can be observed on the spandrel walls of masonry bridges and concrete bridges. Transverse horizontal movements, such as tilting, bulging, and sliding of the spandrel wall, are due to the interaction of the barrel, spandrel wall, lateral earth pressures and live traffic loading - particularly vehicular collisions with the wall.

Excessive horizontal and rotational movements may also occur at bearings. The problems generated by movements depend on the type of bearing.

Figure 3-3 Bulging of a masonry abutment due to excessive earth pressure

3.2.2.6 Scour

Scour is the erosion of the riverbed under or adjacent to the foundations of supporting structures such as abutments, retaining walls, piers, and columns (see Figure 3-1). With a culvert, undercutting and scour of the end elevations can occur.

3.2.2.7 Weathering

Frost, rain, sunlight and air pollution can all affect the condition of the surface of a structure, and the performance of exposed polymeric components.

3.2.2.8 Wetting

The surface of a structure can be wetted in a number of ways.

Wetting can lead to the deterioration of concrete and steel structures, particularly where the water is contaminated with aggressive agents, such as de-icing salts. The wetting of a porous surface can lead to freeze-thaw damage. By promoting rotting and fungal growth, continual wetting can seriously damage timber structures.

3.2.2.9 Leaks

Leaks occur at points where water exits a structure: such as at spots on the underside of the bridge deck, and intermittent or persistent flows from cracks and joints. They can occur on all types of superstructure as well as on abutments, walls, buried structures (see Figure 3-2) and galleries.

3.2.2.10 Efflorescence

Efflorescence is the crystallisation of salts brought to the surface by moisture. It is commonly found on concrete and masonry structures, and it may also be seen on steel structures supporting concrete or masonry decks or infill panels (see Figure 3-4).

It generally takes the form of a hard crust or surface coating, but stalactites and stalagmites are sometimes formed at or under drip points.

Figure 3-4 Efflorescence on steel girders due to leakage through concrete deck

3.2.2.11 Vegetation

Vegetation such as moss, grass and even small trees can establish itself within cracks and joints in concrete and masonry structures. Moss and grass tend to trap moisture so that surface pores remain saturated even in dry conditions. Roots can lead to the disintegration of a concrete surface and widen cracks and joints in masonry structures.

3.2.2.12 Freeze-thaw

The expansive pressure generated by the freezing of water in the pores or capillaries of a material can lead to widespread and intensive deterioration. The visible evidence of freeze-thaw damage is the scaling or disintegration of the material to the depth to which freezing temperatures have penetrated. Both concrete and masonry structures are prone to freeze-thaw damage. Particularly severe damage can be generated in the presence of de-icing salts: the application of such salts can lead to a sudden drop in surface temperature during thawing and thereby induce large internal stresses close to the surface (see Figure 3-5).

3.2.2.13 Collapse

Collapse is the consequence of a loss of load-bearing capacity or structural integrity. It can be promoted by external forces such as the impact of vehicles, rockfalls, avalanches, floods, overloaded vehicles, and by material deterioration.

Figure 3-5 Freeze-thaw damage of a footway aggravated by the action of de-icing salts

3.2.3 Concrete

3.2.3.1 Cracking

A crack can defined as a break in an element that stops short of complete separation. The trajectory, shape and size of a crack and the pattern of cracking vary widely according to the underlying mechanism. In essence, cracks are either structural or non-structural in character.

Non-structural cracking can occur before or after the material has hardened: with the former, cracking may be due to drying shrinkage; with the latter to corrosion of the reinforcement, freeze-thaw effects, temperature variations, and ASR.

Shrinkage cracks are evident on many cast in situ concrete structures and an example is shown in Figure 3-6. These cracks are a result of the construction process and, in most cases, are unlikely to present a problem. However in a few structures some cracks extended through the full thickness of the elements, thus allowing the ingress of water to the reinforcements and threatening the long-term durability of the structure. Usually, because better control can be exercised on the mixing and curing conditions, precast units have a denser and more consistent finish than cast in situ structures: on the other hand, precast units require careful handling to avoid accidental damage during their placement.

Structural cracking can occur through over-stressing of the material or through ground movements, as shown for example in Figure 3-7.

The inherent rigidity of concrete box structures makes them susceptible to differential ground movements. This can lead to vertical cracking in the structure and to the failure of joints. Severe cracking due to differential settlement can be generated, particularly on cast in situ structures that were not provided with movement joints or where there was a wide spacing between such joints. Another common problem associated with differential settlement is the cracking of wing walls and the opening of joints between the wing walls and box structure, as shown for example in Figure 3-8.

Figure 3-6 Vertical shrinkage crack in the sidewall of a concrete box culvert

Figure 3-7 Cracking of a tunnel portal and vault due to foundation instability

Figure 3-8 Cracking of the wing wall to a concrete box structure due to differential ground movements

3.2.3.2 Reinforcement corrosion

Corrosion is an electro-chemical process by which the cross-section of steel reinforcement is reduced either reasonably uniformly or locally (that is, through pitting). The type and extent of corrosion vary according to its principal cause. Carbonation is the process by which carbon dioxide reacts with calcium hydroxide in the cement paste: this reaction reduces the pH of the concrete from above 12.5 to about 9, thereby removing the passivity provided to the reinforcement by the highly alkaline environment. The most common cause of corrosion is the presence of chloride ions - these are usually derived from de-icing salts. Whereas carbonation-induced corrosion tends to result in a reasonably uniform loss in section, chloride-ion promoted corrosion is often characterised by a localized and rapid loss in section; that is, pitting.

Corrosion of ordinary structural steel reinforcements commences quite soon following exposure to humid air, and can then proceed rapidly in honeycombed or extensively cracked concrete. However the process is relatively slow in the absence of aggressive species, such as chloride and sulfate ions. Initially there are no visible traces of corrosion on the concrete surface, but with time staining followed by cracking, spalling and delamination become evident.

Corrosion of prestressing reinforcement will also commence in a humid environment (as may be present at inadequately filled joints between precast segments) due to carbonation of the concrete, and in the presence of aggressive species - such as chloride ions. Corrosion due to chloride ions can occur in partially grouted or open ducts when contaminated water comes in contact with the tendon. Prestressing steel may also fail through stress corrosion and/or hydrogen embrittlement.

As shown in Figure 3-9, corrosion can substantially reduce the load-carrying capacity of a structural element.

Figure 3-9 Broken wires of a corroded tendon

3.2.3.3 Honeycombing

Honeycombing is a commonly met defect of concrete: it can be produced by inadequate grading of the mix and/or poor compaction, both of which produce voids and segregation of the aggregate from the cement paste.

3.2.3.4 Inadequate cover

Inadequate concrete cover is also a commonly met defect of concrete structures. It can occur through poor detailing or construction practices. Its effect may not be noted for sometime. The depth of cover can be measured by NDT techniques.

3.2.3.5 Scaling

Scaling is the gradual but continuous loss of the surface of a structure.

3.2.3.6 Spalling

Spalling occurs as a localised depression on the surface of a structure. It can be caused by corrosion and by frictional forces generated by thermal movements. Where unchecked, spalling will often lead to the exposure of the reinforcement in concrete structures.

3.2.3.7 Delamination

Delamination occurs when concrete layers separate at or near the outermost layer of the reinforcement. It can be generated by corrosion of the reinforcement, and by freeze-thaw cycles. It usually occurs when reinforcing bars are closely spaced and/or where they are installed at too great a depth from the surface of the concrete. It is similar to spalling except that it affects larger areas and can often only be detected by echo-location; that is by tapping.

3.2.3.8 *Disintegration*

Disintegration is a process where the concrete deteriorates into fragments and then into small particles. It can be initiated and promoted by weathering, corrosion, erosion and chemical attack. It is usually only observed on secondary elements, such as concrete slabs, kerbs and the like.

3.2.3.9 *Alkali-silica reaction*

Alkali-silica reaction occurs when alkaline pore water in the cement paste reacts with minerals present in some aggregates to form a calcium alkali-silicate gel. In taking up water from the pores, the gel expands and disrupts the concrete. The signs of ASR deterioration may not become visible until many years following the end of construction. The typical crack pattern of ASR is shown in Figure 3-10.

Figure 3-10 Cracking of a concrete wing wall due to ASR

3.2.3.10 *Breaking-away*

The breaking-away of concrete is usually the consequence of impact forces, or temperature effects where the gap between adjacent elements is too small to be sustained without an adequately designed joint.

3.2.3.11 *Deterioration of protective coatings*

Coatings can deteriorate and eventually fail due to poor application practices and environmental effects - such as ageing, efflorescence, and weathering. Damage can take various forms such as cracking, peeling, and blistering.

3.2.3.12 *Damage to mortar coatings*

Some concrete elements, such as abutments, piers and retaining walls, are sometimes provided with a mortar coating. Through ageing, temperature and other effects such coatings tend to crack, disintegrate and spall.

3.2.3.13 Stratification

This is the separation of concrete into horizontal layers with the increasingly lighter material displaced toward the top. It can result from placing over-wet or over-vibrated concrete, and from placing over-thick lifts of concrete with or without adequate compaction between them.

3.2.4 Structural steel, aluminium, cast and wrought iron

3.2.4.1 Fatigue cracking

Fatigue cracks can occur in steel and aluminium structures through cyclic loading. They can also be initiated by stress-corrosion - particularly in steel elements subject to both tension and cyclic stresses, and by hydrogen embrittlement. Initially the cracks propagate slowly but if they are not treated they can and frequently do lead to a brittle fracture.

3.2.4.2 Fracture cracking

Fracture cracks can be generated by stress or strain concentrations and by low in-service temperatures: they are often triggered by a sudden increase in load. By its nature, fracture cracking occurs with little or no preceding plastic deformation. To avoid such cracking, structural elements must be formed from materials of the appropriate metallurgical composition.

3.2.4.3 Corrosion

Corrosion of metallic components can be initiated and promoted in a number of ways; the main ones are:

- environmental corrosion - this primarily affects metals in contact with soil or water, particularly where it is contains aggressive species such as chloride and sulfate ions
- stray electric currents - primarily in the vicinity of electric rail lines
- stress corrosion cracking - due to cyclic stresses
- galvanic corrosion - this can be induced where electrically incompatible metals are connected together
- crevice corrosion - this can be generated where moisture is present in narrow cracks or gaps between metallic components
- bacteriological corrosion - this is promoted by organisms, such as sulfate-reducing bacteria.

As shown in Figure 3-11, corrosion can seriously reduce the strength of structural members.

Aluminium structures can suffer from pitting corrosion but its effects are rarely serious. However aluminium culverts and underpasses are particularly susceptible to pitting corrosion and so are not permitted in some States.

3.2.5 Corrugated steel buried structures

There are a number of agents of deterioration of corrugated steel buried structures (CSBS); some are specific to culverts but others affect culverts and underpasses alike. They can be loosely grouped into those that affect the structural condition and those that affect material condition, but some may affect both. It should be appreciated that lack of attention to material condition will eventually lead to problems of structural stability; for example, corrosion of the bolts and/or the joints of a CSBS can lead to progressive collapse.

Figure 3-11 Corroded steel superstructure

3.2.5.1 Agents promoting structural instability or distortion

- *Differential settlement* can be generated by variations in the depth or properties of the soils along the line of a CSBS, by the consolidation of the soils beneath a structure, and by movements related to mining activities. Because of their tolerance to differential movement, CSBS are often installed on poor ground and in areas subject to mining. They can withstand significant ground movements without much loss of stability, but the level of service can be reduced.

- *Washout of soil around a structure* - the flow of water into and around a CSBS can lead to the washout of fines from the adjacent soils. If unchecked, this could lead to the loss of support to the structure, which in turn could lead to distortion, and ultimately collapse. The invert of a culvert where hydraulic wear and corrosion have perforated the steel shell is most at risk from this form of degradation.

- *Encroachment of construction plant* - the movement of heavy earth-moving equipment during or immediately following the placement of the backfill to a CSBS can lead to distortion of the structure.

- *Inadequate structural support* - this may occur where a CSBS is installed in particularly poor ground or where the stiffness of the backfill is too low. Lateral support would be reduced where, for example, trenches are dug alongside a CSBS for the installation of service ducts. The stability of a multi-span installation can be compromised by substantial distortion of a single span. Closed invert multi-radii structures are particularly susceptible to deformation due to inadequate foundation support.

- *Differential loading* - a large variation in the depth of cover or (far less commonly) the applied highway loading can lead to distortion of a CSBS.

3.2.5.2 Agents promoting degradation of materials

- *Flow characteristics of the stream* - culverts may carry a continual flow of water, contain near-stagnant water, or carry intermittent flows. Erosive forces, generated by the flow of water and waterborne debris, can scour the interior surface of a structure. Misalignment of a culvert with respect to the watercourse may generate turbulence and erosion within the structure (commonly at the inlet) and lead to overtopping of some part of a pavement.

- *Chemicals in the water flowing through culverts, and in the backfill and soil* - corrosion can be initiated and promoted by the presence of particular ions. The sources of these include; de-icing salts, agricultural chemicals (nitrates), and leachates (contaminated or with a particularly high or low pH) from the soil. Deterioration occurs around points of entry, such as joints and bolt holes, and so is commonly found at the crown, but it may also occur around the springing of an arch at its foundation.
- *Weathering* - this includes exposure to wetting and drying cycles, ultra violet light, and heat: these all affect the longevity of secondary coatings. Hot-dip coatings to AASHTO Standard M190 are susceptible to degradation through wetting and drying cycles. Bituminous materials are prone to deteriorate where they are exposed to sunlight at the ends of a CSBS, particularly one with bevelled ends.
- *Soil and backfill* - factors to be assessed include pH, chemical constituents (essentially the concentrations of chloride, sulfate and sulfide ions), organic content, particle size, resistivity, and the plasticity index of the fines fraction. With a particularly aggressive backfill, such as steel slag, deterioration is extensive and severe and the steel shell may be perforated shortly after the end of construction. With a less aggressive backfill, deterioration may be seen at seepage points on the inside of a structure.
- *Atmospheric conditions* - few CSBS should be at risk of deterioration through the effects of airborne pollution - as generated by power stations and industrial process plants (such as steel and petrochemical works), but the exposed surfaces of CSBS in coastal regions can be degraded by salt-ladened spray.
- *Stray electric currents* - such currents may lead to rapid and localised deterioration. Currents may derive from leakage from damaged buried cables, or from earth currents from railways with overhead or third rail electrical power systems. (There have, however, been no reported incidences in the UK of deterioration of CSBS due to stray currents.)

Of the above, the principal agent of deterioration in culverts is hydraulic wear along the invert and degradation along the wet/dry line. The loss of protective secondary coatings exposes the underlying galvanised steel plate to corrosion: the rate of corrosion can be particularly high in the presence of acidic or chloride ion-rich water. The principal causes of corrosion include (a) the infiltration of chloride ion-rich water originating from de-icing salts spread on the overlying carriageway and (b) the effects of chemically aggressive backfills.

3.2.5.3 Damage to coatings

Protective coatings can be damaged by in-service use, ageing and weathering. Corrosion of the underlying metal substrate can thus follow from the chemical breakdown of the coating, mechanical damage to the coating during transport/erection or in-service use, as well as by electrical disbondment. The damage can take various forms such as cracking, peeling, and blistering.

3.2.5.4 Damaged or missing connectors

Rivets, bolts, nails and the like can be damaged, dislodged from their position or sheared off by applied loads (particularly impact loads) and by corrosion. In some elements, such as pot bearings, connectors may not have been installed during construction. Welded connections may also be cracked.

3.2.5.5 *Silting of inverts*

The silting of inverts occurs in structures built on waterlogged ground or where flow rates are particularly low. In such cases, it is difficult to inspect and maintain the invert. A structure can be damaged by mechanical equipment used to clear the silt: this problem also occurs in concrete box culverts.

3.2.6 Stone and brick masonry

3.2.6.1 *Scaling, spalling and delamination*

Scaling is the gradual and continuous loss of the surface of a structure; it can affect both stone and brick masonry.

Spalling is a localised depression at the surface of a structure: it occurs where the outer layers of masonry break off in parallel layers from the parent blocks.

Delamination occurs when the outer surface of masonry splits into thin layers and peels off the surface.

3.2.6.2 *Falling-out of units*

Masonry blocks can be dislodged from structures due to the disintegration of mortar and movements of the structure.

3.2.6.3 *Cracking*

Cracks in brick and stone masonry have various causes and can take various forms. Cracks are usually found in combination with some form of deformation (such as settlement, tilting, and buckling). Longitudinal cracking between a spandrel wall and the arch barrel of a bridge is a common problem, see Figure 3-12.

Due to the loss of mechanical bond between adjacent rings, cracking can occur as ring separation. Splitting cracks can occur as a result of temperature change, and through frost action. Cracking can form through both mortar joints and masonry units.

Figure 3-12 Cracking of a spandrel wall of a masonry arch bridge

3.2.6.4 Friability

Some types of stone, such as sandstone or limestone, have a tendency to crumble, break up or powder.

3.2.6.5 Disintegration of mortar

Mortar can disintegrate through the effects of ageing, weathering, temperature variations, moisture, freeze-thaw, and chemical reactions with percolating water.

3.2.6.6 Detachment

The detachment of brick and stone units or panels can occur through the failure of construction joints or structural joints and also through the loss of mortar from a structure.

3.2.6.7 Corrosion of metallic connectors

The corrosion of metallic connectors in masonry structures can be promoted in the presence of moisture - particularly where it is contaminated with aggressive ions. The rupture of ties can lead to substantial deformation or even the collapse of a superstructure.

3.2.6.8 Peeling of mortar coating

Some masonry structures are provided with a mortar coating but with time, due to ageing, temperature, moisture and other effects, the mortar tends to peel away from the surface.

3.2.7 Timber

3.2.7.1 Splitting

Splitting of the timber can be generated by loading and by weathering.

3.2.7.2 Decay

Timber is attacked by fungi and other organisms that use woody tissue as food. The rate of attack is usually a function of the in-service environment conditions; principally moisture, temperature and access to oxygen.

3.2.7.3 Deterioration of impregnants

The protection provided by impregnants deteriorates through the effects of ageing and weathering. The signs of deterioration are discolouring of the timber surface and fungal growth.

3.2.7.4 Elongated bolt holes

Oversized bolt holes can develop in timber that has insufficient bearing capacity, or from incorrectly positioned or formed drill holes. The consequence can be the unequal distribution of load among a cluster of bolts.

3.2.7.5 Corrosion of metallic connectors

Corrosion of metallic connectors (such as nails, bolts, screws, and rods) can be promoted by moisture, particularly when it contains aggressive species. Note that some timber preservatives can be aggressive to metallic components.

3.2.8 Asphalt pavement

3.2.8.1 Cracking

Cracks in pavements can be generated by various causes; the most common are temperature changes, shrinkage upon cooling, dynamic loading, discontinuities in the construction, and settlement of the subgrade. Cracks can take various forms including longitudinal, transverse and sets of intersecting diagonal cracks (‘alligator’ cracks).

3.2.8.2 Plucking-out of aggregate

The aggregate within an asphalt matrix can be lost in-service due to inadequate binding action and/or weathering of the binder.

3.2.8.3 Tracking

Tracking can develop on road pavements through the use of inadequate materials, poor construction practices, in-service conditions - particularly the passage of heavy wheel loads, and the ageing of the pavement material.

3.2.9 Waterproofing membrane

Details of waterproofing membranes are provided in the WG 6 report on remedial works (COST, 2004).

3.2.9.1 Deterioration

Waterproofing membranes can fail due to the use of inadequate materials, poor application - particularly during bad weather conditions and on inadequately prepared surfaces, as well as excessively high wheel loads and temperature variations.

3.2.9.2 Detailing

Inadequate detailing of the waterproofing membrane around particular elements, such as pipes, can lead to leakage around such elements - which in turn can lead to localised and severe deterioration.

3.2.10 Bonded plates

The bond between a metallic or plastic plate and the underlying substrate can be lost where stresses in the anchorage zones are too high and the plates have not been provided with adequate mechanical anchorage devices. Debonding can occur where the inherent strength of the adhesive is too weak to resist the stresses or it has not been applied properly; for example, through inadequate preparation of the substrate. Bond failure can occur at various horizons and interfaces, such as:

- in the concrete near the surface or along a weak layer - such as the line of embedded steel reinforcement
- within the adhesive - at the interface between the concrete and adhesive, or between the adhesive and added plates
- between the fibres and resin within an FRP plate.

Peeling-off can be generated at shear cracks or by unevenness over the surface to which the plates are bonded.

3.2.11 Disintegration of mortar

Through the effects of weathering, temperature variations, reaction with percolating water and loading, the mortar in the joints between structural or non-structural elements can degrade with time.

3.2.12 Deterioration of sealants

Sealants tend to deteriorate due to their inherently poor resistance to weathering, through inadequate adhesion to the substrate, and ageing. The evidence of deterioration can be seen from the initiation of cracks, and their propagation, and the disintegration of the material. Vegetation can often establish itself in gaps left by a deteriorated sealant.

3.2.13 Damage to equipment

The equipment installed on highway structures can be damaged by applied loads, vandalism and by material deterioration. Damage due to loading can usually be described as warping, rupture, missing components, displacement, and tilting. The deterioration of safety barriers, kerbs, and drains, is usually due to the disintegration and cracking of the materials and/or connectors, with or without corrosion of the reinforcement. Steel elements, such as lighting columns, safety barriers, and railings can be corroded; sometimes through the breakdown of their corrosion protection system.

The fixing bolts of expansion joints, bearings, sign gantries, safety barriers, lightning columns, and so on can be corroded or damaged in-service: in some cases the bolts may be missing. The effect of this deterioration or deficit varies according to the type of equipment.

The rubber surface of expansion joints can be scarred by wheel loading or the passage of snow ploughs: see Figure 3-13. Similarly, the types of glass used in some noise barriers can be scratched and pock-marked by the impact of salts and sands that are spread on the highway during icy weather.

Figure 3-13 Detachment of elastomer in an expansion joint due to overstretching and/or wheel loading

3.2.14 Vandalism

The most frequent forms of damage due to vandalism are graffiti; broken sign posts, lamps, and drain pipes; and the removal of elements such as traffic signs and the components of safety fences.

3.2.15 Deposits behind piers

Floating objects such as branches, small trees and, in times of particularly high water, even large trees can be caught behind bridge piers. In the course of time, the stockpiling of such debris may increase the loads on a pier and on its foundations.

3.2.16 Reduced clearance under bridges

Flowing water can deposit rocks, sand, and timber under or in the vicinity of a bridge. Such deposits can reduce the clearance under a bridge, which in turn can change the water flow characteristics and hence produce flooding behind or around the bridge. A blockage may lead to water finding its way along the outside of a culvert and thereby lead to erosion of the back-fill around it, which if left unchecked could lead to the collapse of the structure.

3.2.17 Uncommon defects

3.2.17.1 Bullet holes

The presence of bullet holes (see Figure 3-14) from an armed conflict or vandalism must be taken into account.

Figure 3-14 A bullet hole in a steel structure

3.3 RECOMMENDATIONS

Inspecting the condition of a structure and evaluating the observations are essential tasks in managing the stock of highway structures. A good deal of effort has gone into establishing appropriate methods for bridges, but far less has been undertaken for other types of structure.

Recommendation 5 Methods and techniques should be available for assessing the condition of all types of highway structure. As a starting point those developed for bridges

can be adopted to other highway structures, but the evaluation of defects for other structures must be determined with respect to the nature and type of loading acting on them.

New materials and methods of construction are promoted, by various organisations, as means of reducing construction costs, improving serviceability and reducing maintenance costs. However, commonly, little is done to determine how structures built using new materials or methods will be inspected, assessed and monitored in the field.

Recommendation 6 A range of new materials is now being promoted for the construction and repair of bridges but, at present, their long-term durability has only been assessed from laboratory tests. It is essential to observe the in-service performance of these new materials, and continuous performance records should be established for them as a matter of course. Appropriate equipment should be developed for detecting and monitoring deterioration processes.

There is a paucity of information on the performance of the stock of existing structures.

Recommendation 7 Long-term studies should be undertaken to track the initiation and propagation of defects and deterioration processes. Such studies should cover a range of structural types, and both ageing and new structures.

Chapter 4 Inspection

4.1 INTRODUCTION

The underlying reasons for inspecting a highway structure are:

- to confirm that the structure is fit for purpose, and will remain so in the immediate future - that is, the rate of deterioration is acceptably low,
- to identify any obvious defects or instances of misuse, such as vehicle overloading, that may affect the safety of the public using the structure
- to establish plans and estimates for undertaking remedial works.

These are achieved by observing and recording the condition of a structure, or particular elements of one, and when necessary providing appropriate information to an engineer to enable decision(s) to be taken on the timing and type of the remedial works. Thus the aims of an inspection include one or more of the following:

- detection of defects and signs of structural distress
- determination of the occurrence, extent and cause of material degradation
- detection of changes in use that can affect safety and/or durability
- evaluation of the effectiveness of various repair techniques
- provision of information for assessing load-carrying capacity
- determination of the condition of a structure, or of particular elements of one - the use of the results of an inspection to determine a condition rating is covered in Chapter 7.

Inspections may involve:

- a visual examination of the structure
- in situ tests and/or sampling and laboratory tests
- the use of access equipment
- traffic management works
- the completion of standard forms and/or the production of a report.

Various inspection procedures and techniques have been devised and implemented for bridges in different European States. The main differences between them lie in the definition of a bridge, the scope and intensity of the investigation, and the time-interval between the inspections. This chapter reviews the current inspection procedures used in the States participating in COST 345, recommends improvements to these practices, and identifies research needs.

As shown by the review, inspection procedures have only been developed for bridges, but it has been reported that in some States the procedures have been adapted and implemented for other types of highway structure.

4.1.1 Safety

Inspections of highway structures carry an element of risk and so in planning an inspection the safety of the users, inspectors and, on occasions, the structure itself must be considered. A risk assessment may be undertaken prior to an inspection.

By and large, the type of structure will dictate the safety measures required: thus they will be different for a tunnel, a wide viaduct and a narrow arch bridge. But they will also vary according to the location and the weather conditions at the time of the inspection. In most cases some form of traffic management will be required to prevent accidents occurring as a result of the inspection process.

Inspectors must comply with the safety requirements defined in the relevant national code(s), and should use the appropriate equipment necessary to ensure their own safety. The type of equipment varies according to the job at hand, but inspectors should be clearly visible and identifiable by their working dress. For some structural elements, such as high piers and retaining walls, abseiling may have to be used to obtain access for close inspection. In these cases it may be productive to hire specialists who are trained climbers and also have some knowledge about structural engineering and/or material science. Similarly, a specialist would usually be engaged to carry out an underwater inspection.

The safety of the structure must be considered when an inspection involves a loading test using, for example, a heavy vehicle or vibration device. Similarly, safety must be assessed when destructive tests and/or specimens are to be taken, by coring for example, from a structural element - particularly one that has deteriorated.

4.2 CURRENT POSITION

4.2.1 Inspection procedures

The procedures used in a number of European States and in the USA are considered in the following. The aims are to provide an overview of the existing procedures and to highlight their common features and significant differences.

4.2.1.1 Austria

In 1987 the Austrian Ministry for Economic Affairs issued ‘Procedures for assessing the extent of bridge rehabilitation’: this describes the procedures and instructions for assessing the condition of bridges. A systematic inspection is undertaken on all bridges having a span in excess of 2m. The data are used to assess the condition of the stock of bridges. Three types of inspection are carried out:

- **Superficial Inspection**. This type of inspection is carried out by maintenance personnel as they travel the road network. A written report is made only where a defect or improper use of some part of a bridge is observed: thus such reports would mainly concern surfacing, parapets, drains and the like - only rarely would they concern the main structural components.
- **General Inspection**. This type is carried out by trained personnel under the supervision of a bridge engineer. It is carried out every two years, and also following an exceptional event such as an earthquake, flood, landslide, fire or a long period of hot weather. Only the accessible parts of a bridge are inspected. A report on the condition of the structure is produced for each inspection.
- **Major Inspection**. This type is carried out every six years. The aims are to obtain detailed information on the condition of the bridge, and its components; assess serviceability and load-carrying capacity; recommend regular and urgent maintenance work or load restrictions; and set the timing of the next Major Inspection. To achieve these aims all parts of the

bridge are accessed using simple or purpose-built devices. A report on the condition of the bridge is prepared for each inspection.

The condition of a reinforced and/or prestressed concrete bridge is assessed from the condition of its various elements and of other structures in its vicinity. The former include the concrete surface, bearings, expansion joints, carriageway, drainage system, equipment - such as parapets, safety barriers, and lighting columns, whilst the latter include embankments and riverbanks. The presence of cracks and open joints; corrosion of reinforcement, tendons and cables; and wetting of the concrete surface are recorded. Each type of defect is divided into several categories; for example, cracks are classified according to their width.

4.2.1.2 Denmark

The Danish Road Directorate uses the DANBRO system for managing its bridge stock: for details of this system see, for example, Lauridsen and Lassen (1998). The aim of this system is to help decision-makers maintain the stock in the desired condition at the lowest possible cost. To do so requires accurate information on the condition of the bridge stock. Bridges with a span of 5m or more undergo regular inspections; three types are undertaken:

- **Superficial** or **Routine Inspection**. This type of inspection is carried out during regular maintenance work, and is undertaken to detect major defects or abnormal service conditions.
- **Principal** (**Major**) **Inspection**. This type is carried out by well-trained engineers and involves a visual inspection of all accessible parts of a bridge. Normal inspection intervals are 3 years but, depending on the condition of the bridge, that may vary from 1 to 6 years. Significant defects on all components of the bridge are recorded and assessed. A report is prepared for each inspection and this should state when the next Principal Inspection should be carried out, or whether a Special Inspection is required.
- **Special Inspection**. This type is carried out on the basis of the recommendation of a Principal Inspection, or from a ranking list. It comprises a thorough investigation of a bridge, or part of one, including, as necessary, on-site and laboratory tests. The type and extent of any deterioration or deficiencies are established together with their causes and the likelihood of further deterioration. Unless the damage is insignificant and the optimum repair strategy is obvious, this type of inspection is always carried out before remedial works are undertaken: the results are used to select the repair strategy or determine the priority for repair works where funding is insufficient to complete all the work that has been recommended.

For inspection purposes, a bridge is divided into 15 standard components and the type and extent of any damage is determined for each component. The condition of a bridge is evaluated from the condition of its components.

It is assumed that inspectors are capable of assessing the degree of deterioration and are able to identify those parts of a bridge that require a more detailed investigation.

4.2.1.3 France

On the French national road network all bridges with spans greater than 2m are subject to regular inspections and condition assessments. The data from these are used to provide up-to-date information about the condition of the bridge stock. The main types of inspections are:

- **Annual check** (**Superficial Inspection**). A brief inspection is carried out on a bridge at the same time as the annual routine maintenance operation. The report from the inspection identifies the bridge, the date of inspection, and any defects or changes to the structure.

- **Assessment Inspection**. This is a rapid visual inspection of all accessible parts of a bridge. The condition of the bridge is assessed according to the IQOA (Image of Bridge Quality) method, which is covered by a number of publications. In this method, several descriptive categories of defect are defined for different types of structure: in all there are 25 categories. This type of inspection is carried out on all bridges every three years (one third of the stock each year). Where a detailed inspection has been conducted during the year, the IQOA assessment is based on the report for that inspection.
- **Detailed Periodic Inspection**. In principle this type of inspection is carried on medium and long-span bridges every six years, but in practice the interval may be increased to 9 years for a structure in good condition or reduced to 1 or 3 years for a structure in poor condition. The inspection should cover all parts of a bridge, and so it may require the use of access equipment. The inspections are undertaken and supervised by a qualified engineer who has been trained in bridge pathology. The report from the inspection should provide a detailed description of the condition of the bridge.
- **Detailed Inspection**. This type of inspection is undertaken for a specific purpose, such as:
    - Preliminary Inspection - to define a reference state when a bridge is commissioned or following major repair works.
    - Guarantee Inspection - to check the condition of a bridge before the end of the guarantee period (10 years), or at the change over of responsibility for the structure.
- **Exceptional Inspection**. This type is undertaken to check the condition of a bridge following unusual circumstances; for example, a severe anomaly in performance, the start of construction work in the vicinity of the structure, and natural disasters such as earthquakes, floods and fires that may affect the performance of the structure.

Other monitoring activities are:

- Continuous monitoring - undertaken by qualified maintenance personnel.
- Intermediate continuous monitoring - this may be justified by the condition of a bridge or where there is uncertainty about the presence or the effects of defects.
- High level monitoring - this is undertaken where defects threaten the safety and strength of a bridge, or important elements of one.

Standard inspection report forms have been developed for most types of bridge. These are designed to enable personnel without any particular expertise in bridges to classify various defects. The forms contain graphical information about the morphology of the bridge and a checklist with diagrams of all the types of defects that may be present.

4.2.1.4 Germany

The monitoring of structures is undertaken in accordance with DIN 1076, which describes the following types of inspection:

- **Superficial Inspection**. This type of inspection is usually undertaken on a quarterly basis. Its aims are to spot major defects and to check the functioning of expansion joints, bearings, drainage systems and safety barriers. And, annually, a visual inspection of all accessible parts of the bridge is undertaken to check for major defects.
- **General Inspection**. This type is undertaken every three years. It comprises a visual inspection of all parts of the bridge that are accessible without the use of special equipment, and site tests that do not require the use of special equipment.

- **Major Inspection**. For this type of inspection, access must be gained to all parts of the bridge: for large structures this often requires the use of specialised equipment. As well as a visual assessment, field tests may be undertaken to determine material properties. The first Major Inspection is carried out before the bridge structure is opened to traffic; the next is carried out before the end of the guarantee period (after five years service); they are then undertaken every six years.
- **Special Inspection**. This type is carried out on the basis of the results of structural monitoring. Its aim is to obtain an in-depth view of some particular defect, damage or deterioration process.

The results of monitoring and testing are presented in a report, and such reports are added to the construction register for the structure. (A register is prepared for each structure. Its purpose is to document information that is important for maintenance works: thus it also contains design information.)

To help achieve consistency and reliability, inspection teams are equipped with catalogues that illustrate different types of damage.

Standard guidelines are used to determine the condition of a bridge. The basis for deriving a condition assessment is described in the guidance document RI-EBW-PRÜF, and details of the method are provided in AV.4. According to this document, a structural inspection includes the detailed recording and assessment of all damage and faults. In practice, however, identical occurrences are evaluated differently. Furthermore, there is no unique relationship between damage evaluation and the assignment of a condition rating; indeed the rating is derived for the whole structure. Thus although the rating is derived from the condition of individual defects, in the final analysis it is based on the subjective assessment of the inspector.

4.2.1.5 Norway

Structures on the Norwegian road network that are owned by the Public Roads Administration are considered to be bridges when the accumulated span or total length is 2.5m or more. These structures are regularly inspected: the types of inspection vary in terms of their thoroughness and frequency. The inspection cycle starts at the end of construction.

- **Acceptance Inspection**. This type of inspection is undertaken before or at the time a new bridge is handed over, and following the completion of remedial works on an existing bridge. With the former, the purpose is to identify deficiencies, damage or defects that have arisen during construction, as well as inappropriate detailing and any source of deterioration that may generate problems in the future. With the latter, the purpose is to check the quality of the work. The inspection includes a visual check of the entire bridge supplemented, where necessary, with site- and laboratory-based tests.
- **Guarantee Inspection**. As above, this type of inspection includes a visual check of the entire bridge, supplemented by testing. The purposes of a Guarantee Inspection are to check that any construction work or repairs undertaken following the Acceptance Inspection are acceptable, and that no new damage, faults or deficiencies have appeared: any new source of deterioration that may affect maintenance should be identified. A Guarantee Inspection should be undertaken well before the deadline for submitting claims for structural inadequacies for example.

For new bridges, the above may involve the examination of submerged foundations and the examination and testing of suspension cables.

Following hand-over, the following types of routine inspections are carried out throughout the service life of a bridge:

- General Inspection
- Major Inspection
- Inspection of cables
- Underwater inspection.

A Special Inspection may be undertaken as a complement to the above or in the event of an extraordinary occurrence.

- **General Inspection**. The objective of this type of inspection is to check for damage that can adversely affect the load-carrying capacity of the structure, traffic safety, future maintenance and the environment or aesthetics. Particular attention is given to details or locations exposed to the environment. The inspection comprises a visual check but does not include testing or the use of special equipment. The minimum requirement of the inspection is to identify and record damage that needs attention prior to the next inspection. Normally General Inspections are undertaken annually with the first completed within the year following the hand over of the bridge, but a General Inspection need not be undertaken in the year when a Major Inspection is carried out. The frequency of an inspection may be increased or decreased at the discretion of the engineer responsible for managing the structure.
- **Major Inspection**. The purposes of this type of inspection are to check that the bridge is functional and to determine the need for maintenance work - and, if so, to plan and estimate the cost of any such works. It entails a visual check of the structure, supplemented - where necessary - by any investigations necessary to determine its condition. This may involve a check of the condition of cables, hangers and anchorages, and underwater inspections. A Major Inspection is generally required every five years but this can be varied at the discretion of the engineer. The first Major Inspection is carried out at the required interval following the end of the deadline for claims.
- **Special Inspection**. The purposes of this type of inspection are to investigate any damage, out-of-alignment or deterioration identified by previous inspections, and to specify any follow-up work that may be required. Thus such inspections may be carried out where earlier inspections have found defects that require further investigation, and also following incidents such as a collision, overloading and flooding when experience indicates that there is a need to do so. The inspection is normally undertaken on exposed or damaged elements, but it may encompass an entire bridge. It may include a visual check, site measurements, and an investigation of material properties, or a combination of these. The inspection report should describe the damage, defects and deficiencies found on a structure and assesses how these could affect each element and the bridge as a whole. The degree of damage is expressed numerically both to provide a quantitative measure of the magnitude of the problem and to judge whether remedial works are required or not and, if so, when such works should be undertaken.

4.2.1.6 Poland

In the early 1990s, a bridge inspection system was established for the Polish national road network, which is administrated by the General Directorate for Public Roads. The system is in line with the 1992 OECD recommendations for bridge management.

About 15 per cent of the road bridges in Poland are on the national network, but they account for 33 per cent of the total span length - which means that the national network includes the longest and most important bridges. The independent administrators for the other road networks have also adopted the inspection system.

The system only covers bridges, culverts and tunnels. There are no specific guidelines for inspecting other highway structures such as retaining walls, but these structures are examined every quarter as part of the routine inspection of the highway.

The system defines four types of inspection:

- **Routine Inspection**. This type of inspection is undertaken at least every quarter by road maintenance engineers, although an inspection may be triggered by an unusual incident, such as a flood, overloading, or accident involving construction plant or heavy vehicles. The aims of the inspection are to confirm the functionality and safe use of a structure, and to record defects that require attention in the immediate or near future.
- **General Inspection**. This type of inspection is carried out annually, but one may be triggered by an unusual incident (as above) or by the findings of a Routine Inspection. The aim of a General Inspection is to identify and record structural changes that have occurred in service. The following are reported from such an inspection: the functionality and safe use of the structure; potential detriments - which should be treated in the immediate or near future; and the necessity for a Principal Inspection of the structure or a Special Inspection of particular elements. A General Inspection should be undertaken by a civil engineer (at least graduate level) who has attended the appropriate training course(s).
- **Principal Inspection**. This type is undertaken at least every five years, but one may be undertaken on the basis of the findings of a General Inspection. Its aims are much the same as stated above for a General Inspection. A Principal Inspection should be undertaken by a team of specialists led by an experienced civil engineer who has attended the necessary training course(s).
- **Special Inspection**. This type is undertaken, as and when required, by specialist engineers.

The inspections form an integral part of the Bridge Management System, and the findings enable the road maintenance authorities to plan and carry out any necessary remedial works. The results from an inspection are used to assess the condition of particular bridge elements according to a six-point scale ranging from 0 (emergency action required) to 5 (adequate condition). The condition of a bridge is based on the mean assessment of its principal elements.

4.2.1.7 Slovenia

From 1986 to 1988, the Slovenian National Building and Civil Engineering Institute carried out a survey across several European States of current practices for the inspection and assessment of bridges, and prepared guidelines for assessing the condition of bridges managed by the Slovenian State Road Administration. The results of this work form the basis for the inspection and assessment of the condition of bridges and, from 1990, all bridges, viaducts and underpasses with spans of 5m or more have been regularly inspected and assessed. Tunnels are included in the inventory and covered by the system of inspection. For recording and evaluating defects, a bridge is divided into components and main elements, which are further divided into sub-elements. The location of a defect is described by reference to the component or element. The following types of inspection are carried out:

- **Superficial Inspection**. This type of inspection is undertaken, at least annually, by maintenance personnel as part of their regular activities. It comprises a visual check of the condition of the visible components of the structure, such as the pavement, railings, and expansion joints.
- **General Inspection**. This type is undertaken every two years by trained personnel guided by a structural engineer. It comprises a visual examination of all accessible parts of the bridge: inaccessible parts may be inspected using binoculars. The inspection report de-

scribes the type, extent and intensity of observed defects for each component and element of the structure. As appropriate, the report should also give recommendations for maintenance, remedial works, bringing forward a Major Inspection, and for carrying out a Special Inspection with field measurements and/or laboratory tests. The condition rating of the main bridge components, and hence of the entire bridge, is computed on the basis of the intensity and extent of each type of defect and the influence that each of the affected bridge elements has on safety.

- **Major Inspection**. This type is carried out every six years. It comprises a visual check of all bridge elements, and so access via standard or specialized equipment must be provided to every part of the bridge. The inspection may include an underwater examination of the bridge foundations and the riverbed around them. All defects must be assessed from a close distance and an estimate made of their type, extent, and intensity of damage. The report has the same scope and format as for a General Inspection. For a highway bridge, a Major Inspection must be undertaken before it is opened to traffic; before the end of the guarantee period; and following any substantial repair work.
- **Special Inspection**. This type is carried out as and when recommended in the report of a Major or General Inspection. It comprises an in-depth investigation of the distressed parts of a structure. All defects must be mapped. Field measurements and laboratory tests are undertaken to investigate the condition of the damaged areas: the results of the tests are used to categorise the defects and form the basis for determining the most suitable method of repair.

General or Major Inspections of bridges are also carried out after natural disasters, such as earthquakes, floods, fires, and landslides. The scope of the inspection depends on the importance, size and accessibility of the bridge.

4.2.1.8 Spain

Three types of inspection are undertaken in Spain:

- **Superficial Inspection**. This type of inspection is usually undertaken on an ad hoc basis by maintenance personnel. The objectives are to check the functionality of the main elements, to detect major faults that affect safety and (where possible) load capacity, and to report any damage that if not dealt with may lead to higher maintenance expenditure. Inspection is limited to particular elements, such as the pavement, expansion joints, drainage system, safety fences and barriers, parapets, and (where possible) foundations.
- **Principal** and **General Inspections**. These types of inspection are undertaken every 2 to 5 years - the interval varying with the degree of deterioration, maintenance policy and available funds. They comprise a visual inspection by trained engineers. For inspection purposes, the various parts of a structure are broken down into elements: the definition of an element depends on the detail required to evaluate the condition of the structure; for example, a substructure may be defined as a single element, or be broken down into bearings, pier caps, columns and foundation slab. Thus, prior to an inspection, it is necessary to define the elements and groups of elements that must be considered. The standard documents used for an inspection comprise:
    - a list of the structural elements to be inspected
    - a list of the most common types of damage that can occur
    - report forms.

Standard forms are also used to ensure that the vast amount of data generated by a series of inspections can be collated and used to monitor the condition of a structure over time, to compare the condition of different structures, and to obtain a view of the condition of the stock of structures.

4.2.1.9 Sweden

In 1996, the Swedish National Road Administration issued a bridge inspection manual (1996:036 E) that defined standard methods for collecting and assessing information on bridges. The underlying aim of this was to ensure that bridges are inspected on a regular and systematic basis so that the demands of road users regarding safety and traffic flow are satisfied. There are several types of inspection:

- **Regular Inspection**. This type of inspection is undertaken by the maintenance contractor. The aim is to detect acute damage that could affect the safety of road users and the immediate integrity of the structure. Usually, the inspection is limited to the top of the bridge and the embankments adjacent to the structure.
- **Superficial Inspection**. The maintenance contractor carries out this type of inspection at least twice a year for bridges on the national road network, and at least annually for other bridges. The aim is to verify compliance with the requirements of the maintenance contract. The inspection is undertaken on structural members and elements for which performance specifications have been established. The inspection is undertaken by engineers with a good knowledge of the appropriate methods of measurement and who are familiar with the structural design and mode of behaviour of the bridge.
- **General Inspection**. The aims of this type of inspection are:
    - to follow up assessments and recommendations of the preceding Major Inspection
    - to detect and assess damage that could compromise load-carrying capacity or user safety, or lead to a substantial increase in administration costs if it was not detected before the next Major Inspection
    - to check compliance with the requirements of the maintenance contract - and to quantify any deviation from them.

It comprises a visual inspection of all the structural elements of a bridge, except those below water, and includes adjoining structures such as earthworks, abutments, revetments and impact protection barriers. Optical aids can be used where inspection has to be done from a distance. This type of inspection is carried out at least every three years for bridges having a span in excess of 5m: inspections on shorter bridges are undertaken as and when necessary. An inspector should comply with the requirements specified below for a Major Inspection (see also Chapter 8).

- **Major Inspection**. The aims of this type of inspection are:
    - to detect and assess defects that may affect the function of the structure or traffic safety within a ten-year period
    - to detect defects that, if not remedied within this period, may give rise to increased costs
    - to check that the requirements specified in maintenance contracts are complied with - any deviations from these should be quantified.

All structural elements, including those below water, and adjoining structures are inspected: it also covers the mechanical and electrical equipment of a movable bridge. The inspector should be within touching distance of the element being inspected. Measurements are also made of, amongst other items, the alignment and profile of the bridge, the chloride content and depth of carbonation in concrete structures, reinforcement corrosion, and the intensity of cracking in steel structures. This type of inspection is undertaken at least every six years: the first is made just before the end of the Guarantee Inspection period but not later than six years following the opening of the bridge to traffic.

- **Special Inspection**. This type of inspection is carried out, as and when necessary, to investigate defects detected, or presumed to exist, by an earlier inspection. It is also undertaken on the following regardless of their condition:
    - mechanical and electrical equipment on movable bridges
    - butt welds in the primary load-bearing elements of a steel structure - at least 30% of the welds in a flange plate, or similar, are inspected at any one time using measuring devices to detect internal and external defects.

Mechanical devices and electrical equipment on movable bridges are inspected at least every three years. And butt welds in primary load-bearing elements are inspected as part of the Major Inspection, which is undertaken before the end of the Guarantee Inspection period but not later than six years following the opening of the bridge to traffic.

4.2.1.10 Switzerland

In 1998 the Swiss Federal Roads Authority issued a guide on the monitoring and maintenance of structures on the national motorway system. The following is derived from that document.

Monitoring is divided into observations and inspections. Observations are simple control procedures to check serviceability, which includes the use of the structure and the operation of equipment. Inspections are undertaken to assess and evaluate the condition of a structure - this is usually through a visual examination, and by site-specific checks as detailed in the monitoring plan.

The aims of an inspection include:

- early detection of damage and identification of its cause(s)
- recording the condition of a structure in a systematic manner, so that changes in condition can be followed
- identification of structural elements and parts at risk of damage, through misuse for example
- identification of in-service conditions and uses that violate design assumptions; this would include the magnitude and disposition of traffic loads for example
- provision of specifications for maintenance, rehabilitation, strengthening or replacement of structural elements
- initiation of any urgent works required to ensure safety in use.

There are three types of inspection:

- **Principal Inspection**. This type of inspection is undertaken every five years: it comprises a visual examination, using simple means, of the entire structure. Binoculars, or similar equipment, can be used to inspect inaccessible structural elements such as high piers, but a close examination is carried out of critical structural parts such as bearings and hinges.
- **Intermediate Inspection**. The aim of this type of inspection is to monitor the condition of a particular structural element, or a deterioration process.
- **Special Inspection**. This type of inspection is undertaken following an unusual incident that may affect the performance of a structure, such as flooding, rockfalls, earthquakes, and traffic accidents.

4.2.1.11 United Kingdom

In the UK, four main types of inspection are undertaken on bridges that have a span in excess of 3m. They are also undertaken on culverts that have a minimum span of between 1.8 and 3m and multi-cell culverts having a cumulative span of 5m or more, where their depth of cover to the road surface is less than 1m. (In Scotland the minimum span of a culvert is 2m). Procedures and advice on undertaking inspections on most types of structure are provided in BD 63/94 (DMRB 3.1.4) and BA 63/94 (DMRB 3.1.5) respectively: currently, these documents are being updated. Advice on undertaking inspections of road tunnels, and of post-tensioned bridges are given in BD53/95 (DMRB 3.1.6) and BA 50/93 (DMRB 3.1.3) respectively. In addition, the requirements for monitoring bridges constructed with weathering steel are given in BD 7/81 (DMRB 2.3.8).

The types of inspection are:

- **Superficial Inspection**. This type of inspection is carried out at regular intervals by staff of the Maintaining Agent. The inspection comprises a cursory check of obvious defects that may lead to accidents or high maintenance costs. It can be made from the ground, deck level or any walkway or platform built into a structure. Where a possible defect is detected that poses a hazard to road, rail or other users, the Maintaining Agent takes immediate action to safeguard the public, and informs the Overseeing Organisation and the owner of the structure.
- **General Inspection**. This comprises a visual examination of all parts of the structure and adjacent earthworks or waterways that can be inspected without the need for special access or traffic management arrangements. This type of inspection should be undertaken not more than two years following the previous General or Principal Inspection.
- **Principal Inspection**. This type of inspection comprises a close examination, within touching distance, of all accessible parts of a structure and adjacent earthworks and waterways, utilising suitable access and/or traffic management works as necessary. Such an inspection is carried out at intervals set initially by agreement, normally six years but exceptionally up to ten years for less important structures. For a new structure an inspection would be carried out about one month before the end of the maintenance period or before the opening of the structure to traffic. In recent years, an inspection might have included a modest programme of tests.
- **Special Inspection**. This type of inspection comprises a close examination of a particular area(s) or defect(s) that has given cause for concern. It may be undertaken:
    - to investigate a particular problem detected during an earlier inspection of the structure or of similar structures
    - on specific structural forms; for example, cast iron structures, those strengthened with bonded plates, those that have weight or other forms of restrictions on traffic, and post-tensioned structures
    - where the necessary frequency or access arrangements for a particular part of the structure are beyond those applying to General or Principal Inspections
    - on structures that have to carry an abnormally heavy load - inspections may be done before, during and after the passage of such a load.

For Principal and General Inspections and, where relevant, Special Inspections, the observed defects and their severity are entered into a database. The report from a Principal Inspection should comment on the significance of any defects and give a broad statement on the overall condition of the structure (that is, good, fair or poor). It should also state when a more detailed inspection is required, and where attention should be given to particular elements during the following General or Principal Inspection.

Post-tensioned bridges

A programme of Special Inspections of the stock of post-tensioned highway bridges is underway in the UK. The priority of a bridge for inspection is determined through a Total Assessment (TA) rating, which is derived from the following:

- age of bridge rating (R_a) - the rating depends on the year of construction: values range from 1 to 5
- bridge form rating (R_f) - this is a function of the type of construction: permissible values are 1, 3, 4 and 5
- vulnerable detail rating (R_d) - the rating depends on the number of vulnerable details on the bridge: values range from 1 (few details) to 5 (many)
- traffic volume ratings for annual average daily flow over the bridge (R_v), and the annual average daily flow below or adjacent to the bridge (R_u): values range from 1 (up to 20,000 vehicles per day) to 5 (over 80,000 vehicles per day), but a value of 0 is adopted for R_u when there is no traffic below or adjacent to the bridge
- route importance rating (R_i): the rating value ranges from 0 to 5 according to the strategic importance of the route.

(Values for the above ratings are provided in tables.)

The value of TA is calculated from:

$$TA = (4 \times R_a) + (2 \times R_f) + R_d + R_v + R_u + R_i$$

The priority rating (PR) for inspection is determined according to Table 4-1: the lower the value of PR the higher the priority for undertaking an inspection. Further details of the prioritisation and execution of the Special Inspections are provided in BD 54/93 (DMRB 3.1.2) and BA 50/93 (DMRB 3.1. 3) respectively.

Table 4-1 Priority rating system for inspecting post-tensioned bridges

Total assessment rating (TA)	Priority rating (PR)
43 - 50	1
36 - 42	2
29 - 35	3
22 - 28	4
8 - 21	5

4.2.1.12 United States

For the public roads in the USA, bridges having a span greater than 6.1m are inspected at regular intervals. The scope of the inspection depends on several factors, such as age, traffic characteristics, presence of known deficiencies, and maintenance history. The evaluation of such factors is the responsibility of the engineer in charge of the inspection program. Inspections are usually undertaken every two years, but the interval can be longer where it can be justified on the basis of past inspections and analysis.

From the inspection, an overall condition rating is assigned for the three major bridge components: deck, superstructure, and substructure. Based on the deficiencies found, a broad descriptive condition rating (good/fair/poor/not applicable) is derived for each element of the component. And for each element, the type, extent, quantity and severity of deterioration and deficiencies are described.

4.2.1.13 Summary

As can be seen from the foregoing, the inspection procedures used in most countries generally follow those described in the OECD (1992) report. This recommended three basic types of inspection - Superficial, Principal and Special - but, in practice, Principal is commonly subdivided into General and Major categories. Although, for each type of inspection, there is a good deal of commonality in the procedures adopted in various countries there are differences, for example, in the frequency of the inspection and the details of the investigation.

- **Superficial Inspection**. This type of inspection is usually carried out by maintenance personnel who do not have any specialised knowledge of highway structures. The inspection may be little more than a cursory check: it can be undertaken from ground, deck level or from a walkway or platform built into a structure. The aims are to assess the overall condition of the structure, to note any changes in condition, and to identify major anomalies (defects) on and around the structure that may represent a hazard to the public or lead to high maintenance costs. In some States, this type of inspection is undertaken annually, but in most it is undertaken continuously (or effectively so) by road maintenance personnel.
- **General Inspection**. This type of inspection comprises a visual examination of all parts of the structure that can be accessed without specialized equipment. The aims of the inspection are to detect all defects that can be seen from the ground, and to evaluate the condition of the structure. The inspection is undertaken by technicians who may have had some formal training in structural pathology, but training on the job is also commonplace. Qualified or experienced inspectors may be required for particularly complex structures. The recommended frequency of this type of inspection is two to three years - provided that Superficial Inspections are also undertaken. The results of the inspection should contain, where necessary, a description of the defects and recommendations for a more detailed inspection.
- **Major Inspection**. This type of inspection comprises a close visual examination of all the accessible parts of the structure and adjacent earthworks and waterways: in some States it may include a limited programme of tests. Specialized equipment or facilities may be required to enable the inspector to get close enough to the structure. In some States the examination has to be completed from touching distance, but others allow the use of cameras with zoom lenses. The complexity and condition of the structure govern the scope of the investigation. An engineer, adequately trained in structural pathology, should undertake or manage the inspection. The recommended frequency of this type of inspection is five to ten years, but a longer interval may be adopted according to factors such as structural condition, load-carrying capacity, deflections, settlement and joint openings. The report of the inspection should provide, as necessary, details of all defects observed, an assessment of the condition of the structure, and recommendations for further inspections and remedial works. The extent and severity of defects should be described in sufficient detail to enable the engineer to derive an estimate of the cost of any remedial works. The opportunity should also be taken to identify poor construction details.

Specific types of Major Inspections, such as Acceptance and Guarantee Inspections, are used in some States. An Acceptance Inspection is carried out on a new structure before it is opened to traffic (the purpose is to identify and record any work that is still outstanding under the contract), and on an in-service structure before responsibility for it passes to the Maintaining Agent. A Guarantee Inspection should be carried out before the end of the guarantee period.

- **Special Inspection**. This type of inspection is performed where there is a perceived need for detailed information. It may involve an investigation of a particular defect found during an inspection of the structure or of other similar structures. (A recent example of the latter is the inspection of the tendons in post-tensioned concrete bridges in the UK.) Inspections are also undertaken on structures that are deemed to require regular monitoring: these include cast iron structures, those strengthened by bonded plates, those with traffic restrictions, and those required to carry an abnormally heavy load. Such an inspection may also be undertaken following some unusual event that can affect the performance of the structure. These events include flooding - where foundations are at risk from scour, an earthquake, a landslide, a major accident, and a chemical spillage or fire in the vicinity of the structure. Although an inspection can be carried out on the whole structure, it is usually undertaken on some particular component or element (see Figure 4-1), and it usually involves on-site measurements and laboratory tests.

Figure 4-1 Special Inspection of a pier

4.2.2 Reporting and acting upon the findings of an inspection

As described above, the defects revealed during a Superficial Inspection are reported to an engineer so that appropriate action can be taken. However, if during an inspection it is clear that the severity of a defect puts the safety of users at risk, an inspector can propose or put in place immediate measures such as a load restriction, propping of the superstructure, or even closure of the structure. Such measures should remain in place at least until a second opinion or a further, perhaps more detailed, investigation is undertaken.

The findings of more detailed types of inspection are usually recorded on standard forms although some authorities use electronic data capture devices. Such forms usually include a check list of structural items to be inspected, such as foundations, piers or columns, abutments, retaining walls, embankments, fenders, bearings, beams, diaphragms, concrete slabs, waterproofing, surfacing, and expansion joints. The input data include basic information such as the reference number and/or name of the structure, the date and type of inspection, and an assessment of the condition of the structure. Defects should be described in terms of their location, extent and severity; recommendations may also be given on the type and priority of any remedial works.

In addition to the standard forms, detailed reports are often compiled for Principal and Special Inspections: usually these would give an assessment of the condition of the inspected elements. As a necessary background, such a report would usually include text and drawings describing the form of construction and details of the structural components, such as the deck, supports, articulation, and deck ancillaries (which include expansion joints, waterproofing, and parapets). It may also include the maintenance history of the structure and the findings of previous inspections.

The findings of an inspection can be used to derive a condition rating for the structure as a whole or for particular elements of one.

One of the aims of undertaking periodic inspections is to assess the condition of the stock of structures, and this requires a suitable method for evaluating the data from a suite of inspections. A method of ranking the ratings will help in prioritising the remedial works.

4.3 RECOMMENDATIONS

The requirements of an inspection regime are stated in 4.1 above, and inspection procedures should be designed to meet them.

Recommendation 8 Inspection procedures should be reviewed to determine where improvements in current practice can be made. Issues of particular interest are:

- **defining the objectives of an inspection**
- **integration of the inspection process into the management of structures**
- **economic, environmental, safety and social implications**
- **determining the level of detail required in an inspection**
- **setting the frequency for the different types of inspection, but allowing flexibility according to the type of structure and what is being inspected.**

A description of the various types of defect that can occur on highway structures should be provided to an inspector along with standard drawings or photographic records so that the occurrence of damage can be located and quantified. Together these will define terminology and location, and provide a basis for assessing the extent and severity of any defect or damage.

Recommendation 9 The usefulness of the standard inspection report forms and the information provided to an inspector should be reviewed. Consideration should be given to the use of purpose-designed forms for each type of structure.

Recommendation 10 Consideration should be given to the establishment of a register or log for each highway structure. Such a document could contain details of its design and construction, inspection reports and details of any remedial works.

The sudden collapse of a highway structure is not a common event because usually it would be preceded by evidence of distress (such as cracking) and/or large deformations. Design requires robustness in the main structural components and ductility of the materials used, and so most collapses should, and indeed do, result from accidents or natural disasters.

Recommendation 11 The factors that pose the greatest risk to the stability of a structure should be identified and included as part of the inspection process. Such factors may include:

- **traffic accidents - thus there may be a need to check road alignment, visibility, lane markings, and signs for speed, weight restrictions and clearances**
- **seismic activity, subsidence and settlement - some elements are more at risk than others**
- **erosion and scour**.

Chapter 5 Investigations

5.1 INTRODUCTION

An inspection should provide information on the extent and intensity of the defects and damaged areas on a structure; it may also identify the causes of the defects and the deterioration processes, and the impact that these have on the safety and serviceability of the structure. These data can be used to determine what remedial works are required, when they should be undertaken, and the likely costs of such works. However, deterioration may be due to several interacting factors and it is often difficult to pinpoint the root cause of the problem and thereby obtain an understanding of how and why deterioration has occurred; but only when this has been done can appropriate remedial works be identified.

Usually, various types of remedial work are available for a particular defect. The selection process must take account of the likely effectiveness of the solution as well as a wide range of other issues, including safety, the remaining service life of the structure, the operational requirements during the works (such as lane closures and weather conditions) and available funds for such works.

To obtain sufficient information to enable the most appropriate maintenance strategy and repair works to be selected, visual inspections are often supplemented by testing. A wide range of approaches is available, including sampling followed by laboratory-based tests to determine particular material properties, non-destructive methods for detecting hidden defects, site monitoring to determine the change in the condition with time, and on-site loading tests. This chapter describes the approaches used by the States participating in COST 345. It provides an overview of the initiation and role of testing and goes on to review sampling, non-destructive testing, loading tests and monitoring.

Figure 5-1 is a flow chart showing the position of inspection and testing within a Bridge Management System (BMS).

5.2 BACKGROUND

5.2.1 Initiation and role

A programme of tests usually forms part of one of the following activities:

- Inspection - the requirements for tests undertaken during an inspection are described in Chapter 4.
- Assessment of load-carrying capacity - a number of tests may be undertaken including ones to verify the form of construction and the dimensions of the structure, and to determine the nature and condition of the structural components. An on-site load test can be used to determine structural behaviour, which can be compared to the model used in design, and to verify or assess load-carrying capacity: further details are provided in 5.5.
- Remedial works - tests can be undertaken to determine the extent and cause of material deterioration, and thereby help to identify the type of work required.

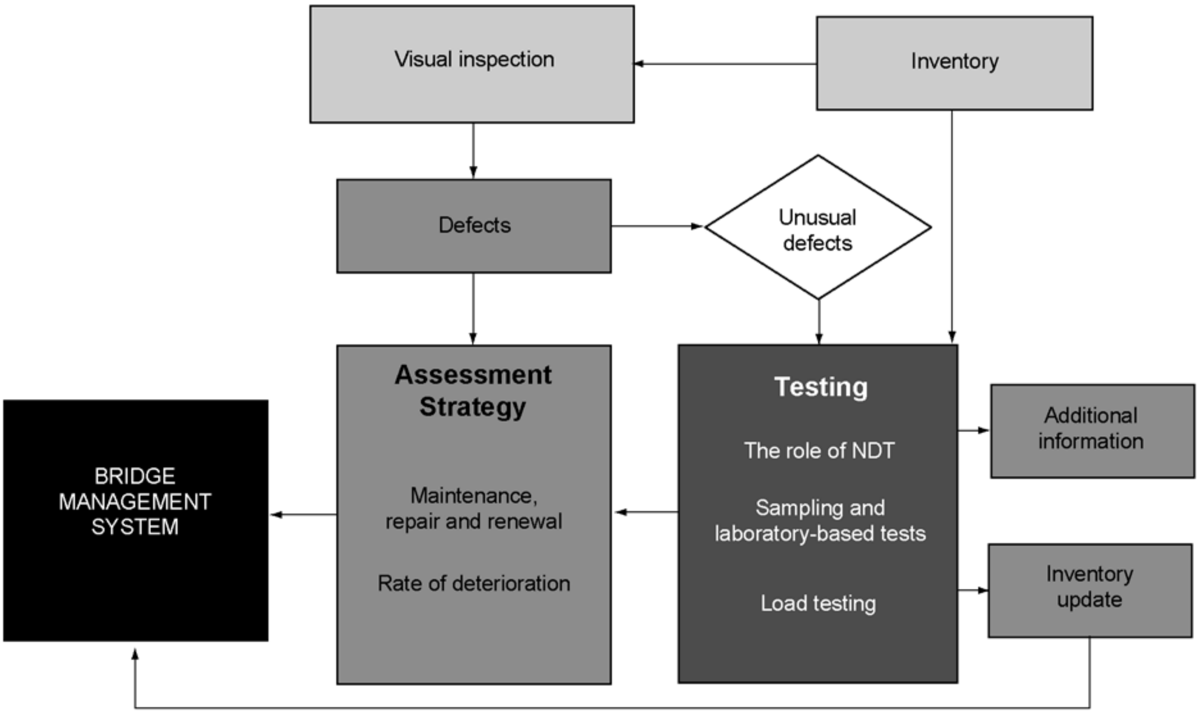

Figure 5-1 The role of testing within a BMS

The requirements for testing are given in national standards, and these usually focus on the information required by the engineer. Usually a particular test is covered by a standard that provides information on its applicability, the procedure(s) to be followed, and how the results should be reported. In the UK, for example, the BS1881 series includes standards for applying NDT techniques to concrete structures; other standards cover the application of NDT to steel structures. However, there may not be much advice available on some of the less well-known techniques and on those that are at the research stage, but the latter should only be undertaken by a specialist.

In most cases a test programme would be based on previous experience and engineering judgement, but it may also take into account recommendations from organisations that specialize in structural testing.

For the same objective, different clients will often select a widely differing schedule of tests. This may arise from the shortage of guidelines and the tendency of clients to base specifications on previous contracts. A client may also adopt a ‘shopping list’ approach, which includes all the tests available for the generic problem, rather than a ‘problem-solving’ one tailored for the case at hand. In many cases, therefore, a programme may include tests that are not particularly relevant or necessary.

5.2.2 Types of test

Various types of test can be undertaken. Some provide information on the overall behaviour of a structure whereas others only cover a particular component or element: some can be applied on a one-off basis but others can or have to be repeated periodically. A description of the different approaches and their application follows.

5.2.2.1 One-off tests

In general, one-off tests provide data on a structural detail, such as the depth of cover, or on a specific material property: in many cases this is all that is required. A one-off test may be used to supplement a visual inspection, provide information on a defect detected during an inspection, or form an integral part of a Special Inspection.

Assessment

One-off measurements are often undertaken as part of an assessment of load-carrying capacity. This involves an inspection as well as an analysis. The former provides information for calculating both the applied loads and the structural resistance. The information includes the dimensions of the structure (obtained from a geometric survey) and the density of the materials: in combination these provide an estimate of the dead loads and the superimposed dead loads. It also includes measurements for determining the strength of structural elements: this includes details such as the location, extent and width of cracks; the location and severity of corrosion; ground movements; and the location and extent of defective materials and structural damage.

There is a hierarchy of assessment methods. Starting from the simplest, the complexity of the method is increased until the structure is shown to be adequate - or it becomes clear that the structure is indeed inadequate. The higher and more elaborate the method, the more detailed and thorough the investigation and associated test programme. A method may involve sampling and testing to obtain a more accurate estimate of the material properties, and on-site measurements to determine the stress level in some of the structural components, such as prestressing tendons. Additional information may be obtained from weigh-in-motion studies, to provide data on actual traffic loading, and from loading tests to investigate structural behaviour and strength characteristics.

Determining material properties from on-site tests and/or sampling and laboratory-based tests can justify an increase in the material strength used in an analysis, and thereby increase the assessed load-carrying capacity. However, care is necessary in collecting and interpreting the data and a large sample size may be required to ensure the reliability of the assessment.

As noted above, a loading test is sometimes used for assessment purposes - as either a supplementary or a proving test - and it provides information on the behaviour of the structure as a whole. The former is an adjunct to theoretical calculations whereas the latter is intended to provide a self-supporting alternative to theoretical assessments.

Deterioration

Where deterioration has been noted during an inspection, one-off tests may be used to obtain information that can help to identify the most appropriate course of action. An accurate diagnosis of the cause of deterioration can only be achieved by carrying out appropriate tests. For some forms of deterioration a single test may be sufficient - for example, ASR can usually be diagnosed by a petrographic examination of cores taken from the structure, but for most forms it is necessary to undertake a variety of tests. There are numerous factors that need to be considered when planning a test programme. For example, some deterioration mechanisms are affected by the microclimate; thus in-service conditions on the leeward side may differ from those on the windward side, and the orientation of the structure (north-south and east-west) may also have an effect. It would seem necessary to undertake tests in areas where deterioration is most likely to occur, but these are not necessarily the most readily accessible parts of a structure. The supervising engineer, perhaps acting in conjunction with a test house, has to select the types of test and identify the most appropriate sites for sampling and/or on-site tests.

When interpreting the data from a test, full account should be taken of all relevant information such as the type of structure, construction records, as-built drawings, in-service conditions - including the environment, maintenance history, inspection records and data from other tests.

Sampling and testing may cause local damage to the structure and care is required to ensure that any such damage is repaired; otherwise it may itself be a source of deterioration.

5.2.2.2 Periodic/continuous monitoring

There are many instances where measurements can be repeated periodically so that the condition of a structure can be monitored over time. One of the advantages of monitoring, particularly where it is carried out remotely, is that it provides information on the condition of the structure without repeatedly disrupting traffic. The main reasons for monitoring the performance of a structure are, in brief:

- to check its behaviour during construction
- to help direct the management of its maintenance
- to check that there is no further loss in capacity or utility (that is, strength or serviceability)
- to confirm the stability and serviceability of a structure that has a load-carrying capacity below that required by current standards but which does not appear to be suffering from distress.

The frequency of measurement depends on what is being monitored, the rate at which this may change and the effect this change may have on the performance of the structure. For example, it may be appropriate to measure chloride-ion concentrations as part of a Principal Inspection, which might be at 6 to 10-year intervals. Other measurements need to be repeated more frequently. For example, measurements of the length, width and depth of cracking may be taken on a weekly or monthly basis, measurements of temperature and strain at hourly intervals, whilst some measurements, such as acoustic monitoring, can provide near-continuous information.

5.2.3 Specification and procurement

5.2.3.1 Specification

In most European States there are no standards or guidelines that deal specifically with the specification and procurement of tests for highway structures. For example, in the UK the documents within the Design Manual for Roads and Bridges (DMRB) focus on the structure, the types of defect and the tests that may be required, and although the documents provide engineering advice they do not form the basis of a specification. Similarly, British Standards may describe the general applicability of test methods but they provide little advice on their application to highway structures and do not cover how the methods could be specified in a contract. In the case of non-destructive testing (NDT) techniques, which are described in various British Standards, the HA have established a Steering Group to oversee the preparation of Advice Notes covering the application and specification of the methods to highway structures.

5.2.3.2 Procurement

The requirements of a test programme must be defined clearly in the contract documents.

Usually a test programme is procured through competitive tendering, and one of a number of forms of contract can be used. The current situation could be improved by the availability of a model contract and specification designed specifically for testing.

In many cases, the traffic management costs can account for more than half of the total contract value. Often, however, these costs are uncertain because they have been derived by subcontractors responding to a short tender period and for work in locations unfamiliar to them. In some cases it may be beneficial to separate the costs of traffic management from testing, and to let the tender on the basis of the cost and quality of the test programme. The appointed contractor can, in consultation with the client, then select the most cost-effective traffic management scheme. Whenever possible, sampling and testing should be programmed to coincide with other work on the network so as to minimise traffic delays and management costs.

Where appropriate, contractors should be accredited - such as by UKAS (United Kingdom Accreditation Scheme) or an equivalent body, and asked to provide details of previous or similar contracts. In most cases a test house would undertake much of the work, but research institutes and/or universities with the appropriate expertise may undertake specialized tests. Although many specialized tests would usually be undertaken on a trial basis; for example, to determine their effectiveness, applicability and whether further development is required, the results of such tests may still be used by the engineer.

Tenders are often awarded on the basis of minimum cost, but to ensure good quality there is an increasing trend towards awarding tenders on the basis of both cost and quality. A dual envelope system can be used in which the quality of the submission is assessed first, and the envelopes containing details of the cost are only opened for those meeting the acceptable level of quality. The contract may then be awarded to the submission with the lowest cost that met that level. Alternatively, a contract can be awarded on the basis of marks awarded for quality and cost. Marks for quality may be based on the experience of the bidder (that is, the named operatives) with the particular tests required; the proposed methodology; and the health and safety record of the bidder. Marks for cost may be given according to the mobilisation fee; the cost of the initial series of tests and any additional work required; and for the allocation of resources to interpretation and reporting. The final mark is based on a combination of the marks for quality and cost, but often it will be weighted towards the former.

5.2.4 Interpretation and application

Following, or even during, the test programme there are two stages to complete: firstly the validation and evaluation of the results of a test, and secondly an assessment of the implications of all the test results, on the stability of the structure for example.

In many cases little interpretation is required and so the first stage is relatively straightforward: with these it is only necessary to ensure that the tests have been carried out to the appropriate standards and that the data are consistent and reliable. For example, physical and chemical characteristics, such as concrete strength, chloride ion concentration, and the depth of carbonation, can be reported as measured. However the results of surveys and some types of test require interpretation - sometimes by a specialist: these include a ground-penetrating radar survey, a radiographic survey, and a half-cell potential test. In these cases a test house will usually produce an interpretative report, which will provide the raw or processed data and an interpretation of that data.

The test data are essential input to the process of deciding the necessary course of action, which may be to do nothing, monitor, undertake remedial work at some time or other, or replace the structure - but only rarely are they sufficient to short-circuit that process. Data are commonly used as input to a calculation - for example, measurements of concrete strength in determining load-carrying capacity. The results of a survey may help to define what action is required - for example, a radiographic survey will show the extent of the voids in a post-tensioning duct. The role of testing depends on the techniques used, what is being measured and the problem at hand: in many instances it will only have a minor role, but in some it will be the principal factor.

Some management systems store test data and this may enable changes in condition to be tracked. This information may then be used to predict future deterioration and to determine the optimum time for maintenance on the basis of a whole-life cost model. However, at present there is a paucity of data and the reliability of most of these models has not been verified by experience: nonetheless, this situation should improve with time.

5.3 SEMI-DESTRUCTIVE TESTS

A structure can be damaged by on-site tests and also through the recovery of samples for laboratory-based tests. The elements and areas affected by such operations and the severity of the ensuing damage vary according to the type of on-site test and the method used to recover the samples. In selecting the number and location of the test/sampling sites account should be taken of:

- the aims of the investigation
- the proposed tests - and viable alternatives to them
- the proposed application of the test data
- the extent and intensity of the deterioration
- the number of areas showing deterioration of a particular type
- the type of structure
- accessibility.

It is usually necessary to undertake on-site tests or take samples from all areas where deterioration has occurred, or where it is thought to have occurred. To provide a reference, testing and/or sampling should be undertaken at locations that show no signs of deterioration.

A range of tests may be carried out at a particular location and/or on a recovered sample to provide sufficient information to determine the current condition of the structure, predict future performance and, where necessary, determine the most appropriate remedial works.

5.3.1 Concrete structures

Destructive operations include:

- Taking cores for laboratory-based tests to measure physical and chemical characteristics. The former includes concrete strength (compressive, tensile, shear), modulus of elasticity, Poisson’s ratio, density and freeze-thaw resistance. The latter includes the concentration of chloride ions, depth of carbonation, and petrographic analysis - to determine cement content and the extent of any alkali-carbonate and/or alkali-silica reaction. Cores can also be used to measure the bond strength between the concrete and a reinforcement (through a pull-off test), and between different layers of concrete. Cores can also provide other information, such as the thickness of the structural elements, and the depth and width of cracks, and be used for calibrating the output from NDT techniques.
- Taking cores or cutting slots to determine the in situ stresses in concrete.

- Drilling access holes to allow the use of an endoscope to inspect the conditions within a post-tensioning duct.
- Removal of the concrete cover - this may have a number of interacting purposes, such as:
    - to allow a detailed examination at a particular location
    - to determine the cross-section of the reinforcement or the condition of a tendon
    - for access to determine the stress in a tendon - this is done by measuring the strain released by cutting a wire
    - to obtain samples of concrete and/or the reinforcement - to determine, for example, chemical composition and/or mechanical properties.
- Undertaking on-site tests - damage can be generated by undertaking some tests; for example using impact hammers and the Windsor probe (ASTM, 2003). Furthermore, setting-up tests, which are themselves considered to be non-destructive, can generate some minor damage; for example, electrode potential methods require a connection to be made to the reinforcement.

5.3.2 Steel structures

Destructive operations include:

- Taking samples for determining the mechanical characteristics, chemical composition and the susceptibility of material to fatigue and/or brittle failure.
- Drilling holes or cutting slots to determine the in situ stress regime - in particular the magnitude and orientation of the principal stresses.
- Taking samples for investigating the competency of welds.

5.3.3 Masonry structures

Destructive operations include:

- Sampling to determine the mechanical properties (compressive, bending and tensile strength) and chemical composition of the masonry units and the mortar; the composition and properties of the fill materials - normally through trial pits; and the durability of the masonry units (freeze-thaw resistance, absorption and saturation coefficients).
- In situ measurements of the strength of the masonry.
- On-site tests and/or sampling to determine the strength of any anchors, ties or fixings.

5.3.4 Timber structures

Destructive operations include:

- Taking specimens for investigating the mechanical properties of the wood and fixings and the resistance of the wood to decay.
- Coring to determine the depth of decay or the depth of fire damage - the depth of decay may be estimated by the resistance to drilling.

5.3.5 Soils and fills

On occasions, ground conditions have to be investigated as part of a structural assessment. When undertaking such investigations care should be taken to ensure, as best can be, that (a) the samples are representative, and (b) sampling disturbance will not significantly affect the outcome of the test(s). Whenever appropriate, standard test procedures should be followed, but any departures from these must be reported: such departures may be necessary for some field tests. It is axiomatic that all instruments should have a valid calibration certificate. In most cases it is necessary for the test data to be interpreted by appropriately qualified and experienced personnel.

General requirements for site investigations are described in Eurocode 7 (ENV 1997-2. Design assisted by laboratory testing, and ENV 1997-3. Design assisted by field-testing).

Laboratory tests are commonly undertaken to determine the following characteristics of soils:

- identification and classification, tests include the determination of water content, bulk density, particle density, and consistency limits
- shear strength - through, for example, triaxial compression tests, direct shear tests, vane tests, and the use of a pocket penetrometer
- compressibility - of clayey soils via an oedometer test
- permeability
- chemical composition - such as organic content, carbonate content, pH value, and sulfate and sulfide ion contents
- compaction characteristics - as described by the dry density/moisture content relation.

Laboratory tests are also undertaken to determine the properties of rocks, such as:

- material classification
- strength - through uniaxial compressive strength tests and point load tests
- shear strength of seams and joints
- swelling characteristics.

The following are commonly undertaken as part of an on-site investigation:

- penetration tests using one or other of the range of standard equipment and procedures - such as by driving or pushing in a solid cone or open-ended tube
- pressuremeter tests - to determine, for example, the stress regime in the ground
- dilatometer tests - again, a variety of equipment and procedures are used
- permeability tests.

5.4 NON-DESTRUCTIVE TESTS

5.4.1 Introduction

The importance of NDT within a management system for structures is increasing. By reducing the subjectivity associated with a visual inspection, NDT can improve the quality of information on the condition of a structure. Although it can play an important role in investigating the condition of a particular structure, guidelines are required to ensure the consistent use of NDT techniques and the interpretation of the data across a wide range of structures.

Where the cause and extent of a defect cannot be determined through a visual inspection, the inspector or engineer may undertake additional investigations and these would usually involve non-destructive or semi-destructive tests. Thus the existing guidelines on assessment must be able to take account of the information derived from NDT. Furthermore, it should be possible to use this information to help define the possible maintenance measures, the costs of such measures and the future behaviour of a structure - with and without measures being put in place. In brief, it is necessary for NDT to be an integral part of the management system.

As well as its uses for inspection, NDT can be used for establishing or updating an inventory; for example, by providing data on material properties and on the dimensions and layout of a component or element.

The following provides brief details of the NDT techniques more commonly used for inspecting and assessing the condition of structures.

5.4.2 Mechanical methods

5.4.2.1 Schmidt hammer

The Schmidt or rebound hammer is used to determine the hardness of the upper 30mm or so of concrete. Its main use is for mapping variations in concrete properties. The measurements can be calibrated against other physical properties; for example, they may be calibrated (to an accuracy of ±15 per cent) with the crushing strength of concrete as measured by tests on cores. However, because the results of the hammer tests are, obviously, sensitive to the condition of the surface, a calibration must be done for each site.

5.4.2.2 Falling weight deflectometer

There are a number of different types of falling weight deflectometers (FWD), but they basically comprise a standard ‘weight’ - which can be lifted and then released in a controlled manner from a known height, a contact plate, and an array of sensors. The sensors record the deflection generated by dropping the weight onto the plate, which is placed on the surface of the structure under test. At present, the devices are rarely used other than for testing pavements. The data can be processed to determine the thickness of different layers of a pavement and provide a qualitative measure of its overall condition.

5.4.2.3 Mechanical gauges

Mechanical gauges, such as Demec gauges, are used to measure small movements between relatively close reference points. The points are bonded to the surface of a structure and a gauge fitted between them. Such gauges are mainly used to monitor the width of a crack, but they have also been used to monitor the swelling or shrinkage of an element. They provide a cheap and simple alternative to the use of electrical strain gauges, but usually the gauge has to be read by eye in which case it is not well suited to online monitoring or situations where access is restricted.

5.4.3 Electro-magnetic methods

5.4.3.1 Ground penetrating radar

Ground penetrating radar (GPR) utilises electromagnetic waves typically in the frequency range 100MHz to 1GHz. The electromagnetic energy is pulsed into the structure under test and is reflected at boundaries between materials of differing electrical properties. The reflected signal is captured and can be interpreted to determine the internal details of the structure. The speed of propagation is a function of the dielectric constant of the material, which for concrete is influenced, amongst other factors, by its moisture content, porosity and the presence of chloride ions. It is necessary to measure the dielectric constant or to calibrate the radar trace (for example, using cores), to translate the arrival times of a signal into distance.

Typical applications of GPR are:

- investigating the form of a structural element - for example, the number and thickness of various layers and the location of reinforcement
- detecting variations in the composition and condition of concrete - for example to identify areas having a high moisture content
- detecting cracks and areas of delamination and honeycombing in concrete structures, and ring separation in masonry structures
- determining the location of reinforcements
- determining the location and/or condition of buried objects, such as foundations, service lines, pipes, anchors, ties, and connectors
- determining the thickness of a retaining wall, for which no construction records exist, and assessing the consistency of the retained soil.

The level of detail that can be discerned is a function of the frequency of the waves and the variation in the electrical properties of the materials in the structure: the lower the frequency the greater the depth of penetration, but the higher the frequency the better the resolution. The choice of frequency is, therefore, a compromise between these competing requirements.

It is relatively easy to pick out the position of steel reinforcement in a concrete structure; see for example Figure 5-2. It should also be possible to pick out substantial variations in the composition of concrete, such as in its moisture content and porosity, but it may be difficult to detect relatively subtle variations.

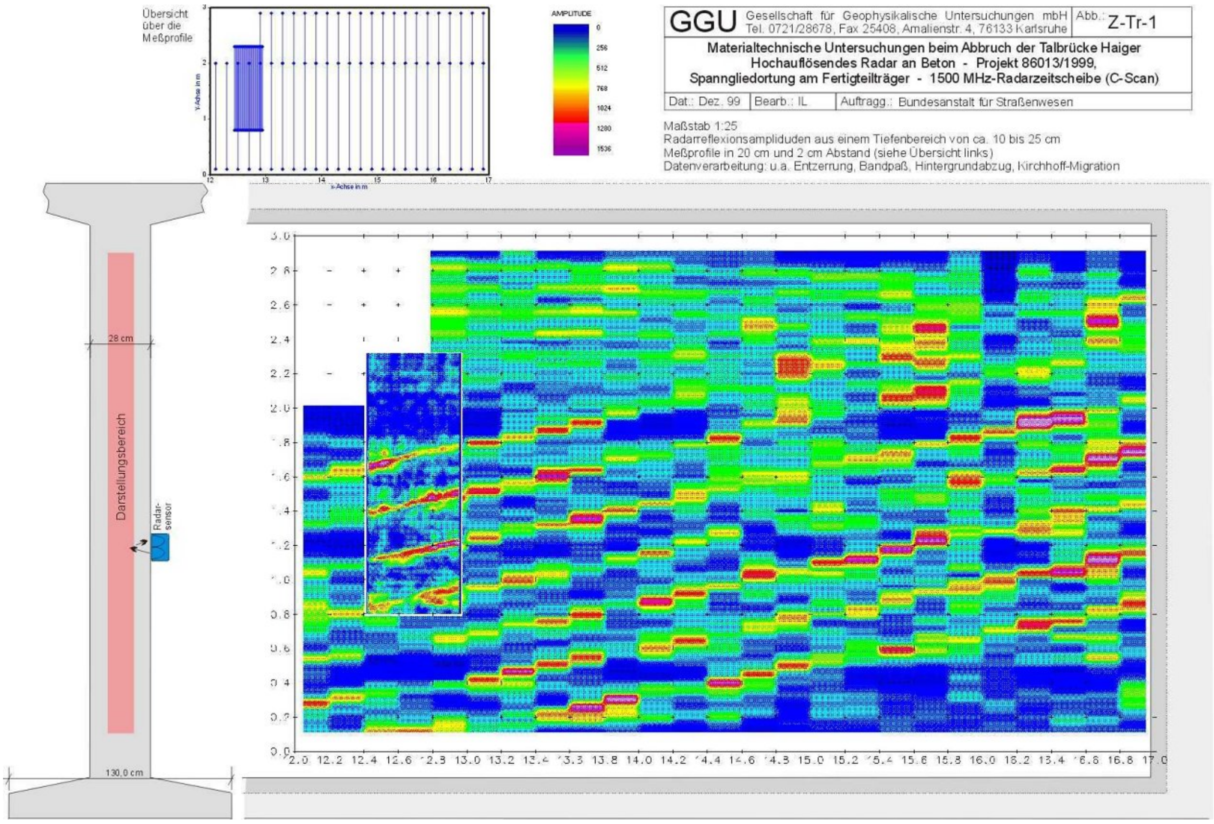

Figure 5-2 GPR trace showing location of reinforcement in concrete

High-speed surveys can be undertaken using high frequency GPR (> 1 GHz). As shown in Figure 5-3, in this case the antennae are not in contact with the surface of the formation. At high frequencies the depth of penetration may be limited to a few centimetres or so.

Figure 5-3 Undertaking GPR surveys

Interpreting a GPR trace can be particularly difficult, and so it usually undertaken by a specialist operator.

It may be difficult to relate the results of a GPR survey to a particular deterioration mechanism, in some cases there may not be a definitive physical link between them. Further research is required here; of particular interest is the potential for assessing the level of corrosion on reinforcements and the concentration of chloride ions in concrete structures. Usually the GPR traces are interpreted off-site and improvements in real-time data processing are required to extend the use of GPR to provide an on-site diagnosis.

5.4.3.2 Infrared thermography

As the temperature of a structure changes thermal gradients are set up within it; quite steep gradients can be set up in poor conductors such as concrete and masonry. Dry or water-filled features such as cracks, delaminations, and discontinuties affect the transfer of heat through a structure, and their presence may be identified by variations in the temperature of the surface. The effect on surface temperature is a function of several factors including the type, size and depth of the feature. Quite small variations in surface temperature can be measured using sensitive infrared detection systems. The use of a device for measuring the surface temperature of a concrete road is shown in Figure 5-4: also shown is an image obtained from the device.

There are two basic operational modes:

- a steady-state mode, or passive approach, in which the in-service temperature variations are related to features located below the surface
- a transient mode where the investigation is limited to surface or near-surface conditions; in this case an active approach may be adopted where the temperature of the surface is artificially varied in some way.

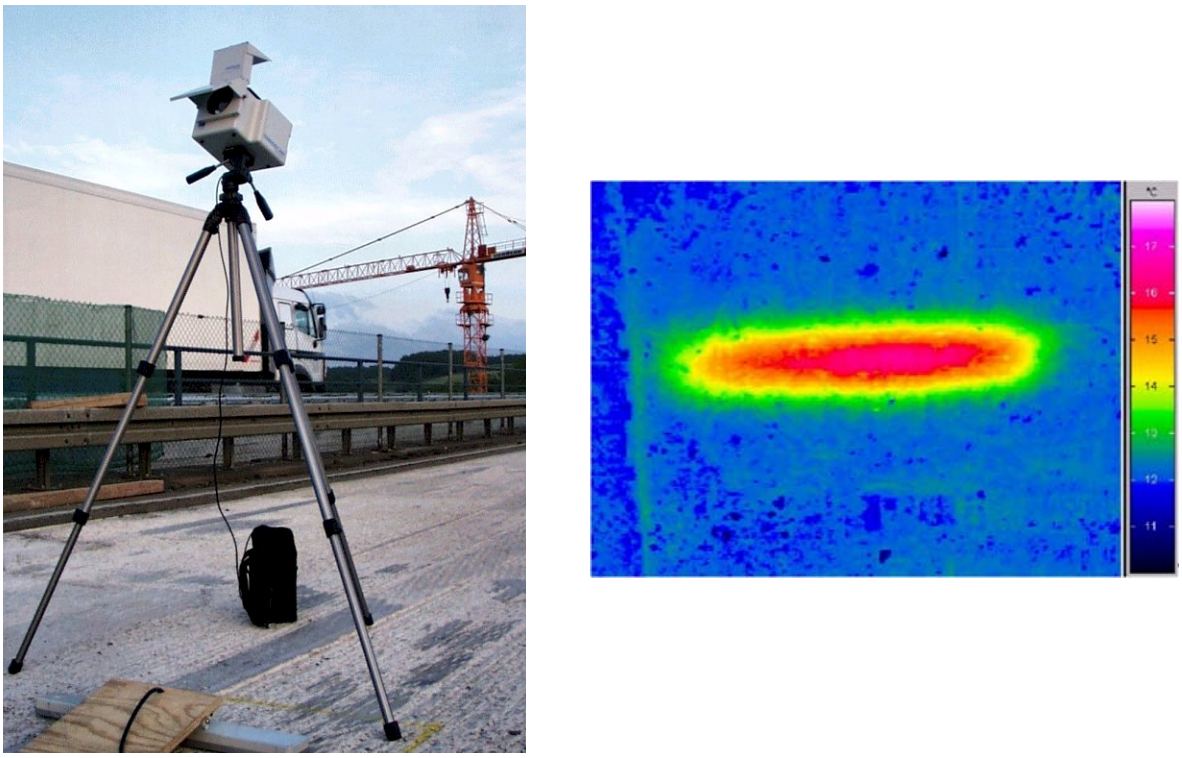

Figure 5-4 Infrared thermographic device and output

5.4.3.3 Radiography

Radiography is not widely used for inspecting concrete structures because:

- only limited penetration is obtained through thick heavily reinforced sections
- most systems require access to both sides of the element under examination
- it presents operational and logistical difficulties
- it is expensive.

Nevertheless, gamma radiography can be an effective means of determining damage within thin, lightly reinforced structures, and is of particular value for locating voids and determining the condition of reinforcements, prestressing tendons contained in ducts, and the external cables of suspension and cable-stayed bridges.

X-ray radiography can be used to detect defects, such as pores and slag inclusions, in welds and steel castings. It can also be used to detect planar features, such as cracks, but the ease of detection depends on the orientation of the feature. It is possible to pick up planar features that run parallel to the X-ray beam, but those that run perpendicular to the axis do not significantly affect the absorption of the X-ray. The advantages of using X-ray radiography on steel structures are:

- the availability of a photographic record, which is of particular value for analysis and reference
- its ability to determine the size and shape of internal defects
- its widespread use and acceptance - it is covered in most national codes of practice.

Apart from its limitations in detecting cracks at particular orientations, another big drawback of the technique is the difficulty of setting up and using the equipment on site.

Recent developments of interest are the production of portable, compact high-energy X-ray accelerators, and the application of X-ray tomography. The potential value of the information that can be gained from a tomographic image is considerable, but the technique is difficult to apply on site unless the element under test is relatively thin and cylindrical. Nonetheless it is a particularly useful inspection technique, particularly for laboratory specimens.

Neutron radiography has been used for inspecting structures, but it has proved to be less practical than other radiographic methods.

5.4.4 Acoustic methods

Acoustic test methods are those based on the transmission and reflection of stress waves through the test piece. They are used to:

- determine the properties of the material - based on measurements of the speed of propagation
- locate and identify discrete buried objects or features - from reflections of the stress wave.

5.4.4.1 Sonic

Mechanical-sonic methods are commonly used for testing concrete structures and elements, up to about 1m thick. They are also used for testing steel structures, and may also find some applications on composite structures and timber structures. Chain drags, sounding rods, and even hammers are used on horizontal surfaces, such as concrete decks and the tops of piers, to detect delaminations. A large area can be traversed quite quickly with a chain drag and an experienced operator can define areas of delamination reasonably accurately.

The impact-echo technique is also commonly applied to concrete structures. With this, a stress wave is introduced at the surface of the structure: the wave propagates through the material and is reflected by flaws and cavities, and at interfaces. A view of the equipment and output from the device are shown in Figure 5-5. The minute displacements of the surface generated by the reflected signal are recorded and transformed into the frequency domain. The measurements are presented as plots of signal amplitude against frequency. The thickness of an element and the position of flaws, cavities and the like, can be determined from the fundamental relation between distance, frequency, and the speed of propagation. The technique is effective for detecting flaws over wide concrete slabs, but the rate of investigation may be rather slow. Analysis of the data can be difficult where the geometry or form of the test piece is complex.

5.4.4.2 Ultrasonic

Most ultrasonic devices use a piezoelectric transducer to generate and detect stress waves: the composition and properties of the material - principally its elastic modulus, dictate the velocity of the wave through a material. Two procedures are used:

- the direct transmission method where the transmission and receiving probes are in line on opposite sides of the sample under test
- the ultrasonic pulse echo method, which is comparable to the impact-echo method described above but the former operates at higher frequencies.

A view of a device and the output from a test are shown in Figure 5-6.

The presence of defects and interfaces affects the transmission of the pulse and thereby changes the characteristics of the signal. A number of approaches can be used to assess the condition of the material from such changes:

- analysis of the frequency content of the signal - this approach works best with distinct, well-characterised features
- a time-domain analysis of the signal - similar to that obtained using GPR
- using scanning techniques to generate images of the components and features within the test piece.

Each approach has its drawbacks - often these are associated with the geometry of the test piece. However, the ultrasonic scanning technique seems to have the potential for development into a useful diagnostic tool, but improvements could be made to signal generation and processing techniques.

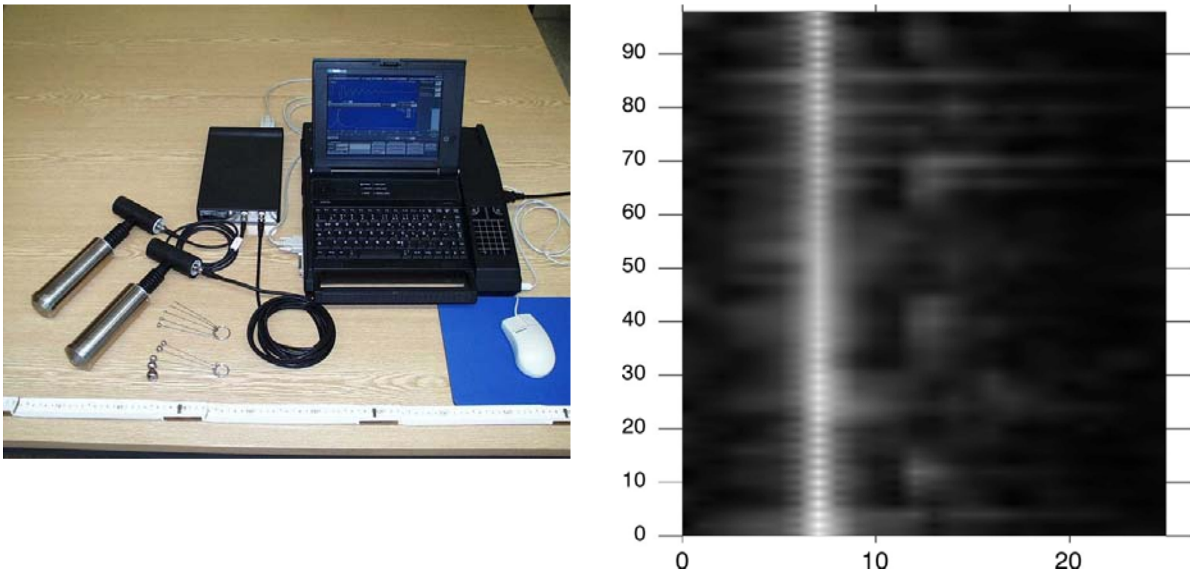

Figure 5-5 View of impact-echo device and test data

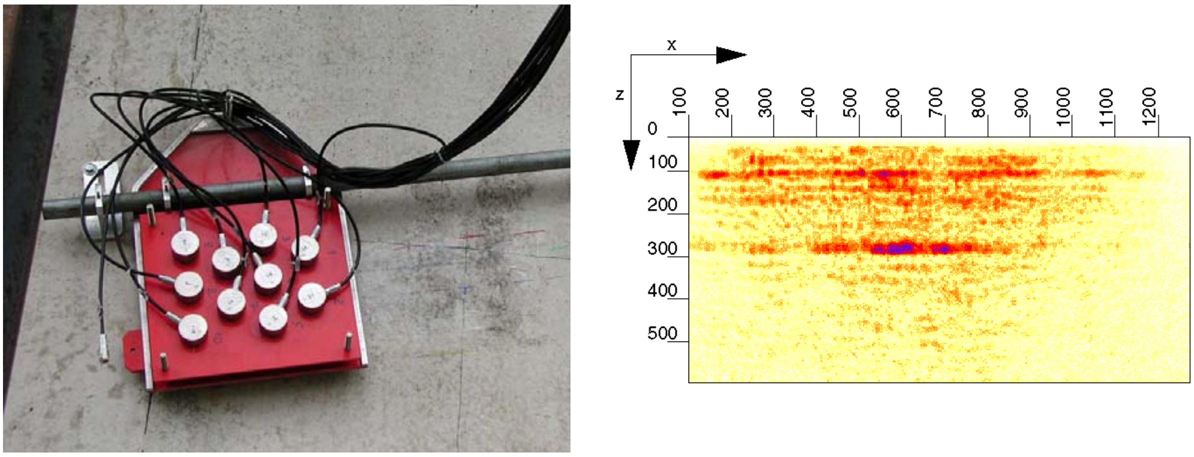

Figure 5-6 Ultrasonic device and test data

5.4.5 Electrical and electrochemical methods

5.4.5.1 Half-cell potentials

Corrosion is an electrochemical process and so it may be possible to detect or monitor its occurrence, or at least the likelihood of its occurrence, through measurements of electrical potential. A half-cell - such as a copper-copper sulfate half-cell, can be used to measure the potential difference between the surface of a concrete structure and the embedded reinforcement.

Half-cell measurements are affected by the resistivity of the concrete and the pH of the pore solution - which is a function of the level of carbonation. It may, therefore, be necessary to complete a statistical analysis of the measurements on an individual structure to identify areas where corrosion is most likely.

Although the measurements may provide a good indication of the likelihood of corrosion they do not provide an indication of the rate of corrosion.

The measured potential difference varies according to the type of half-cell used. In practice it is generally accepted that a potential of less than -0.35 Volts, as measured by a copper-copper sulfate half-cell, is equivalent to a higher than 90 per cent probability of corrosion. But it is not possible to set boundary limits to distinguish between active and passive zones of corrosion.

A wide range of electrode configurations has been used, and several have been shown to have some advantages over standard arrangements. A view of site operations and typical data are shown in Figure 5-7.

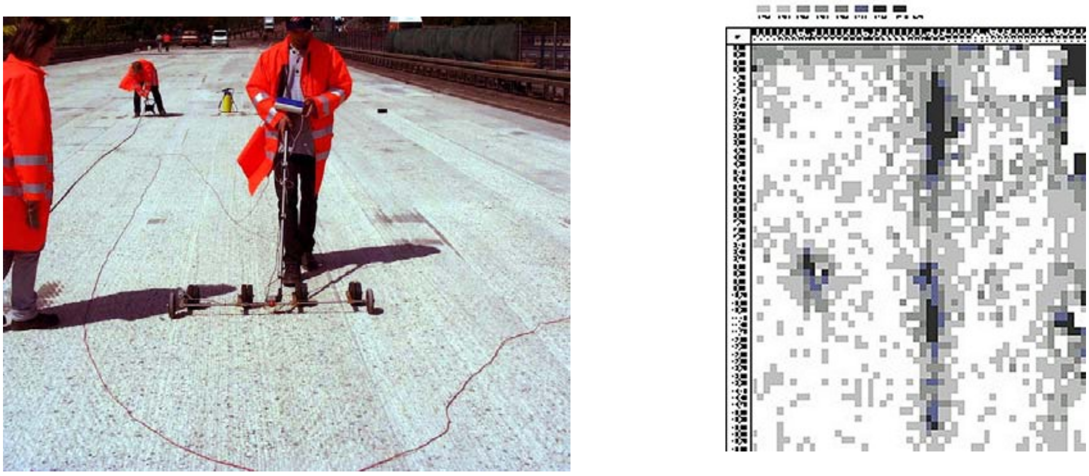

Figure 5-7 Half-cell potential survey: site operations and output data

5.4.5.2 Resistivity

The resistivity of a material is affected by the presence of moisture within its pores. Thus resistivity measurements on concrete may provide an indirect means of assessing the likelihood, extent, and rate of corrosion of the embedded reinforcement. However, resistivity measurements are sensitive to the disposition of reinforcement and so any such assessment must take careful account of the form of construction. Resistivity measurements can also be made to determine the permeability and effectiveness of a seal coat applied to a concrete surface.

5.4.5.3 Polarisation Resistance

On large reinforced concrete structures, the Polarisation Resistance technique can be used to estimate the instantaneous corrosion current (I_{corr}) within the reinforcements, and thereby assess the rate of degradation of the structure. However the technique does not provide information on the loss in cross-section of the reinforcement - at present this can only be assessed by visual observation.

5.4.5.4 Eddy currents

Changes within the structure of a steel element can be detected by the perturbations they create in an electrical field induced in the element. Thus the presence of cracks and voids in welds and plates may be identified from an examination of such perturbations. A coil carrying an alternating current produces eddy currents in an adjacent conductor; in turn, the eddy currents in the conductor generate impedance in the exciting cell or, if desired, a separate search coil. As the coil is scanned over the test area, defects such as cracks and voids produce a characteristic change in impedance, which can be recorded by a dial or meter. At present the technique is limited to elements with a simple geometry; further work is required to extend its range of application.

5.4.6 Magnetic methods

5.4.6.1 Cover meters

Several portable devices, known as cover meters, are available for measuring the thickness of the concrete cover to the embedded reinforcement. In such devices a magnetic field is generated between the two poles of the probe: the intensity of the field at a point is proportional to the cube of the distance from the faces of the pole. The magnetic field is distorted in the presence of a conductor, such as steel reinforcement, and the degree of distortion is a function of the bar diameter and its distance from the probe. Thus the device can be used to provide a measure of the depth of cover and the diameter of the reinforcement. The devices provide reasonably accurate data for lightly reinforced elements, but they may not do so for heavily reinforced sections.

5.4.6.2 Flux measurements

With this technique, steel elements are magnetised by an applied field. Local disturbances to the field are produced by a change in the cross-section of the steel element, such as at a wire break, and the disturbance is accompanied by a leakage of magnetic flux from the element; that is, the generation of a stray field. In application, a probe housing the magnetisation device (the yoke magnet) and sensors - to pick up the stray field, is moved over the concrete surface along the line of the element. A view of the equipment and typical test data are shown in Figure 5-8.

The technique is commonly used to examine the post-tensioned cables of suspension and cable-stayed bridges. The disturbance to the field produced by mild steel reinforcement can be suppressed by adopting particular methods of measurement and analysis, and so with development the technique may be able to detect breaks in prestressing tendons. However, because of their complex geometry, the technique is not used to examine the condition of anchorage zones.

5.4.6.3 Particle examination

With this technique, the part of a steel structure being examined is placed in a magnetic field and a fine powder of iron particles is blown onto its surface. In the absence of any surface or subsurface discontinuities, the particles will form a uniformly aligned film. However, in the presence of a discontinuity the alignment of the particles will map the disturbance created in the magnetic field.

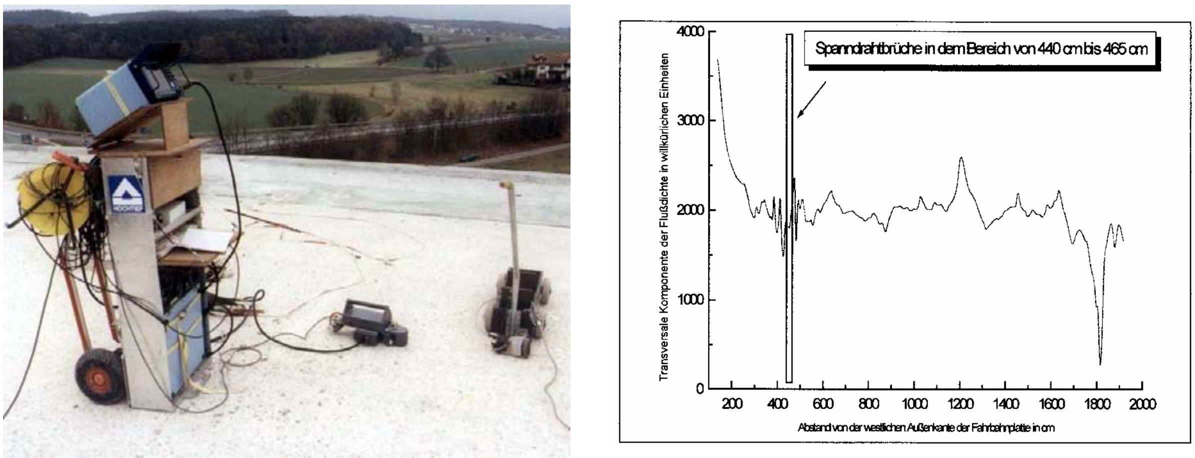

Figure 5-8 Magnetic flux measurement device and test data

The method is limited, obviously to magnetic materials, and to the detection of surface or near-surface defects. Furthermore, for detection, the discontinuity must also be aligned transversely (or nearly so) to the applied field. The advantages of this method are the portability of the equipment, its ease of use by relatively unskilled operatives, and its ability to detect tight cracks.

5.4.7 Modal analysis

The resonance characteristics of a structural component are affected, to some degree or other, by the presence of a defect located anywhere within it. Thus an analysis of the resonance spectra can be used to complete a global, or at least a regional, assessment of integrity and condition; that is, a health check.

There are two options for generating resonance in the component. A forced vibration test uses a controlled and measured input to determine the dynamic behaviour of the component, whereas an ambient vibration test makes use of the unknown and unmeasured input generated in-service, such as by traffic loading.

To ensure stability and serviceability, most civil engineering structures are relatively heavy and have low resonant frequencies. Thus for an effective forced vibration test, a good deal of low frequency energy has to be put into the structure, and this requires the use of heavy exciters and bulky ancillary equipment. Furthermore, normal in-service excitations can much reduce the effectiveness of this type of test. The ambient vibration test method needs no such exciters, which reduces costs considerably, but this method works best where the energy input into the structure is evenly distributed over the frequency band concerned; that is - ‘white noise’.

It may be possible to evaluate the resonance spectra of a pristine component through modelling. This approach is best suited to applications where a number of similar components require evaluation, or where the form of the structure is relatively simple so that the spectra can be determined with some confidence. However, because only rarely is it possible to quantify the resonance spectra of the structure under examination, the application of this approach is always likely to be limited.

5.4.8 Laser scanner

Because of the large area to be covered and the time-consuming procedures used, the inspection of a tunnel can lead to substantial traffic delays and/or detours. Furthermore, the closure of one bore with the adoption of bi-directional traffic in the other parallel bore has serious implications for the safety of the travelling public. Thus the use of scanning devices for tunnel inspections can be very cost-effective.

Laser scanning systems provide a high-resolution image and the data can be captured in digital format. A view of a laser scanner in use in a tunnel is shown in Figure 5-9, along with typical output from the device. In this example, a two-channel laser was mounted on a horizontal axis: the maximum resolution was 10,000 points per 360° for the conventional image and 2,500 points per 360° for the infrared image. Analysis of the images can detect the location of near-surface cracks, cavities and water leaks. Detailed maps showing the location of specific features can be produced from such images.

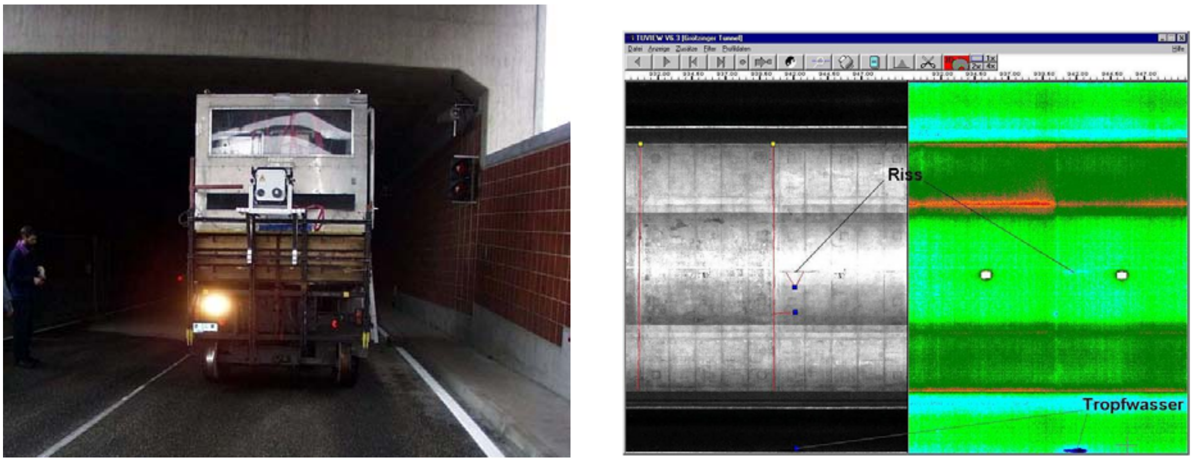

Figure 5-9 The use of a laser scanner in a tunnel, and an example of the output

5.4.9 Other techniques

Many other NDT techniques are used for inspecting and assessing highway structures but, for brevity, are not described here. Some of these may not have a widespread use, but have particular attributes that make them useful for specific situations and purposes. Examples include acoustic emission techniques, permeability tests, the measurement of moisture content using microwaves or nuclear methods, thermo-elastic stress analysis, holography, Barkhausen noise measurement and tomography. Techniques of minor importance include the dye-penetrant examination of steel structures; and penetration, electrical and ultrasonic tests on timber structures.

5.4.10 Summary of applications

Table 5-1 and Table 5-2 summarise the applications of some of the techniques described above.

Table 5-1 Capability of NDT for concrete structures

Technique	**Capability of detection**							
	Cracks	Delaminations	Corrosion	Buried objects	Honey -combing	Thickness	Voids in ducts	Fracture in reinforcements
Radar	O	+	–	+	O	O	+/O[3]	–
Thermography	O[1]	+	–	O[2]	O[1]	–	–	–
Radiography	O	–	–	O	O	–	–	O[2]
Impact echo	O	+	–	O	O	+	+/O[3]	–
Ultrasonic	O	+	–	O	O	+	O[2]	–
Potential map	–	–	+	–	–	–	–	–
Magnetic flux	–	–	–	–	–	–	O[2]	+

1 - water-filled
2 - capability largely dependent upon depth of burial
3 - performance dependent upon whether duct is plastic or metal
+ good O medium – poor

Table 5-2 Capability of NDT for steel structures

Technique	**Capability of detection**							
	Surface crack	Internal crack	Fatigue crack	Internal void	Pores and slag inclusions	Thickness	Delaminations; blistering	Corrosion
Radiography	–	O*	O*	+	+	O	O	+
Magnetic	+	–	–	+	–	–	–	O
Eddy current	O	–	–	–	O	O	–	–
Ultrasonic and impact echo	O	+	–	O	O	+	–	–

* where the axis of the beam is parallel to the crack
+ good O medium – poor

5.4.11 Combination of methods

In some circumstances, the reliability and usefulness of the data derived from NDT can be improved by using a combination of tests. In some cases the first test may represent a preliminary investigation, whilst the second is used to check the veracity of the data or to provide additional details. Typical examples are as follows.

- A cover meter might be used to locate the reinforcement prior to recovering cores or undertaking an ultrasonic survey.
- Magnetic techniques may be used to map out zones that have a high risk of corrosion, followed by resistivity tests in these zones to determine the likelihood of corrosion.
- Where a bituminous layer overlays a concrete bridge deck, a combination of radar and magnetic flux measurements may be used to identify areas where the reinforcement is

likely to be corroding. The radar scans will show changes in the dielectric constant, which is affected by, amongst other factors, the moisture content of the concrete. Measurements of magnetic flux may then be used to calibrate the scans and define the depth of cover of the reinforcement.

- A combination of tests can be used to measure the same property and thereby increase the level of confidence in the data and its interpretation; for example, the prediction of strength using a combination of Schmidt hammer and ultrasonic tests.
- An improvement in the calibration or interpretation of the test data can be obtained by combining the results of different tests; for example, the accuracy of predictions of strength may be improved by taking account of measured variations in density.

5.4.12 Research needs

Although NDT techniques have been used successfully on a variety of concrete and steel structures, in general there is not a high level of confidence in the techniques because there is little independent advice available on their applicability, capability, reliability and accuracy. Advice is particularly wanting on the interpretation of the test data, because often this is not straightforward.

Areas where improvements in NDT methods could have substantial benefits are discussed below.

Radar - there is a potential for developing signal and image processing to improve the resolution around and immediately beyond the first layer of reinforcement.

Effort should be directed at improving the real-time processing of data.

The development of inexpensive, specialized antennae (for example, ones with a variable frequency) may be useful for specific applications.

Research should be directed at developing physical models linking the results of GPR with the condition of the test specimen.

Other aspects that have potential for development include the use of GPR to assess the degree of corrosion in concrete reinforcements and for detecting zones that have a high concentration of chloride ions. This will require research to assess the influence of moisture content and chloride ion content on the electric and dielectric properties of concrete.

Ultrasonic tests have the potential to become a useful tool for inspection and assessment, but improvements are required in signal generation and processing techniques.

There is also a need to improve the means of attaching and coupling the transducers - a recently developed system uses spring suspensions for the transmitter and receiver.

The availability of increasingly powerful personal computers has led to an interest in the use of ultrasonic tomography. More sophisticated processing techniques may also be applied to standard data sets to improve resolution and thereby the identification of defects.

Inexpensive, multi-probe ultrasonic transmission and reception equipment should be developed to increase the depth of interrogation.

Impact echo is a practical means of detecting voids and delaminations, and spectral analysis of surface waves can provide information on the condition of layered systems. Nevertheless, there is a need to investigate the capabilities of the equipment in measuring thickness, mapping or sizing layers of reinforcement, detecting and mapping delaminations and cracks that run parallel to the surface - particularly in areas of congested reinforcement.

Research should also be directed at developing scanning procedures and multi-array sensors.

Any of the above experimental studies should be complemented by work to collect and publish reference data sets, and document the application of the technique to specific types of problem.

Magnetic flux - there is a high potential for developing techniques for detecting ruptures in prestressing tendons. However there is a need for further investigations into the capabilities of various sensors - such as the Hall and the SQUID sensor.

There is also a need to improve the methods used to identify and hence eliminate the signals given by non-prestressing reinforcement so that, for example, the technique could be used to identify a rupture in a prestressing reinforcement.

5.4.13 Standards and guidelines

Standards and guidelines are required to ensure consistency in the use of NDT techniques and in the collection and handling of the data. Such documents should provide information on the limitations of the various methods, specifications on test procedures, and direction on the presentation of the data and its analysis and interpretation. In addition, advice should be given on the useful combination of NDT techniques, and on the use of the data arising from them in deriving a condition rating for the structure.

5.5 LOADING TESTS

5.5.1 Introduction

The origin of load testing comes from the need to check the performance of a bridge prior to its commissioning. In many countries there is a long history of testing: in some, traditionally, a designer was obliged to stand underneath an arch bridge while the centering was struck.

National policies and practices vary widely, and the background to some of these is given in Table AIV-1 of Annex AIV, whilst Table AIV-2 and Table AIV-3 provide, respectively, information on obligatory codes and the application of load testing in some European States.

There are two basic approaches:

(a) In some States, load testing forms an important part of an investigation into the performance of a bridge: beginning with an acceptance test on a newly erected or substantially rehabilitated bridge, through to assessing the load-carrying capacity of old and perhaps deteriorated structures. The prevailing view here is that load testing is cost-effective. It can indicate a much higher live load capacity than derived from calculations alone, and thereby enable a bridge to remain in service and avoid unnecessary expensive strengthening or replacement works. In rare cases testing may identify a current, and perhaps, dangerous shortfall in stability or serviceability.

(b) In other States a loading test would only be permitted in exceptional circumstances. The view here is that an adequate measure of stability can be obtained from a combination of an inspection and analysis. Furthermore, it is thought that undertaking a test to determine load-carrying capacity may damage the structure.

A summary of the position on load testing in some European States is given in Table 5-3.

Table 5-3 Load testing: policy and applications in some European States

State	Prior to putting bridge into service			Research investigation	Assessment of load-carrying capacity
	New typical road bridge	Prototype structure	Renovated or strengthened bridge		
Austria	–	–	–	+	
Czech Republic	+/–	+	+/–	+	+/–
Denmark	–	–	–	+	–
Germany	–	–	–	+	–
Italy	+	+	+/–	+	+
Netherlands	–	–	–	+	–
Norway	–	+/–	–	+	–
Poland	+	+	+	+	+
Slovenia	+	+	+	+	+
Spain	+	+	+/–	+	+
Switzerland	–	+/–	–	+	+
United Kingdom	–	–	–	+	+

+ yes – no +/– decision dependent on various factors

As shown in Table 5-3, all States allow the use of load testing for research purposes: for example, to determine the performance of a new prototype structure, or to gather data on the collapse of a redundant structure.

In the USA, the Association of State Highway and Transportation Officials (AASHTO) sets the national policy on load testing, but some States have their own regulations. At present there is no requirement to undertake a loading test on a bridge, but in 1998 the TRB produced a manual (HRD234) on the use of non-destructive load testing for deriving a bridge rating. As elsewhere, load testing is also used as a research tool to improve understanding of the way loads are carried by and distributed through a bridge.

5.5.2 Test loads

The principal test variable is the magnitude of the applied load. Usually it is either related to the characteristic load, or is calculated on the basis of the effect that the load would have on the structure; but it may also be based on the expected day-to-day in-service load.

The type and distribution of the load have also to be considered.

A bridge can be loaded with static and/or dynamic loads. Usually, static loads would be applied through loaded heavy goods vehicles. The magnitude of the static load adopted in some European States is summarized in Table AIV-4. Dynamic loads are usually applied using loaded goods vehicles: the dynamic load is mainly a function of the speed and weight of the vehicle, but it is also affected by the characteristics of the vehicle suspension and the unevenness of the road surface. Other methods for applying dynamic loads have included dropping weights, moving weights along a bridge, rotating weights, the use of hydraulic jacks to apply cyclic loads, impact loading, and the deliberate excitation of footbridges by pedestrians: a summary of the methods used in some European States is given in Table AIV-5.

5.5.3 Types of investigation and methods of measurement

The types of investigation and the methods of measurement used in a loading test are much the same in all States.

Type of investigation

- visual examination - before and/or during and/or following a load test
- measurements made during a test
    - applied load
    - deflection of span
    - displacement at supports
    - strain/stress
    - width of cracks
- secondary effects - such as temperature, and exposure to sun and wind conditions

Variables measured and the methods of measurement

- applied load
    - load cells
    - pressure cells
- deflection/displacement
    - inductive displacement gauges
    - dial gauges
    - inclinometers
    - accelerometers - for dynamic loading
    - surveying techniques - using standard equipment (such as graduated tapes and levels), electronic distance measuring devices, lasers, and photogrammetry
- strain
    - vibrating wire gauges
    - electric resistance gauges
- temperature
    - thermocouples

Further details of the observations and measurements made during a loading test, and of the methods of measurement are provided in Table AIV-6 and Table AIV-7 respectively.

5.5.4 Analysis and application of test data

In some States, the data from a load test are analyzed and assessed to compare the measured and calculated responses - usually it would include a comparison of deflections.

Other States have no standard assessment criteria, and analysis is an integral part of the test procedure: analysis is undertaken to ensure that the applied load is unlikely to generate any permanent deformation or damage. The results from a load test are mainly used to improve the structural model used for assessment purposes.

The assessment criteria and the approaches used to analyze the test data are summarized in Table AIV-8.

5.5.5 Future strategy and research needs

Within Europe, there are many research and development projects underway on the load testing of bridges: details of some of these are provided in Table AIV-9.

The more important issues that require further work are:

- At present the test load is defined in various ways, and there is a need to devise a standard method of calculating the load; for example, based on the design loads and the expected in-service live load.
- The development of methods for monitoring the performance of a structure under test; for example, to reduce problems of access and setting up the equipment, and to improve the resolution and reliability of the data.
- To determine how particular defects may affect the elastic response of a structure (as might be assumed to occur under the test load). This may provide a means of detecting the presence of defects.
- The role of load testing for assessment purposes; in particular the use of proof load tests.

5.6 MONITORING

5.6.1 Introduction

Monitoring can be defined as any periodic or continuous operation where the behaviour of a structure, or of its components - such as the foundations, is quantified in some way so that its serviceability and stability can be evaluated.

Observations and measurements are taken to:

- compare the predicted to the actual in-service performance - this can be used to check the validity of some of the assumptions made in design
- detect defects as they occur in-service - and which may affect serviceability or safety
- provide data for assessing the level of serviceability or safety.

Monitoring works may be implemented:

- before construction - to determine the effect of construction works; for example, on the change in ground water level brought about by the construction of a retaining wall
- during construction - perhaps in response to a problem that arises, or a change in some construction detail
- in-service - as part of an assessment of condition and performance.

The type of monitoring adopted varies according to the type and purpose of the structure, the loading regime, the behaviour of the structure, and with the problems or uncertainties met during construction. A number of factors affect the scale of the monitoring exercise and the accuracy and frequency of the measurements. Usually the requirements of the work, and hence the site operations, change with time; for example, with few exceptions the frequency of measurement will reduce following the end of construction or shortly after this - such as at the commissioning stage.

The following should be taken into account when planning monitoring works:

- mechanisms that may dictate the behaviour of the structure
- selection of the element(s) to be monitored
- selection of the variables to be measured (such as deflection and strain), and the location of the instruments

- prediction of the magnitude of the variables to be measured
- selection of the instruments - taking account of the ease of installation, and the cost, robustness, sensitivity and reliability in service
- the need for duplicate instruments and measurements to allow for the breakdown of equipment in service and to check consistency
- data collection, storage and retrieval
- safety
- the effect of the instrumentation system on the use of the structure - for example, the location of bulky cabinets on a bridge may distract motorists and cause an obstruction.

5.6.2 Current position

It was known from the outset of the Action that the use of monitoring for assessing highway structures varied widely across Europe, and so information on current practice was gathered by means of a questionnaire circulated to the States participating in the Action: eight replies were received.

In most States, monitoring is used to provide data for assessing structural condition, usually of bridges and tunnels. It would seem that monitoring works are usually implemented before or during the construction of walls and tunnels, whilst for bridges they are usually implemented following the end of construction. This variation in timing probably reflects the different purposes of the monitoring works.

Usually the collection and analysis of the site data is undertaken by the owner or maintaining agent for the structure, aided by a research centre or University.

Some States have produced guidelines on the monitoring of highway structures, and many of the on-site tests are covered by national standards (such as issued by BSI and DIN). Although guidelines and standards are available the accuracy and reliability of the measurements are dependent on, in order:

- the type of equipment used, including the data collection and processing unit(s)
- the adequacy of the calibration and installation procedures
- the experience of the site operatives - for example, in spotting malfunctions of the equipment.

The following covers various measurement techniques and the application of the data: visual inspection is covered in Chapter 4.

5.6.2.1 Structural types

Bridges

The number of bridges monitored in a particular State could be expected to vary with the size, age and condition of the bridge stock, but in most States less than 25 bridges will be monitored in any detail at any one time.

Commonly, measurements are made of: deformations or displacements generated by loading and/or creep movements; the width of cracks; and, in some indirect way, the degree or rate of corrosion. In some cases the strain in cables and tendons, and/or the force at their anchorage points, may also measured.

Earth retaining structures

There are many different types of retaining wall, such as reinforced concrete cantilever, embedded secant pile, masonry-faced gravity, reinforced soil, timber crib, and tied-back sheet piled walls. Within a particular State or region, the proportion of each type of wall in the stock, and the number of particularly high retaining walls are a function of the extent and maturity of the transport system, geological and geographical conditions, and various social and economic factors.

The need to monitor such structures depends on their condition, their rate of deterioration, and the consequences of their failure. Thus the use of monitoring for assessing the condition of such structures varies widely across Europe. In most States there is provision for undertaking periodic visual inspections of particularly important retaining walls, but in only a few are detailed monitoring works undertaken for other than research purposes. Typically, around 25 walls will be monitored in a State at any given time.

The type of wall influences the details of the monitoring works, but most commonly measurements will be made of (a) changes in the vertical and horizontal position of the face of the structure and, perhaps also, of movements within the retained ground and foundations, and (b) pore water pressures. In some States the restraining forces provided by ground anchorages, ties and the like are also measured: for example, this is standard practice in the UK.

Tunnels

There is a wide diversity in the number and length of highway tunnels within Europe and so, as with retaining walls, the use and type of monitoring works for highway tunnels also varies widely.

All road tunnels are inspected at regular intervals, but measurements are not commonly made. The profile of a tunnel can be monitored, to check convergence for example, using conventional surveying techniques or, more commonly now, automatic scanning devices. Measurements might also be taken of the width and extent of cracks within the tunnel. Movements of the ground in and around a tunnel might also be made using, for example, conventional surveying techniques, slope indicators, and inclinometers. The lock-off load in bolts, anchorages and the like may also be measured.

5.6.2.2 Variables

Pore water pressures

The pore water pressures sustained in soils and backfills affect the performance of buried structures and earth-retaining structures: in some cases these pressures can have a dominant effect on performance. Several methods are used to measure such pressures, including an open standpipe, twin-tube hydraulic piezometers and sealed pneumatic piezometers. Ridley et al (2003) reviewed the methods available for measuring pore water pressures in the field.

Deformation

Surface movements can be determined using conventional optical techniques, automatic electronic distance measuring devices, or by GPS. Commonly, measurements are taken of:

- convergence (that is, the change in distance between two reference points) - using a tape extensometer, convergence meter, induction transducer, or dial gauges

- movement across a crack or joint in the structure or exposed rock face - using one of the range of proprietary devices (crackmeter, fissurometer, 3D jointmeter)
- vibrations - using accelerometers.

A range of equipment is available for measuring subsurface settlement including:

- extensometers, which measure the change in distance between two or more points along a common axis - different types have been devised to suit specific purposes
- buried settlement plates and gauges - a wide range of types are available
- hydrostatic profile gauges - typically comprising a torpedo that is drawn through a tube laid horizontally in a trench.

Instruments used to detect subsurface horizontal movements and rotations include:

- inclinometers - various proprietary devices are available for determining the magnitude and rate of lateral deformation in soils (these are based on the use of a sliding sensor) and in structures (using fixed sensors)
- tilt-beam sensors and electro-levels - which measure the rotation between two fixed points
- direct or inverted pendulum.

Loads and stresses

The equipment for measuring loads and stresses include:

- earth pressure cells, these are used to monitor the total stresses in soils and soft rocks - the cells can be installed in the material (to measure the free-field vertical or horizontal stress) or in a borehole, or attached to the back of a wall or tunnel lining (to measure the boundary stress)
- load cells to measure the tensile forces in ground anchors, bolts, ties and the like - a range of devices is available
- load cells to measure the compressive force in structural components, such as struts, bearings and piles.

Strain

The strains developed in structural components can be measured by a number of devices, such as vibrating wire gauges, electrical resistance gauges and accelerometers. Usually the strains are converted into loads using the elastic modulus of the material.

Other variables

Measurements of other variables - such as temperature, wind speed, precipitation, moisture content and water flow, may be taken to provide a better understanding of how performance is affected by these, perhaps second-order, variables, and also to correct the output from the instruments to a reference temperature.

5.6.3 Future strategy and research needs

It would seem that monitoring works are rarely undertaken as a matter of routine. The use of such works should be increased to meet the recommendation given in Eurocode 1 that the performance of structures should be recorded and reported to establish reference databases. Furthermore it is clear that the value of long-term monitoring is usually overlooked, but its value is emphasised in some current European projects.

It would seem that the data from monitoring exercises are not always archived systematically or transparently, particularly that obtained from the monitoring of walls and tunnels. This hinders the retrieval and subsequent analysis of that data. Further effort should be directed at improving the traceability of data.

In many States, there are no guidelines or codes of practice on the monitoring of structures: it would seem necessary to address this shortage as a matter of priority. It would seem reasonable to draw up guidelines covering the following:

- establishing a plan for monitoring works; this would include the selection of
    - the objectives of the works
    - the variables to be measured
    - the type, number and locations of the instruments
    - the frequency of readings and the type and capacity of the data acquisition system
    - critical values for particular actions
    - measured values that would trigger an alarm or intervention
- an overview of measurement techniques
- installation procedures, including safety measures
- analysis and reporting procedures
- the maintenance of instruments
- qualification and training of site personnel.

To help stimulate the wider use of continuous monitoring of structures, there is a demand for smaller and less expensive instruments and for computer-based recording equipment. The availability of near-continuous performance data should improve understanding of the in-service behaviour of structures. A back-analysis of the data collected during construction and in-service may enable improvements to be made to current design methods.

5.7 RECOMMENDATIONS

Recommendation 12 The methods of procurement and the specifications used for testing highway structures should be reviewed. From this, model contract documents should be established to suit various requirements for testing.

Recommendation 13 Advice or guidance notes on various NDT methods are required to extend the ranges of application, to encourage consistent and appropriate usage, and to improve the interpretation and application of the test data in assessing the condition of a structure. Such notes should include detailed information from case studies.

Recommendation 14 Research should be directed at producing cheaper, more reliable and user-friendly NDT equipment. Emphasis should be given to improving the signal processing equipment used for radar and ultrasonic surveys.

Recommendation 15 The use of load tests for assessment purposes should be reviewed: this should cover cost-effectiveness, instrumentation, and data collection and analysis.

Recommendation 16 It is recommended that loading tests are undertaken on novel or prototype structures.

Recommendation 17 In-service structures should be monitored as a matter of routine. Advice or guidance notes should be produced to encourage such exercises: these should cover the planning of such work; data collection, analysis and application to whole-life cost models; measurement techniques and equipment; and personnel qualifications. Where possible, they should also include information from case studies.

Recommendation 18 The data obtained from monitoring exercises should be held centrally, and in a form that makes them easy to retrieve and interrogate.

Chapter 6 Data management

6.1 TYPE AND FORMAT OF DATA

The findings of a formal inspection are usually recorded on purpose-designed forms; nowadays these are mainly available in an electronic format. Such forms usually include a list of structural components or elements, such as foundations, piers or columns, abutments, wing walls, retaining walls, approach embankments, bearings, main and transverse beams, diaphragms, slabs, waterproofing, surfacing, and expansion joints.

The information required includes:

- basic information about the structure, such as its identification number, reference and/or name, and location
- details of the type of inspection, including any limitations generated by problems of access
- the type and location of defects, and an assessment of their extent and severity
- an overall assessment of the structure
- recommendations for short-term or long-term actions; for example, on the timing of subsequent inspections and on the priority for remedial works.

In addition to the standard forms, interpretive reports are usually produced for Principal and Special Inspections.

The report from a Special Inspection should normally include drawings showing the form of construction, and a description of the important structural elements - such as the deck and supporting structure, and ancillaries - such as expansion joints, waterproofing, and parapets. The location of substantial defects should be shown on drawings. Such a report should also provide a detailed description of the condition of the elements inspected and, where possible, details of the construction and maintenance history of the structure and the results of previous inspections.

All the information available on a particular structure, such as its dimensions, material characteristics and the results of inspections should be coded appropriately so that it can be readily input to databases and also retrieved from them. The availability of suitably structured and populated databases is a fundamental requirement for generating and improving inspection procedures, for deriving a strategy for the long-term maintenance of highway structures, and for developing whole life cost models.

6.2 APPLICATION OF DATA

As shown by the flowchart given in Figure 6-1 the data obtained from an inspection are used to decide the next course of action: this may be an immediate action or one that follows from a condition assessment of the structure.

One of the objectives of an inspection is to confirm that the structure is fit for purpose. If during an inspection it becomes clear that the use or condition of the structure, or one of its components or elements, puts the safety of users at risk, an inspector can propose immediate measures, such as a load restriction, propping of the superstructure or even closure of the highway. Such measures should remain in place at least until a further, and perhaps more detailed, investigation is completed.

It is important that repair works are regularly inspected and assessed, and for the findings to be recorded in a systematic manner. These data can be used to assess the effectiveness of the repair work undertaken at a particular site, and to compare the cost-effectiveness and durability of different works undertaken at other sites with differing service conditions.

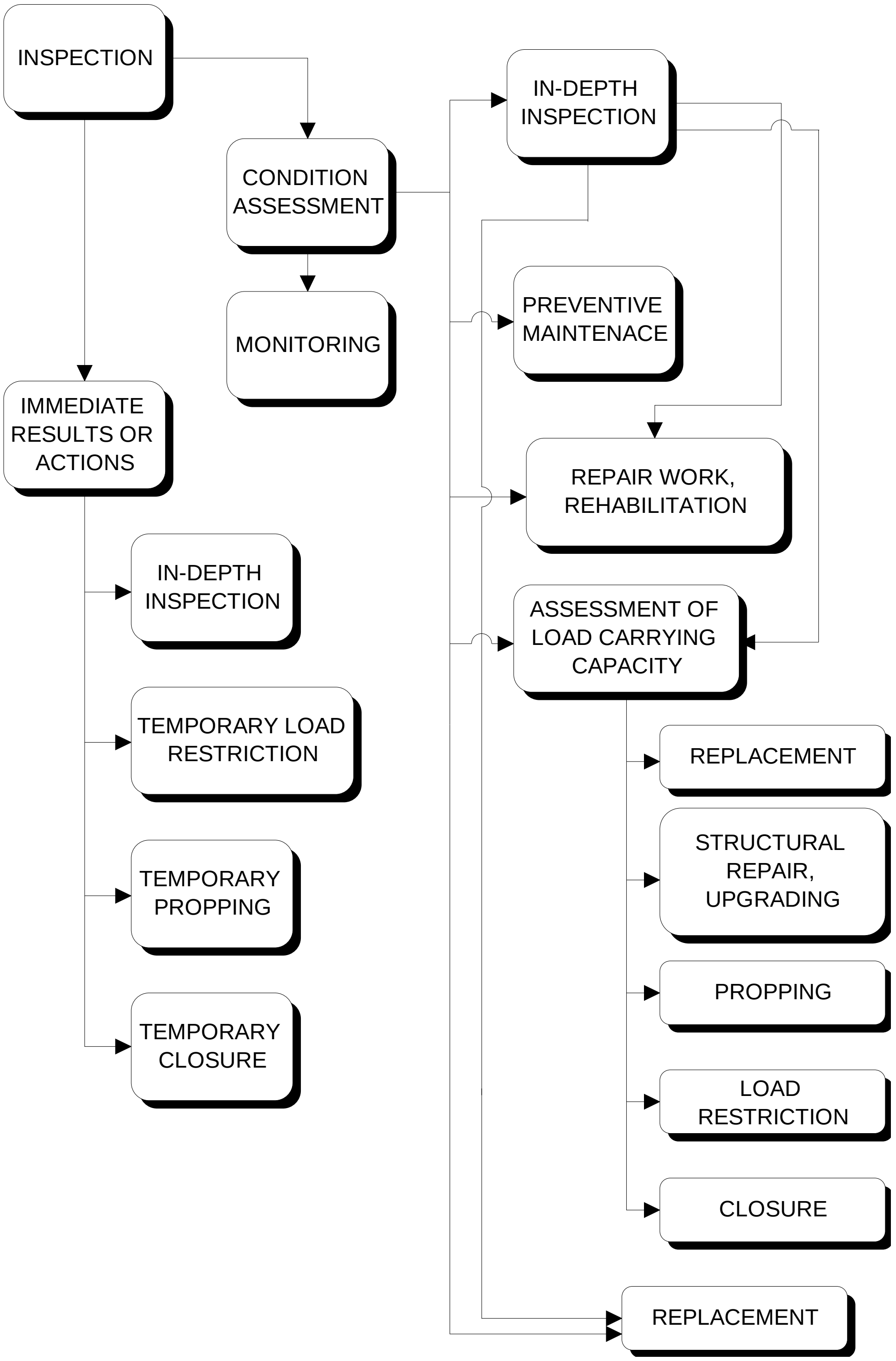

Figure 6-1 Flowchart of data obtained from an inspection

Another objective is to obtain data that can be used to assess the condition of the structure, and, thereby, of the stock of structures. The means of deriving a condition rating of a structure are described in the following chapter.

Data on the rate of change of the condition of a structure, or of its components and elements, are essential input to decisions on the type and timing of maintenance and remedial works. For example, as shown in Figure 6-2, the condition of a column can be tracked through successive inspections to help fix the timing of the repair works. The timing may be based on a cost-benefit analysis - perhaps of particular use when resources are scarce, whilst also ensuring that the level of deterioration does not raise concerns regarding safety and aesthetics. Such data can also be used to help prioritise maintenance work on the stock of structures.

Figure 6-2 Condition of a column in 1997 and 2000

Data on the rate of change in condition can also be used to develop new or improved models for predicting the rate of deterioration, and for whole life costing. The development of such models requires:

- the collection of relevant data
- consistency in the inspection and assessment of a structure, by different personnel at different times
- a suitable quantified means of expressing condition.

Selection of the most appropriate type of remedial works requires the identification of the cause of the deterioration. But this is not always straightforward, particularly with ageing structures where there is limited historical information available. It is necessary, therefore, for structures to be inspected at the end of construction, and perhaps also before they are put into service. Problems and defects met during construction and changes to the as-designed layout should be recorded. This may help identify the underlying cause of a defect, and thereby improve the reliability of the inspection and assessment process and the prediction of the rate of deterioration.

6.3 RECOMMENDATIONS

Recommendation 19 The methods used to collect and record the data obtained from inspections of highway structures should be reviewed. This should cover the use of photographic techniques, including stereo-photogrammetry and video recording.

Recommendation 20 The type and amount of data collected, archived and analysed from inspections should be reviewed periodically to ensure that they meet the requirements of the management system.

Chapter 7 Condition assessment

7.1 DEFINITION AND OBJECTIVES

A Condition Assessment (CA) is undertaken to provide information on:

- the overall condition of a structure and/or of its components or elements
- the intensity and extent of defects and areas of deterioration - and also on the nature and cause of these
- the effect of the defects and areas of deterioration on the stability and serviceability of the structure - the latter covers, for example, aesthetics, durability and traffic safety.

The main objectives of a CA are thus:

- to identify deterioration processes
- to provide an indication of the condition of a structure and/or of its components or elements
- to identify what further works are required, such as inspection, maintenance and/or remedial works - and also the likely cost and optimum timing of such works
- to rank a structure according to its need for further work
- from a number of assessments, to provide an indication of the condition of the stock of structures
- to optimise expenditure on further works.

However completing a CA is not always straightforward. Some deterioration processes can be initiated and promoted by one or more of a number of factors, which are often interrelated, and so it may be difficult to derive a simple explanation or obtain a complete understanding of the problem(s). But only when a problem has been well defined and understood can the most effective treatment be identified, planned and executed. For a particular defect there are usually several potential remedial options; selection will be based on factors such as the residual life of the structure, the estimated cost, timing and effectiveness of the treatment, operational requirements during the works - such as user safety, lane closures, and the likely weather conditions.

7.2 PROCEDURES

The following requirements must be met to obtain the data necessary for undertaking a condition assessment and for analysing the results of one or a series of assessments:

- inspections must be undertaken regularly at appropriate intervals, starting from the commissioning of the structure and following the completion of any major repair work
- inspections must be completed by adequately trained and qualified personnel, and be undertaken using appropriate equipment
- the availability of a catalogue that gives details of the possible defects and deterioration processes, and information on the factors that can initiate and promote them
- the availability of a well-defined method for quantifying the severity and extent of defects and damaged areas

- a means of assessing the impact that defects and areas of deterioration may have on the safety and durability of a structure.

Furthermore, some defects can originate during construction and so knowledge of the construction stage - particularly of any problems met then, can be particularly helpful in completing a condition assessment.

7.2.1 Review of existing procedures

The general condition of a structure could be expressed qualitatively, using such terms as very good, good, satisfactory, bad and very bad, but most procedures use a rating to quantify condition. A rating provides a convenient and effective means of expressing the general level of deterioration of a structure, or one of its components or elements. Various methods of deriving a condition rating have been developed for bridge management systems to identify bridges that require further (and perhaps more detailed) inspection, assessment and analysis, and to establish priorities for maintenance and remedial works.

A condition rating should be based on a simple scoring system. The evaluation of the level of deterioration should take into account all the defects that may have an impact on user safety and/or the durability of the structure. Thus the evaluation of every incidence of damage should take into account:

- the nature and character of the damage
- its effect on the safety and durability of the structural element
- the effect that the damaged element (such as beam) has on the safety and durability of the structural component (such as a span of a bridge) and on the structure as a whole (such as a bridge)
- the maximum severity of the damage, and the likely future rate of deterioration
- the current extent of the damage and its likely future rate of propagation.

The methods used in Europe and the USA were reviewed by the BRIME project. This showed that two approaches were used to derive a condition rating for a bridge based on the ratings awarded to its structural elements.

- A cumulative condition rating - where the rating for the most severe damage on each element is summed for each span of the superstructure, each part of the substructure, the carriageway and accessories: the total sum is taken as the condition rating for the structure. The rating can be used to prioritise follow-up work. An example of a cumulative condition rating is shown on Figure 7-1.
- A rating classification - where the rating for a bridge is taken as the highest of the ratings given to its components. This approach shows the number of bridges in each class but does not allow direct comparisons between different structures. An example of this approach is shown in Figure 7-2.

More detailed information on the methods used for assessing the condition of elements, components and the bridge as a whole is provided in deliverable D2 of the BRIME project.

7.2.2 Limitations

It will be appreciated that a rating is an assessment of the condition and/or state of deterioration of a structure and, because no account is taken of the applied loads, it does not provide a measure of the level of safety - thus structures having the same rating may have widely different levels of safety. Furthermore, in general, ratings do not rank a group of structures according to the urgency of remedial or strengthening works: this would only be the case for identical structures with identical in-service loading conditions.

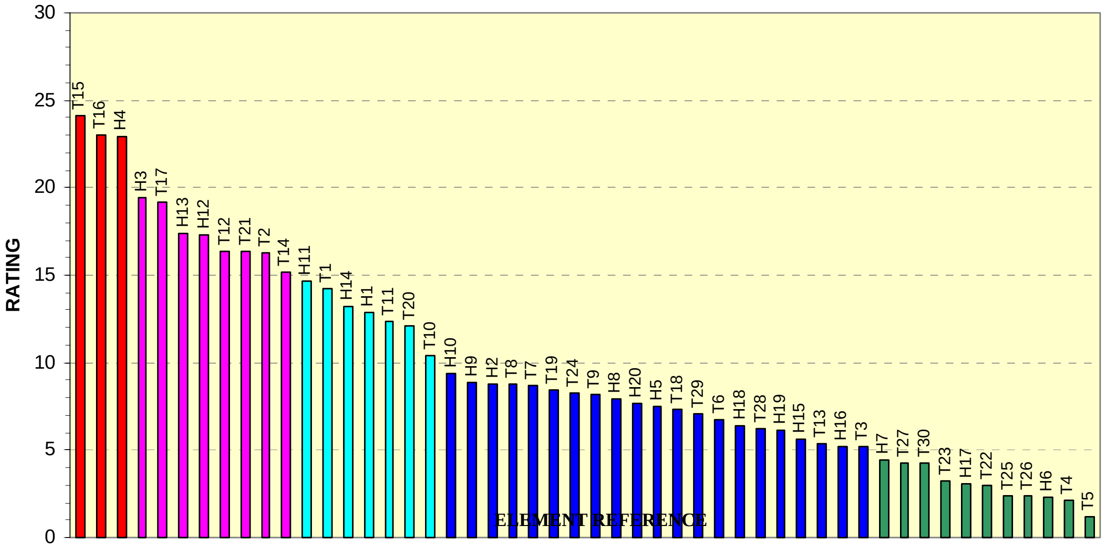

Figure 7-1 Cumulative condition rating

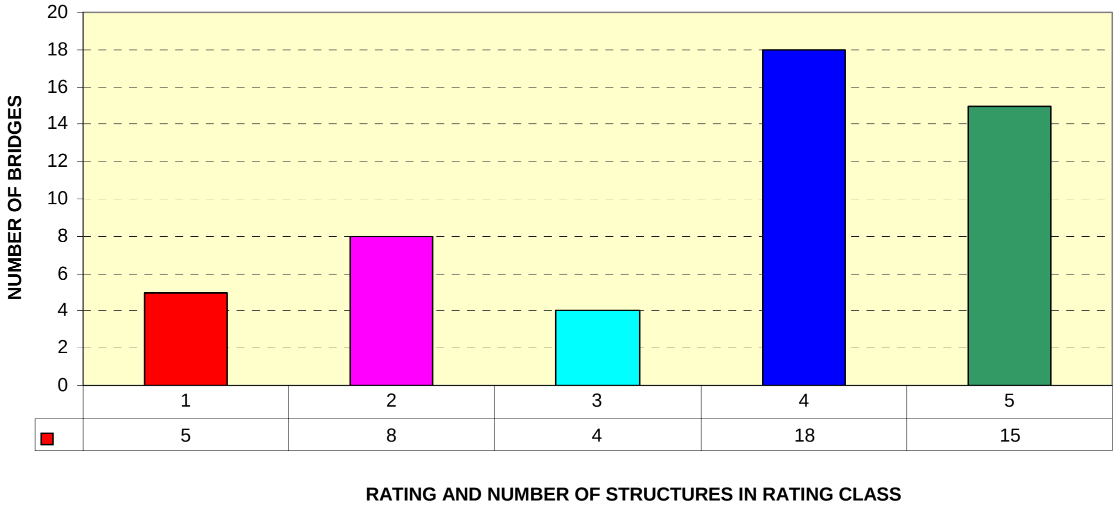

Figure 7-2 Condition rating classification

7.3 IMPROVED PROCEDURES AND RESEARCH NEEDS

The experience and knowledge gained through the use of an inspection and condition assessment regime can be used to develop and improve techniques and procedures, and thereby improve the effectiveness of the existing regime. A philosophy of continual improvement should be enacted by reviewing and, where necessary, updating training courses, the catalogue of defects, and the methods used to quantify the severity of defects. Thus inspection techniques and methods of analysis can be expected to change with time.

To ensure the safety of users, whilst aiming to optimise expenditure on remedial and renewal works, it is essential that reliable assessments are made of deteriorated structures. Such assessments should, therefore, be carried out by experienced engineers. Assessing such structures requires the application of a pre-defined assessment method combined with engineering judgement, and the latter introduces an element of subjectivity into the process.

To help rationalise and quantify engineering judgement, and thereby reduce or control the level of subjectivity, probabilistic methods and new mathematical methods, such as neural networks and fuzzy logic, have been used in the assessment of deteriorated structures. Such methods are increasingly being used to analyse the data from a condition assessment to predict the future rate of deterioration and to optimise the selection and timing of remedial works.

Methods, based on neural network theory, have been developed to provide an adequacy rating of a structure; the rating is derived from a set of indicators such as the condition rating, the safety or reliability index, the remaining service life, and the importance of the structure to the integrity of the highway network. By taking account of a wide range of factors, the adequacy rating (or priority ranking) is a better means of prioritising structures in terms of their need for remedial works than a condition rating, which at best provides a measure of the current state of deterioration.

As stated earlier, to ensure reliability, inspections and assessments should be undertaken by experienced personnel. Experience is subjective, and so represents ‘fuzzy’ information, but it can be included in an assessment process through the use of fuzzy set theory: this has proven to be a useful way of applying expert opinion to engineering problems. Furthermore, by managing and analysing the information from inspections and assessments, fuzzy logic can help to derive condition ratings for structures.

Further work is required to introduce these methods into the routine assessment of highway structures. Although most (if not all) of the assessment techniques described above are specific for bridges, they could be adopted and modified to suit other highway structures - such as retaining walls and culverts.

7.4 PHASES

A condition assessment comprises two phases:

- an in situ inspection to gather information for analysis; it is essential that the data are appropriate and relevant to the derivation of the required index - for example, a condition rating or priority ranking
- evaluation of the value of the index.

7.4.1 Inspection

Clearly, the reliability of a CA is dependent upon the quality of the inspection. Two types of inspection can be considered:

- standard inspection(s)
- monitoring works.

7.4.1.1 Standard

As described in Chapter 4, standard inspection techniques are widely used across Europe. Such inspections provide data on the condition of the structure at a particular time. But, immediately following an inspection, damage can be inflicted and deterioration processes can commence or accelerate substantially. Thus substantial remedial works might be necessary where the time between successive inspections is too long, or where a defect is not picked up at an early stage. Continuous or long-term monitoring works can be a more efficient means of managing particular structures.

7.4.1.2 Monitoring

Experimental techniques and equipment, based on the use of fibre optics for example, can be used to continuously monitor (or effectively so) some aspect of the performance of a highway structure, such as deflection under live loading. Long-life sensors can be installed at the construction stage to provide the data required for assessing the condition of a structure, and so it may be possible to track, continuously and remotely, the condition of a structure. In time, it may be possible to construct ‘smart’ or ‘self-diagnostic’ structures that contain a variety of sensors which will warn the bridge manager of a problem, such as the onset of corrosion. However, more research is required to develop cheap, reliable sensors, complete with data transfer and analysis equipment, to collect all the data required to complete a CA.

7.4.2 Evaluation

At present, usually the general condition of a structure is expressed through a single number, which may also indicate the priority for remedial works. A review of the condition ratings used in some European States was undertaken as part of the BRIME project: some of the results of that review are reproduced in Annex V.

7.5 RECOMMENDATIONS

Recommendation 21 The extent to which the type, quality and quantity of data from an inspection satisfies the requirements of a condition assessment should be reviewed periodically. And, where necessary, work should be directed at improving or developing investigatory techniques, instruments, and the collection and analysis of site data.

Recommendation 22 Further work should be directed at improving the methods used to identify and rank the importance of defects with regard to the safety, durability and cost of maintaining highway structures.

Recommendation 23 Methods for deriving an adequacy rating or priority ranking of structures should be investigated. This should include a review of the potential of new mathematical techniques, such as fuzzy set theory and neural networks.

Recommendation 24 Taking the methods used for bridges as a starting point, methods for assessing the condition of earth retaining walls and buried structures should be established.

Recommendation 25 Long-term monitoring works should be undertaken as a matter of course, and the results of such case studies made available for reference purposes.

Chapter 8 Qualification and certification

8.1 INTRODUCTION

The requirements and procedures used to inspect, assess and maintain a highway structure vary according to the size, importance and complexity of the structure. Particularly complex structures require the application, by competent personnel, of well-defined procedures and sophisticated inspection and analysis tools.

As stated earlier, the results of an inspection can be used to derive a CA for a structure, which in turn determines the selection and timing of any remedial works. Thus the results underpin the asset management system and so it is essential that inspections are carried out in a consistently reliable manner. Whereas inspection procedures and test methods can be specified in standards (and their reliability checked through comparative studies), an inspector must draw on intelligence, training and experience to decide where an examination is to be undertaken and what should be measured. Therefore, in a well-tried and tested BMS the human factor is likely to be the weakest link, and so highway authorities have introduced procedures to check the competence of inspectors: this covers professional qualifications as well as personal skills. Across most of Europe it is standard practice for inspectors to only undertake inspection work.

8.2 CURRENT POSITION

All the States involved in COST 345 have developed standards for the qualification and training of inspectors. The various approaches have some common elements but they have different requirements regarding the knowledge and experience required of inspectors: for example, some States require an inspector to have a formal educational qualification whilst others require only that an inspector has some relevant practical training or experience. A summary of practice in a number of European States follows.

8.2.1 Austria

No formal requirements are laid down for those undertaking routine bridge inspections, but inspectors are required to have appropriate specialised training in the subject: much of the training is provided on the job by experienced inspectors. Also, there are no formal requirements for checking the reliability of the results of an inspection.

8.2.2 Czech Republic

An inspector must obtain an appropriate certificate from the Ministry of Transport. To obtain a certificate, an applicant must:

- be a civil engineering graduate
- have at least five years experience as a bridge engineer
- pass a training course in bridge inspection - this must be renewed annually, through a two-day course.

There are no special requirements regarding the physical condition of inspectors.

8.2.3 Ireland

A training system for inspectors is under development. At present, inspectors would have had some training (although further training is likely to be required by the new system) but there are no formal requirements concerning the education and qualification of inspectors. However, the consultants that undertake inspections are chosen on the basis of quality. The Danish Roads Authority is providing training for the eight companies that have been awarded inspection contracts, and the reliability and consistency of the inspections will be checked by one of the three Area Managers for Ireland.

8.2.4 Italy

Inspectors are required to have some formal educational qualifications as well as undergoing intensive training on site, but there are no specific requirements for certification or for attending specialized courses. The health requirements for an inspector are the same as for others who work in unfavourable conditions; that is, a health check upon recruitment, and then repeated annually, and some clinical tests as demanded by the Italian National Health Service. Specific tests are carried out regularly - for example, to check colour blindness and balance disability.

The accuracy of inspection reports is checked regularly.

8.2.5 Netherlands

The qualification system for inspectors is not based on the issue of formal approvals or certificates. Instead, inspectors have to show that their work has been completed according to the rules laid down by the Road Authorities: the accuracy of inspection reports is checked, on a regular basis, by the head of the subdivision (of which there are six in the Netherlands) for inspection and maintenance. This thorough system of supervision and checking eliminates the need for any formal requirements for inspectors.

8.2.6 Norway

The system for qualifying inspectors for routine work is based on requirements for regular training, a basic knowledge of bridges and other engineering structures, and the application of an inspection manual. However, a formal qualification in bridge engineering is required for those undertaking either Major or Special Inspections. The system does not require a check of the physical or medical condition of an inspector.

8.2.7 Poland

Those undertaking detailed and/or Special Inspections must have:

- a degree in civil engineering, with some specialization in bridge engineering
- 10 years experience in bridge engineering
- attended a training course on bridge inspection practices
- knowledge of the design and construction of bridges
- the ability to identify structural damage and assess its impact on the condition of the structure
- the ability to assess the safe load-carrying capacity of a structure
- the ability to decide on the actions required to maintain a structure in a safe condition
- a good health record - no evidence of acrophobia for example.

The General Directorate of Public Roads sets standards for inspection and reporting requirements - and these are used as guidelines by the other road administrations in Poland.

8.2.8 Slovenia

At present, inspectors are not required to have any training or experience of structural pathology, nor is there a system for issuing certificates of competence. However, when tendering for inspection works, bidders must name the inspectors and provide details of their qualifications, experience, and references for projects completed in the previous three years.

8.2.9 Spain

For undertaking a Principal Inspection, an inspector is required to have a degree in civil engineering (from a 3-year University course). In addition, they are obliged to attend a training course where the following are covered:

- types of bridge, and the definition of structural elements
- usual types of damage found on bridges - grouped by elements and by materials
- evaluation of damage.

During this course, on-site inspections are undertaken by instructors (by way of example) and practical exercises in bridge inspection are completed by the candidates.

8.2.10 Sweden

In Sweden, regular inspections are carried out by the maintenance contractor. Personnel undertaking Superficial Inspections must have a good knowledge of appropriate methods of measurement and be familiar with the structural design and mode of behaviour of the bridge. Those undertaking a General or Major Inspection must have:

- some engineering competence
- attended a training course on inspection - run by the Swedish National Road Administration (SNRA)
- an understanding of the degradation processes that affect bridges, and of the durability of such structures
- the knowledge and experience required for predicting the propagation of damage
- the knowledge and experience required for identifying appropriate technical and economical solutions to remedy defects and damage
- knowledge of the SNRA regulations.

Those undertaking underwater inspections must also have the appropriate diving certificate.

Those inspecting mechanical and electrical equipment for movable bridges must also have:

- proven professional competence - in accordance with the national ‘Electrical Installations Ordinance’
- the knowledge required to perform trial runs on machinery and electrical equipment
- knowledge and experience of the operation of hydraulic equipment
- knowledge of the relevant Swedish regulations covering the design and maintenance of electrical installations.

The requirements for undertaking a Special Inspection are the same as listed above for a Major Inspection, but specialised knowledge might also be required on instrumentation techniques using, for example, ultrasonic, radiography, and thermographic devices.

8.2.11 United Kingdom

At present inspections are undertaken by graduate engineers and/or technicians, and, in general, inspectors are trained on the job. Although there is no formal training or certification scheme for inspectors, plans are in place to introduce such a scheme. In the 1990s, before undertaking Special Inspections of post-tensioned bridges, inspectors were required to attend a one-day training seminar at TRL.

Principal and Special Inspections would usually be supervised by a Chartered Engineer. The interpretation of an inspection report would also be undertaken by a Chartered Engineer.

8.2.12 United States

The collapse of the Silver Bridge over the Ohio River in 1967, initiated in the following year the National Bridge Inspection Program which requires the periodic inspection of highway bridges. This, in turn, led to the implementation of Standards for Bridge Inspections which specify inspection criteria - such as the procedures to be followed, the frequency of inspection, and staff requirements. There is a requirement to produce an annual report on each bridge. The Federal Highway Administration (FHWA) is responsible for the standards covering inspection, including reporting requirements.

The leader of a bridge inspection team must have a certificate issued through the National Certification in Engineering Technologies program. Furthermore, a professional engineer must head up the unit responsible for the inventory and inspection of bridges: this engineer must also have completed a recent, comprehensive training course.

8.3 THE TRAINING OF INSPECTORS

As shown in previous chapters, the principal requirements for undertaking an inspection and deriving a condition rating for a bridge are much the same in many European States. This is not surprising given that there is a common aim to maintain the bridge stock in a safe, serviceable condition at somewhere near minimum cost. However, there are clear differences in the requirements for inspectors regarding their formal education, training and experience, but it is difficult to rank the various approaches in terms of their cost-effectiveness.

As BMS are imported from one State to another, for example from Denmark to Ireland, and new technology and software become evermore widely available there may be an increasing commonality in such systems, and so the basis of future training schemes for inspectors raises political and commercial issues. To encourage co-operation and increase efficiency, it would seem inescapable that a strategy for training inspectors should be based on a consensus view across Europe. However, any training system must take account of ‘local’ needs - because, for example, the number of steel bridges varies widely from State to State.

There is no over-riding reason why elements of training schemes used outside Europe could not be imported and/or adopted to suit: for example, a means of assessing the reliability of visual inspections, which is a crucial part of any assessment, is used in the United States.

For efficiency and effectiveness, an inspector must have up-to-date knowledge of material science, structural behaviour, and construction practices and techniques. Thus training/education courses should cover:

- the use of new materials for construction and repair works
- the use of new structural forms - in particular their vulnerabilities
- the use of more effective and reliable investigative techniques

- the change in traffic loading with time
- changes in the environment - particularly those that may affect safety and durability
- the identification of new defects and/or a sudden increase in the incidence of particular defects.

With regard to the last in the list, in some States a substantial number of structures were built at more or less the same time (for example, to cover losses sustained during war or through a rapid expansion of the national highway network) and therefore serious but relatively unfamiliar defects may arise almost simultaneously on a number of structures.

Thus the basis of any qualification or approval system for inspectors should be continual training and education.

The physical condition of inspectors should not be overlooked. Ideally, an inspector would be physically fit, experienced in the use of ropes and have diving skills, but this combination is rarely found in practice - not least because professional experience comes with age. An inspector may be able to view the image produced by a camera operated by a climber or diver, and in this way an inspector may be able to direct operations from a distance. However, in many cases it is necessary for an inspector to access rather remote locations on a structure, and it is often necessary to provide secure scaffolding or a mobile crane to allow an inspection to be carried out properly and safely.

8.4 INTERPRETATION AND ANALYSIS

As discussed in earlier chapters, testing and monitoring works have important roles in a BMS, and the data from such investigations are essential input to the assessment of the stability, serviceability and durability of a structure. There is no need to reiterate the earlier text on instrumentation techniques, for example, but it is necessary here to consider the evaluation of data.

The methods and procedures used to evaluate and analyse the results of tests, and also report the findings of inspections and assessments should be formalised or standardised (as best this can be done and without unduly restricting the inspection and assessment processes). Standardisation is required to promote consistency in reporting and assessment so that comparisons of condition, for example, can be made with some confidence - as required to establish a reliable priority ranking for remedial works. Standardisation should cover, amongst other things, terminology, computer packages, investigative and analytical techniques, and qualitative and quantitative measures of condition - including the units used to report deflection and deformation. The aim should be to provide a clear, concise and reliable description of the condition of the structure, and of any further work that is required.

It would seem necessary, therefore, to set up training/education courses for assessors, and perhaps even to make attendance at such courses mandatory. It may also be worthwhile establishing a certification scheme for assessors of Special, Major and Principal Inspections.

8.5 RECOMMENDATIONS

There is little doubt that there is scope for improving the standard of inspections and the reliability of structural assessments. Improvements may be achieved through:

- an increase in the use of remote-controlled inspection and data collection devices
- an increase in the use of continuous monitoring exercises

- standardisation of, for example, terminology, units of measurement, software, and investigative and analytical techniques
- the use of better methods of interpreting data
- the use of more consistent, reliable methods of quantifying structural condition.

Recommendation 26 Work should be directed at improving the methods used to inspect and monitor the condition of in-service structures, the methods used to analyse the data from such exercises, and the quality of inspection reports.

However, in most cases the reliability of an inspection is dominated by the skill and experience of the inspector: and, as stated in 1.3.2, the quality of an inspection is crucial to an asset management system. Thus, although the above factors should not be ignored, the main research effort should be concentrated on the training/education and qualification of inspectors. It would seem essential to introduce a scheme for checking the competence of inspectors. This should test physical attributes (such as vision and balance), psychological attributes (such as decision-making and initiative), and professional knowledge: for specialised work it may also cover fitness, the use of ropes for access, and diving skills. The scheme should require the tests to be repeated at regular intervals. There is also a need, although it is less pressing, to introduce a similar scheme for assessors.

Recommendation 27 As a matter or priority, work should be undertaken to develop and implement a certification scheme for inspectors. This should include attendance at training/educational courses, and checks on the competence of prospective candidates and inspectors. This work should be undertaken on a pan-European basis.

Recommendation 28 Work should be undertaken to check the consistency and reliability of structural assessments. It would also seem necessary to introduce a certification scheme for assessors: again, there is merit in a pan-European approach.

Chapter 9 Concluding remarks

The importance of the highway network within the EU can hardly be overstated. Bridges, buried structures, earth-retaining structures and so on are vital elements of that network and so it is crucial that they are maintained in good order. There are similarities in the inspection and assessment procedures adopted for highway structures in various European States. This is not surprising given that there is a common aim to maintain the structures in a satisfactory condition at the lowest possible cost. However, there are differences in the details of the procedures and some of these, such as the use of loading tests, warrant a closer examination. Furthermore, although assessment codes are used in some States, in others in-service structures are assessed through design codes for new structures - and this latter approach is unsatisfactory. There is also a widespread need to expand condition assessment methods to provide an adequacy rating (for safety) or a priority ranking (for remedial works).

Given the undoubted importance of the quality of inspections and assessments, it is surprising that there is such diversity in the requirements for the education and training of the personnel undertaking such work. And in many States there is no standard way of checking the reliability of inspections and assessments. It would seem necessary to introduce a certification scheme for inspectors and/or assessors at a national level, but there is merit in adopting a pan-European approach.

It would seem necessary to adopt a philosophy of continual improvement through periodic reviews and updating of inspection and assessment procedures - these include the utility of standard inspection report forms, and the content of catalogues, advice notes and training courses.

The current inspection and assessment procedures have been developed, almost exclusively, for highway bridges. It seems necessary to devise procedures for all major highway structures: although such procedures can be based on those developed for bridges they must take account of differences in the nature and type of defects and loading regimes. Furthermore, current procedures have been devised for structures on the primary road network but because of differences in, for example, performance requirements, consequences of failure and maintenance budgets it is inappropriate to apply the same procedures to structures on all other categories of road. Thus, as a matter of priority, it would seem necessary to devise an asset management system for structures on the secondary and tertiary road networks.

Of the 28 recommendations of this report, about ⅓ concern data management and more than ⅓ concern some aspect of testing within an asset management system. A common theme of some of the recommendations is the paucity of published data on the monitoring of in-service structures. Such data are essential for establishing reference databases, used to validate whole life cost models for example, and so monitoring works should be undertaken as a matter of routine.

One of the driving forces behind the COST 345 Action was to identify where improvements could be made in the efficiency and economy of maintaining the stock of highway structures in Europe. It is now necessary to follow-up the recommendations given in the report for improving current practice. It is clear that there is excellent potential for sharing and transferring experience within Europe on the management of highway structures, and for collaborative research on the subject.

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APPENDIX: FURTHER DETAILS OF THE COST 345 ACTION

The present position

Bridges, earth retaining walls, tunnels, culverts and the like make up a substantial proportion of the fixed assets of the land based transportation infrastructure. The stock of such structures has been accumulating in developed countries over the years; some structures predate the 20th century and a number of masonry arch bridges on the European highway system date back to Roman times. Some of these old structures are of historic importance and have architectural merit.

Considerable effort has been put into the development of new standards and codes, such as CEN Eurocodes, covering the design of new structures and earthworks but few of the structures on the existing road system will have been designed to the requirements of such documents. It may be difficult to identify which version, if any, of the standard or code was used to design a particular highway structure, and in many cases the design process would have invoked a quite different approach to that promulgated in current design documents. Furthermore, for some structures, there may not be accurate as-built records. Problems of documentation could be expected to increase with the age of a structure.

What is important is that, despite many years of maintenance-free operation, the inherent level of safety of many in-service structures can be shown to be inadequate relative to current design documents. Owners and maintenance authorities are therefore in a difficult position in a world where public safety is paramount and the financial and other consequences of failure are great. The inherent uncertainty in methods of analysis has led, fairly recently, to the use of load tests for bridges, but advice on the operation and interpretation of such tests is lacking. Tests undertaken on redundant masonry arch bridges have shown that, in general, the ultimate carrying capacity of such bridges was well in excess of that estimated by numerical analysis. It is likely therefore that weight restrictions imposed on some bridges as a result of numerical analysis are unnecessary, and that the associated traffic diversions and delays in these areas could be avoided. Furthermore, little progress has been made on the structural assessment of earth retaining walls and buried structures such as tunnels, culverts and pipes.

It is not feasible to close or demolish structures that do not comply with current design criteria and standards, even if the financial resources required for their replacement were available. (As shown in the following section, the costs of replacement would be astronomic.) However, in the absence of adequate documentation covering the inspection and assessment of highway structures, there will be a tendency to assess stability using current design documents, and such assessments are likely to underestimate the inherent stability of a wide range of structures. In some cases, this will lead to the unnecessary replacement or strengthening of existing structures with all the attendant costs, particularly those associated with traffic delays. On the other hand, a reliable system of inspection, assessment and maintenance is required to ensure the safety of the public at large.

The processes involved in the design of a new structure and the assessment of an existing structure can be quite different, but little work has been undertaken on the development of codes or standards, which would, for example, compliment the structural Eurocodes for assessing the condition of in-service structures. The age (longevity), condition and the likelihood of failure of a structure are intuitively related and what is needed, therefore, is a system of assessment within which longevity and condition are qualitatively or quantitatively balanced against the factors of safety specified in current design standards. Information will often be limited, and at times even lacking, but the inspection regime and assessment process must provide a sensible procedure which enables the existing structures which have performed adequately over the years to continue to do so in the future.

Assessments are most needed at times of change to determine whether the stock of structures is adequate for the new situation. The introduction of 40 tonne lorries throughout the European Union is a good example of this. Structures which have sustained the current traffic loads since the previous increase in 1983 must be re-evaluated, and either passed as fit to carry the higher loads, or be strengthened appropriately. This can be a particularly difficult process with certain types of structure, such as drystone retaining walls, where current theory suggests that the majority of these structures are unstable but experience has shown that they are perfectly adequate.

Assessments are also needed on a more routine basis as part of a sensible maintenance programme. Importantly, such a programme should ensure that a satisfactory level of maintenance applies to the whole infrastructure.

Use of the COST framework

COST was seen as the most appropriate mechanism for dealing with this subject because it is essential to have agreement between the technical representatives of national governments. It is also highly desirable that there is input from, and to, those COST States which are not yet a part of the European Union.

Primary Objectives

The main objective of this Action is to specify the procedures and documentation required to inspect and assess the condition of in-service highway structures (e.g. bridges, earth retaining walls, tunnels and culverts). The project will also define the requirements for future research work into the inspection and assessment of highway structures.

Secondary Objectives

This project will also provide information on the age and condition of the stock of the more common types of highway structure in Europe. An inventory of highway structures and information on current maintenance expenditure are necessary input to the development of budgetary plans for maintenance works and for operating cost models for highways. Such information can be used to establish or refine whole life cost models for these types of structure, and could lead to recommendations regarding the building of particular types of structure.

The project will also identify those types of structure, such as masonry arch bridges, that are not amenable to analysis by simple numerical methods.

Benefits

The potential economic benefits of the project are substantial. For example, preliminary studies of the stock of masonry faced earth retaining walls along the highway network in the UK have shown that an annual expenditure of less than 1 per cent of their replacement cost is needed to keep the stock of such walls in satisfactory condition. The economic benefits for such a small sum are considerable; not only are the structures preserved in good condition but the costs of replacement works and the very much greater traffic delay costs associated with such works are avoided. The majority of these walls were constructed in the 19th and early part of the 20th centuries predominantly in drystone walling. However, despite the fact that the majority of such walls are still true to line and level, often a hundred years or more after their construction, numerical assessments of their stability undertaken to the strictures of current design documents generally lead to the erroneous conclusion that they are unsafe and, by implication, need to be replaced. The replacement costs of drystone walls, and their derivatives, along the highway network in the UK, for example, would be at least 10 billion Euros and could possibly be much higher.

In European terms, the development and application of successful inspection, assessment and maintenance procedures to a highway network would ensure the continued high performance of the network and save billions of Euros in construction, maintenance and traffic delay costs. The development and acceptance, throughout Europe, of such procedures and standards would also give rise to tangible and intangible benefits to highway users, maintaining authorities and owners.

A European-wide project would allow an exchange of information and, in particular, it would advertise the experience and expertise of those States which have a developed, mature highway network and, in that way, promote sound engineering practices. It would provide continuity and allow regional variations such as climate and environment to be considered and, by drawing from the expertise of the various States, maximise the value of the project to Europe as a whole.

In order to maximise the benefits from the work carried out in the Action, national delegates would be asked to supply lists of the most appropriate recipients of the results at national level and subsequently discuss implementation with them. The majority of recipients will be at national and regional levels, but there will also be significant users outside these two categories.

Depending on the country, responsibilities for highway structure inventories, inspection, assessment, maintenance and budgetary planning at national, regional and local levels will vary between public and private sector organisations. These variations are to be taken into account when producing the deliverables and final report, and when targeting the most appropriate recipients of the results of the Action. The needs of those responsible for whole life costing of infrastructure and highway operating cost models will also be addressed.

At European level, the work of the CEN Committee dealing with Eurocode 1 (Basis of Design and Actions on Structures) will be taken into account in the work and input will be given to future standardisation work in this area. Consideration will also be given to interaction with initiatives at global level such as those of the Permanent International Association of Road Congresses (PIARC).

In addition to the requirements of users in the field of highway maintenance, those of researchers will also be considered, and the specification of future research to be undertaken, mainly at national and European level, will be an important outcome of the Action. Again, the identification of those academic, public and private sector organisations which are in a position to maximise the benefits arising from the results of the work will form a critical part of the dissemination process.

For all the dissemination and implementation initiatives, the involvement of the embryonic Forum of European National Highway Research Laboratories (FEHRL) network will provide significant impetus in ensuring maximisation of the benefits in terms of cost, safety and environmental considerations.

Scientific Programme

Specification of Requirements

The owners of highway structures, whether at local, national or international level, and those charged with maintenance, are legally responsible for their safety and owe a duty of care to the public. By following a formalised and documented procedure of inspection, assessment and maintenance, maintaining authorities will be able to show that they have taken due care and owners will be assured that their fixed assets, i.e. the highway infrastructure, are being protected. This project is the necessary precursor to the development of procedures and documents covering inspection regimes and methods of assessment.

In the initial phase, the following information will be sought for representative lengths of the public highway network in various COST States:

- The number, type, age and condition of structures and, where possible, estimates of the cost of replacement. This will provide an estimate of the value of the existing highway infrastructure. Different classes of route, for example principal, primary and secondary, will be considered separately.

- The current expenditure on new highway works and on the maintenance of existing structures. The ratio of these expenditures gives an indication of the maturity of the highway infrastructure, and also provides an estimate of the in-service life currently required of highway structures. Where necessary, the ratio can be projected by taking into account the likely expenditure on construction and maintenance in future years.

- Current statutory requirements for the inspection, assessment and maintenance of in-service highway structures. This will identify procedures that have proven to be effective and also, by omission, define those types of structure for which no suitable procedures have so far been devised or documented.

- A review of the methods used to determine the stability of structures, this will include both proof testing and numerical analysis.

The above information will help to define those types of structure which are difficult to inspect and assess, and those that consume the highest expenditure on maintenance. In doing so, key areas for further research work will be identified.

The project will incorporate any relevant information obtained from the current Framework IV Transport RTD project BRIME, which is concerned with the evaluation of bridge management procedures. Also, it should be noted that the results will be made available for rail research purposes.

Work Programme

Implementation of the work, in order to meet the primary and secondary objectives, will require the completion of the following tasks and the generation of the associated deliverables.

a) Generation of a European highway structures database incorporating:

- the number, age and condition of various types of structure on representative lengths of the highway system in Europe
- information on the current replacement costs and maintenance expenditure on various types of highway structure
- the procedures used to inspect and assess the condition and performance of various types of highway structure including a comparison of the statutory requirements for different types of structure
- information on the methods used to define the serviceability and stability of a structure both at design and in-service stages.

The database generation phase will be implemented by undertaking reviews of literature, procedures and documentation and terminology, together with a comprehensive questionnaire exercise.

b) Assessment of the information contained in the European highways structures database.

c) Determination of the requirements (in terms of cost and safety) for procedures and documentation for the inspection and assessment of structures, taking into account environmental considerations and objectives.

d) Specification of the procedures and documentation for the inspection and assessment of structures.

e) Specifications of future research work necessary to improve methods for inspection and assessment of highway structures.

f) Guidelines to the development of budgetary plans for maintenance works and for operating cost models for highways.

g) Guidelines for input to the building of specific types of structure.

h) Generation of the Final Report.

Organisation

The Management Committee of the COST 345 Action is responsible to the COST Technical Committee on Transport and their programme of work is being co-ordinated by the Chairman Dr K C Brady, United Kingdom and Vice-Chairman Dr A Znidaric, Slovenia.

Six Working Groups have been set up to deal with the Action, their members providing the appropriate mixture of technical expertise and experience to address the tasks in hand. The six Working Groups are as follows:

WG 1 - Inventory
WG 2 - Inspection
WG 3 - Condition assessment
WG 4 - Numerical techniques
WG 5 - Safety and serviceability
WG 6 - Remedial measures

In due course a seventh Working Group will be initiated to integrate the outputs of the other Working Groups and prepare the final report.

Participation

As well as the European Commission, sixteen countries – Austria, Belgium, Czech Republic, Denmark, France, Germany, Ireland, Italy, Netherlands, Poland, Romania, Slovenia, Spain, Sweden, Switzerland and the United Kingdom – are participating in the deliberations of the Management Committee of the COST 345 Action.

This provides a strong basis of technical expertise and geographical spread which should ensure very high quality results. A number of other countries have expressed interest in joining this project. Each of the Working Groups will produce at least one technical report and these will form a major part of the final report of the Action.

Conclusion

It is of note that little, if any, research has been carried out at European level on the assessment of highway structures and the successful completion of this project should remedy this situation and lead the way in developing future thinking in this area.

Sustainability becomes an ever more pressing consideration with the realisation that our material and financial resources are finite and limited. Although some further development of the highway system is undoubtedly required the more pressing consideration in many countries is fast becoming the conservation of the existing highway infrastructure in good condition. This unfortunately is a mundane and routine task which may well be overlooked in the short term by authorities with apparently more important problems on their hands. However curtailment of maintenance expenditure on the highway infrastructure wastes money since it almost invariably results in some structural damage which is more expensive to rectify in the long term. The outputs from this Action will help to ensure that such oversights are less likely in the future and provide a sounder basis for highway authorities to develop a systematic long term policy for the maintenance of the existing stock of structures on the road system.

Annex II Actions covered by Structural Eurocodes

Actions that apply to highway structures are highlighted in Table AII-1. This information was taken from 'Policy Guidelines and Procedures for CEN/TC 250 Structural Eurocodes' (Annex C), which was issued on 18 September 2000.

Table AII-1 Actions covered by the Structural Eurocodes

Number	Title	Base document	Scope
EN 1990	**Basis of design for structural Eurocodes**	ENV 1991-1	The basis and general principles for the design and verification of buildings and civil engineering works including geotechnical aspects, the principles and requirements for safety and serviceability of structures, and guidelines for related aspects of structural reliability in circumstances where the structure is required to give adequate performance – including fire and seismic events.
EN 1991	**ACTIONS ON STRUCTURES**		
EN 1991-1-1	**General actions - Densities, self-weight and imposed loads**	ENV 1991-2-1	Assessment of the actions to be used in the design of buildings and civil engineering works derived from the density of construction materials and stored materials, the self-weight of construction elements and imposed loads on the floors and roofs of buildings.
EN 1991-1-2	**Actions on structures exposed to fire**	ENV 1991-2-2	Assessment of actions to be used in the design of buildings and civil engineering works required to give adequate performance to exposure to fire.
EN 1991-1-3	**General actions - Snow loads**	ENV 1991-2-3	Assessment of loads imposed by snow to be used in the design of buildings and civil engineering works on sites at altitudes below 1500 m.
EN 1991-1-4	**General actions - Wind**	ENV 1991-2-4	Assessment of wind loads to be used in the design of buildings up to 200 m high, chimneys and other cantilevered structures, road and railway bridges with a span up to 200 m and cycle/foot bridges with a span up to 30 m.
EN 1991-1-5	**General actions - Thermal actions**	ENV 1991-2-5	Assessment of thermal actions to be used in the design of buildings and civil engineering works due to their exposure to daily or seasonal climatic changes and variations due to their use.
EN 1991-1-6	**General actions - Actions during execution**	ENV 1991-2-6	Assessment of actions, combinations of actions and environmental influences applied during the execution stage, including those applied to auxiliary construction works, to be used in the design of buildings and civil engineering works.

EN 1991-1-7	**General actions - Accidental actions due to impact and explosions**	ENV 1991-2-7	Assessment of actions arising from accidental human activity including impact and collisions from wheeled vehicles, ships, derailed trains, helicopters landing on roofs, and gas explosions in buildings - the analysis and determination of design values to be used in the design of buildings and civil engineering works. Procedures for risk analysis and measures to reduce the consequences of such events.
EN 1991-2	**Traffic loads on bridges**	ENV 1991-3	Assessment of imposed loads associated with road traffic, pedestrians, and rail traffic including dynamic effects, centrifugal, braking, acceleration and accidental forces, to be used for the design of road, railway and pedestrian/cycle bridges. Guidance on the combination of such actions with non-traffic loads, other actions on road and railway bridges, and loads on parapets.
EN 1991-3	Actions induced by cranes and machinery	ENV 1991-5	Specifies actions, self-weights and imposed loads (models and representative values) associated with hoists, crabs and cranes on runway beams, static and dynamic actions induced in supporting structures by machinery and permanent, variable and accidental actions induced by transport vehicles (forklifts, wheeled, tracked and rail transportation vehicles, devices for maintenance, and helicopters).
EN 1991-4	Actions in silos and tanks	ENV 1991-4	General principles and actions for the design of tanks and silos.
EN 1997	**GEOTECHNICAL DESIGN**		
EN 1997-1	**General rules**	ENV 1997-1	General basis for geotechnical aspects of the design of buildings and civil engineering works, assessment of geotechnical data, use of ground improvement, ground reinforcement, dewatering and fill. Geotechnical design of spread foundations, piles, retaining structures, embankments and slopes. Calculation rules for actions originating from the ground; for example, soil and ground water pressures.
EN 1998	**DESIGN OF STRUCTURES FOR EARTHQUAKE RESISTANCE**		
EN 1998-1	**General rules seismic actions and rules for buildings**	ENV 1998-1-1, ENV 1998-1-2, ENV 1998-1-3	Complementary to Eurocodes 1 to 7 and 9. Additional provisions for the design of buildings and civil engineering works to be constructed in seismic regions where the risk to life and/or structural damage is/are required to be reduced. General requirements and rules for assessing seismic actions and combinations with other actions. General rules for earthquake-resistant design of buildings and specific rules for buildings and elements constructed with various materials.

EN 1998-2	**Bridges**	ENV 1998-2	Complementary to EN 1992-2, EN 1993-2 and EN 1994-2. Design rules for earthquake resistant design of steel, concrete and composite bridges.
EN 1998-3	Strengthening and repair of buildings	ENV 1998-1-4	Guidelines for the evaluation of the seismic performance of existing structures, the selection of corrective measures and the design of repair and/or strengthening measures with additional considerations for monuments and historic buildings.
EN 1998-4	Silos, tanks and pipelines	ENV 1998-4	Complementary to material-related parts of the Eurocodes dealing with silos, tanks and pipelines. Design rules for the earthquake-resistant design of groups of silos, storage tanks including single water towers and pipeline systems.
EN 1998-5	**Foundations, retaining structures and geotechnical aspects**	ENV 1998-5	Complementary to Eurocode 7. Additional rules for the design of various foundation systems, earth retaining structures and soil-structure interaction under seismic actions in conjunction with the structural design of buildings, bridges, towers, masts, chimneys, silos, tanks and pipelines.
EN 1998-6	Towers, masts and chimneys	ENV 1998-3	Complementary to material related Eurocode parts dealing with towers, masts and chimneys. Design rules for the earthquake-resistant design of tall, slender structures: towers, including bell-towers and intake towers, masts, industrial chimneys and lighthouses constructed in reinforced concrete or steel.

Annex III Examples of typical defects

Information on where to find examples of typical defects can be found on the COST 345 website at http://cost345.zag.si/defects/.

Annex IV Load testing

The policies of various European States on the use of load testing are described in Table AIV-1.

Load testing is an important part of many national bridge assessment programmes: acceptance tests are undertaken on newly completed or substantially rehabilitated bridges, and tests are used to assess the load-carrying capacity of ageing and/or deteriorated structures, and for investigating the behaviour of prototype structures. Details of the standards and codes covering loads tests are given in Table AIV-2, whilst the fields of application of load testing are described in Table AIV-3.

Static and/or dynamic loads can be applied in a test, although the former are much more common - with the load usually being applied through loaded goods vehicles. The magnitude of the load is the principal variable in a static load test: this is chosen either as a function of the characteristic design load (OC) or in terms of the anticipated effect that the applied load would have on the structure (OO). The methods used to define the static load are described in Table AIV-4.

Dynamic loads are usually applied through loaded goods vehicles traversing the bridge in which case the principal variables are the speed and weight of the vehicles, but secondary factors include the type of vehicle suspension and the evenness of the road surfacing. Other means of applying dynamic loads are also used, details of the methods used in various States are provided in Table AIV-5.

The performance of a structure will be monitored through a loading test. Details of the variables that are measured, and the instruments used to take the measurements, are provided in Table AIV-6 and Table AIV-7 respectively. Details of the methods used to analyse the test data are provided in Table AIV-8.

Finally in this Annex, details of some current research and development projects on load testing are provided in Table AIV-9.

Table AIV-1 Background to policies on loading tests

State	Are loading tests undertaken?	Reasons for adopting policy
Austria	Not usually	Engineers are not convinced of the benefits of load testing. However, destructive loading tests are sometimes performed on redundant structures for research purposes and to improve knowledge of structural and/or material performance.
Czech Republic	Yes	A loading test is carried out at the request of the client or investor. Such a request is usually made for a long-span bridge, or where an unusual form of construction has been adopted.
Denmark	Not usually	Loading tests are not undertaken because it is thought that regular inspections and refined calculation methods provide sufficient information.
Germany	Generally not	It is thought that a bridge may be damaged by measuring its load-carrying capacity. Thus, for assessment purposes, a loading test on a bridge on the federal highway network is permitted only in exceptional circumstances.
Italy	Yes	One of the main advantages of a static load test is that it is possible to determine the behaviour of the whole structure, and/or the components of one, at loads close to the design values.
Netherlands	No	A combination of inspection and the (re)analysis of load-carrying capacity is deemed sufficient for management purposes. Current codes require checks on both the Serviceability and Ultimate Limit States: it is not feasible to check the latter through a loading test.
Norway	Not usually	A loading test is only performed in exceptional cases - usually for research and development (R&D) purposes. The following structures have been tested in the past five years or so: • an aluminum bridge (verification of design, and for R&D) • redundant three-span flyover taken to collapse (for R&D) • composite bridge (to validate new measurement system, and for R&D). Loading tests are carried out so infrequently that no formal guidelines exist for them: a test would be treated as an experimental investigation.
Poland	Yes	It is accepted practice (tradition) to test a bridge before putting it into service. The results of a loading test provide engineering data on the actual behaviour of an in-service bridge under load. On occasions, a test will highlight a defect - usually excessive displacement at a support.

State	Are loading tests undertaken?	Reasons for adopting policy
Slovenia	Yes	Static and dynamic loading tests are carried out to confirm that: • the behaviour of the structure accords with design assumptions • the quality of the workmanship meets that specified • the structure is able to carry the design load • the structure meets the requirements of the construction project.
Spain	Yes	It is the norm (tradition) to test a bridge following the end of construction before it is put into service. A loading test is used as a means of checking the quality of the construction work.
Switzerland	Yes, but only in special cases	Until the 1980s, loading tests were performed on all major highway bridges. Such tests were usually undertaken in the Eastern part of Switzerland by EMPA (Swiss Federal Laboratories for Materials Testing and Research), and in the Western part by EPFL (Swiss Federal Institute of Technology at Lausanne). However, following changes in the core competences at EMPA and the retirement of Prof. Favre from EPFL, testing is now not so strongly promoted and now bridge owners only require tests to be undertaken in special circumstances.
United Kingdom	Yes	Tests are undertaken to provide information to improve the models of structural behaviour used for assessing load-carrying capacity. For bridges on the national road network the test load is limited to that carried by the bridge on a day-to-day basis. However, some authorities have allowed the full unfactored design load to be applied to structures on the secondary and tertiary road networks.

Table AIV-2 National codes and standards covering loading tests

State	Standard or code reference	Field of application
Austria	None.	
Czech Republic	CSN 73 6209: Load testing of bridges.	New structures.
Denmark	None.	
Germany	No codes, but regulations for organizations that manage the federal highway network are given in DAfStb-Richtlinie: Belastungsversuche an Betonbauwerken [Guideline for load testing engineering structures (except bridges)]. It is planned to produce a guide on the testing of bridges.	
Italy	D.M.LLPP 09/01/96 (concrete and steel structures). D.M.LLPP 04/05/90 (bridges).	
Norway	No codes: load testing is only mentioned as a possible investigative procedure.	
Poland	PN-89/S-10050 Bridges. Steel structures: requirements and testing. PN-/S-10040 Reinforced, prestressed, stayed and concrete bridges: specifications and technical testing.	
Slovenia	JUS U.M1.046 Load testing of bridges (1984).	• New, strengthened or rehabilitated structures. • Where the passage of an exceptional load would impose internal forces greater than those due to the design load. • All structures that do not meet design specifications regarding, for example, the quality of the material, dimensions, and load-bearing capacity of the foundations.
Spain	Recomendaciones para la realización de pruebas de carga de recepción en puentes de carreteran (1999).	New structures.

State	Standard or code reference	Field of application
Switzerland	The 1970 version of SIA 160 [Load assumptions, commissioning and monitoring of structures] required load testing of railway bridges having a span (L) in excess of 10 m and highway bridges where L > 20 m. Owners and authorities adopted/adapted these requirements for their own purposes. The 1989 version of SIA 160 [Actions on structures] does not cover commissioning nor, therefore, loading tests. In 1987, load testing was regulated by SIA 169 [Preservation of engineering structures]. In 1997, this guide was replaced by SIA 469 [Preservation of construction works] which, although it had a broader remit, did not cover load testing.	
United Kingdom	BD 21 (The assessment of highway bridges and structures) permits the use of supplementary load testing as an aid to assessment. BA 54 (The use of load testing for bridge assessment) provides guidelines for load testing (supplementary and proving load tests) and defines the limitations of its use: for example, proof load testing for assessment is not permitted. Additional information is provided in ‘Guidelines for the supplementary load testing of bridges’ issued by the ICE in 1998.	Loading tests are only permitted to check structural behaviour, or to verify the method of analysis. Load testing of new bridges is rarely undertaken.

Table AIV-3 Application of loading tests

State	Type of loading applied to structure	Application
Czech Republic	**Static loading** Bridge works (in general), turntables, travelling platforms, wagon weighbridges, and other miscellaneous structures. Bridges of unusual construction such as long-span bridges, structures constructed from new materials or new technologies, reconstructed bridges, and provisional structures. **Dynamic loading** For checking reliability through measurements of dynamic behaviour of, for example, self-excited frequencies and modes of vibration attenuation.	
Germany	In general, load tests are only used for research purposes; see, for example, the report of the project EXTRA (experimental analysis of load-carrying capacity) undertaken by the universities of Bremen, Dresden, Weimar, and Leipzig.	
Italy	Load tests are undertaken before a bridge is opened to traffic, and also during service to check structural performance.	
Poland	**Static loading** Prototype structures. Typical road bridges. Strengthened bridges or where the superstructure of a bridge has been renovated. Other structures according to demand of owner or user. **Dynamic loading** According to the demands of the owner or user.	All Span >20 m All
Slovenia	**Routine load test** Static and dynamic load tests are carried out on road and railway bridges. The testing of pedestrian footbridges is carried out according to the requirements of the designer or owner. Load tests are carried out on reinforced and prestressed concrete bridges, steel bridges and composite structures. **Special load test** All structures (no limitations on span) that do not meet the design specifications regarding, for example, the quality of the construction materials, dimensions, foundation competency, and connections (steel structures). A routine load test will be repeated where the specified performance requirements have not been met and a special load test undertaken where the requirements are not met in the repeat routine test. **Exceptional load test** Static load test of a structure (no span limitation) where the passage of an exceptional load will generate higher internal forces than the design load. The results of such tests are only valid for the particular exceptional load.	All new, strengthened or rehabilitated structures. L ≥ 10 m
Spain	Static loading is used for an acceptance test on a new structure. Dynamic loading is used where a SLS governing vibration may be at-	L ≥ 10 m

State	**Type of loading applied to structure**	**Application**
	tained.	
Switzerland	Important, complex or exceptional structures; particularly highway bridges with a span > 20 m. As an acceptance test, or prior to the passage of a heavy in-service load. As a part of a Principal or Special Inspection.	As recommended in SIA 169 (1987) Option in SIA 169
	Clause 9.2 of 'Project and execution of structures of the national highway network' issued by the Swiss National Road Office in 1999 states: 'The advisability of a load test is evaluated by the Canton [the state authority] from case to case. It may be performed during commissioning of new bridge or after an extensive rehabilitation. .. The advisability of a load test may be ascertained in the following cases: (a) complex structures, where modelling of the serviceability limit state is difficult (b) innovative structures; that is, following a new design concept (c) structures that are sensitive to deformations, and so where knowledge of the 'effective' stiffness is important (d) before and after strengthening a structure where the structural system is changed substantially or where the strengthening works provide much of the load bearing capacity (e) where severe difficulties were met in construction.'	
United Kingdom	**Static loading** Load testing is only permitted as an aid to assessment - see previous tables. **Dynamic loading** Not required and rarely applied except for research purposes.	The magnitude of the load is limited to that carried by the bridge on a day-to-day basis.

Table AIV-4 The magnitude of the static load used in loading tests

State	Applied static load	Remarks
Czech Republic	For highway bridges and footbridges, loads are usually applied through wheeled vehicles, but in exceptional cases tracked vehicles, dozers, water tanks and other types of kentledge may be used. The test static load is determined from: $U_N = k\ U_{Vs}$ where k efficiency U_N test load U_{Vs} characteristic vertical live short-term load	
Germany	According to the 'EXTRA' project the maximum applied load should be defined by deformation criteria - such as the strains developed in concrete and reinforcement steel, maximum crack width, and the onset of nonlinear deflection.	Conformance to deformation criteria has to be checked during a test.
Italy	The test load is usually 80% of the design load.	
Norway	Typically the load would be equal to the unfactored axle loading on the bridge (that is, excluding the UDL).	The load should be measured.
Poland	The internal force generated by the applied load (L) should be: for steel structures $0.75\ OO \le L \le 1.05\ OO$ for concrete structures $1.0\ OC \le L$ Where OO is a calculated load and OC is the characteristic load.	The load is applied until the change in deflection is ≤ 2% over a 15 minute interval.
Slovenia	For routine load tests $0.5\ OO \le L \le 1.0\ OO$ For special load tests $1.0\ OO \le L \le 1.1\ OO$ Exceptional load tests (for spans up to 100 m) $1.1\ OO \le L \le (1.3 - S/1000)\ OO$; (where S is the span in m)	
Spain	The static load is limited to 60% of the nominal load, provided that 70% of maximum allowable stress is not reached.	
Switzerland	The static load should be less than the representative traffic load as defined in SIA 169 (1987).	
United Kingdom	The applied static load must not exceed the normal day-to-day load carried by the structure.	

Table AIV-5 Methods used to apply dynamic loads

State	**Methods of applying dynamic load**	**Remarks**
Czech Republic	Suitably loaded rail or road vehicle(s). On a road bridge, the passage of a vehicle over a raised obstruction(s) fixed to the bridge deck. Miscellaneous devices and techniques; such as a vibrator with a changeable frequency, impulse rocket engine, and unloading by a sudden relaxation of an applied load. For footbridges, the passage of a pedestrian(s).	
Germany	A dynamic load would, inevitably, be applied by heavy goods vehicles running at various constant speeds across the bridge.	
Italy	Loaded goods vehicles, and/or rotating eccentric weights (vibrodine).	
Norway	Heavy truck travelling at different constant speeds across the bridge, with and without a 50mm high obstruction (neoprene plank) fixed to the deck.	
Poland	The passage of one or two trucks at various speeds (10, 30, 50km/h ..) up to maximum allowed. To induce vibration of the deck, the truck(s) have to traverse a 100mm high discontinuity fixed to the deck.	
Slovenia	A moving truck travelling at various constant speeds (10, 20, 30, 40km/h .. up to maximum allowed). In special cases, dynamic loads are induced by falling weights. Various techniques are used to dynamically excite the deck of a pedestrian bridge.	
Spain	One or two heavy trucks moving at various constant speeds (from 5 to 60km/h) across the deck.	
Switzerland	In general, the following are used for applying dynamic loads: rotating eccentric masses, hydraulic jacks, and impact loads. However, for highway bridges loads are usually applied by a heavy truck running at various constant speeds over the deck, and passing over a 45mm thick board fixed to the deck.	SIA 169 (1987). See also Cantieni, R (1983): Dynamische Belastungsversuche an Strassenbrücken in der Schweiz – 60 Jahre Erfahrung der EMPA [Dynamic load tests with highway bridges in Switzerland - 60 years of experience at EMPA]. Report Nr. 116/1, EMPA.
United Kingdom	Only used for research and development purposes. Methods have included dropping weights, rotating eccentric masses, and the excitation of footbridges by pedestrians.	

Table AIV-6 Observations and measurements made during loading tests

State	The scope of investigation and measurements	Remarks
Czech Republic	Primary measurements: • vertical displacement at the point along the span where the largest deflection is anticipated • settlement of supports and bearings. Observations also taken of: • temperature of the air and structure (continuous basis) • relative movements in accessible locations of the structure • deflection, displacements and rotations of important parts of the bridge • settlement of foundations • horizontal transverse deformation of the compression flanges of bridges having an open cross-section • initiation and growth of cracks.	
Germany	Measurements made of: • applied load • reaction load • deflections • strain/stress relations • crack width • temperature.	
Italy	In the main, accelerations and displacements.	
Norway	Because testing is undertaken for R&D purposes, the measurements vary according to the requirements of the test. However, commonly (in the following order) measurements are made of: deflection, temperature, strain, acceleration, velocity, the forces in cables, and wind speed.	
Poland	Visual examinations of the structure are undertaken before, during and following a load test. Measurements are made of the following: • deflection (requirement for a ‘basic’ test) • displacement of supports (as above) • stress (requirement of a ‘special’ test).	

State	The scope of investigation and measurements	Remarks
Slovenia	Visual examinations of the structure are undertaken before, during and following a load test. Measurements are made of the following: • vertical deflection at the centre of each span (for a 'basic' test) • horizontal and vertical displacement of the bearings (for a 'special' test) • displacement at supports (basic test) • crack width (special test) • temperature (special test) • stress level at location where maximum value is anticipated (a requirement of a basic test undertaken on prestressed, steel, and composite structures) • tilting (additional requirement).	
Spain	A visual examination is completed before undertaking a load test. Measurements of deflection are taken during a load test.	
Switzerland	Measurements of elastic deformation and residual deflection are taken before, between and following two load cycles. Measurements are also taken of secondary load effects, such as temperature and wind speed. Strains, rotations, bearing forces and other measurements. Natural frequencies, damping ratio, dynamic increment.	Mandatory Mandatory Optional For dynamic loads
United Kingdom	A visual inspection is undertaken before, during and following a load test. Measurements of the following are taken during a test: • applied load • deflection • strain.	

Table AIV-7 Methods of measurement used in loading tests

State	Range of investigation and measurements	Remarks
Czech Republic	Measurements: • applied load - using load cells • deflections - using dial gauges and inductive mechanical devices • strains - using vibrating wire gauges and electrical resistance gauges • temperature - using thermocouples. Investigations are also undertaken using geodesic methods and photogrammetry.	
Germany	Measurements: • applied load - using load cells • deflection - using dial gauges, inductive mechanical devices, inclinometers, accelerometers and laser devices • strain - using vibrating wire gauges and electrical resistance gauges • temperature - using thermocouples.	
Italy	Various types of data are collected throughout a load test either on a continuous or discontinuous basis: the former provide a time-based trace of the response of the bridge during a test.	
Norway	The type and frequency of the measurements are selected according to the objectives of the test. Nonetheless, in most cases some or all of the following would be measured: • applied load - a test vehicle must be weighed beforehand at a calibrated weigh-station • deflection - using inductive mechanical devices, dial gauges, conventional surveying equipment, and laser devices • strain - using electric resistance gauges and vibrating wire gauges • inclination and tilt - using inclinometers • crack widths - using proprietary devices • temperature • vibrations - using accelerometers.	
Poland	Measurements of displacement/deflection are made using: • dial gauges (S) and inductive mechanic devices (S & D) • geodesic methods - standard surveying techniques (S) and laser devices (S & D) • photogrammetry methods (S & D). Measurements of strain are made using electric resistance gauges (S & D).	S = static load test D = dynamic load test No details of the types of instruments required for loading tests are given in the Polish codes.

State	**Range of investigation and measurements**	**Remarks**
Slovenia	Measurements: • applied load - a test truck must be weighed beforehand at calibrated weigh station • deflection - using inductive mechanical devices, dial gauges, and surveying techniques • strain - using electric resistance gauges • tilting and inclination - using inclinometers • cracks - using proprietary crack meters • temperature • laser devices (for dynamic load tests).	
Spain	Measurements of deformation and deflections are made using gauges (various types), conventional surveying techniques, and laser-based devices.	
Switzerland	No information on instrumentation is provided in the relevant codes and guides.	
United Kingdom	Measurements include: • applied load - using weigh pads or load cells • deflection - using inductive mechanical devices, dial gauges, and surveying techniques • strain - using DEMEC gauges, vibrating wire gauges, and electric resistance gauges • temperature.	Comprehensive instrumentation is required where a supplementary loading test is used to help assess structural behaviour.

Table AIV-8 Analysis of results from loading tests and assessment criteria

<table>
<tr><th>State</th><th>Analysis of results and assessment criteria</th></tr>
<tr><td>Czech Republic</td><td>

Static loading test

Following the completion of a loading test, the permanent (S_r) and elastic (S_e) components of a particular effect (S_{tot}) - such as deflection - are determined from the measured values. That is;

$S_{tot} = S_r + S_e$

In addition, estimates of these effects are calculated (S_{cal}) from the magnitude of the applied load.

The bridge structure is deemed to be serviceable when all the following conditions are fulfilled:

a) $\beta < S_e/S_{cal} \leq \alpha$ (see Table 1)
b) $S_r/S_{tot} \leq \alpha_1$ (see Table 1)
c) at the maximum applied load, the width of the cracks do not exceed the limiting values given in Table 2.

<table>
<tr><th>Type of construction</th><th>Elements composed of prestressed concrete (wholly or in part), or composite steel-concrete.</th><th>Units composed of reinforced concrete (wholly or in part).</th></tr>
<tr><td>α</td><td>1.05</td><td>1.1</td></tr>
<tr><td>α_1</td><td>0.2</td><td>0.25</td></tr>
<tr><td>B</td><td>0.7</td><td>0.6</td></tr>
</table>

Table 1: Values of coefficients α, α_1, β

<table>
<tr><th>Type of superstructure</th><th>Environmental class (determined in accordance with CSN 73 6206)</th><th>Limiting crack width (millimetres)</th></tr>
<tr><td>Reinforced concrete</td><td>1 (dry)
2,3 (moist)</td><td>According to the actual level of aggressivity, but with a maximum of 0.1</td></tr>
<tr><td>Partially prestressed</td><td>1
2,3
4,5</td><td>Additional prestress 0.1
Prestressed in advance 0.0</td></tr>
<tr><td>Restrictedly and fully prestressed</td><td>All</td><td>0.0</td></tr>
</table>

Table 2: Limiting crack widths

</td></tr>
</table>

State	Analysis of results and assessment criteria
Czech Republic (cont.)	**Dynamic loading test** The following requirements are specified: • natural modes of vibration, and associated frequencies, for the unloaded bridge • time-response and modes of vibration for the constrained structure • logarithmic damping decrement (Θ) of the unloaded bridge • under the applied loading, various dynamic factors such as dynamic rates, resonance curves, amplitudes, velocity and acceleration of oscillation • measured dynamic coefficient δ_{obs} derived from: $\delta_{obs} = S_{max}/S_m$ where: S_{max} = the largest value (effect) generated by the dynamic load S_m = the largest value (effect) that would be produced by the same static load.
Germany	The results of a loading test are used to improve the accuracy of the structural model of behaviour as used for assessment purposes.
Italy	The results of a load test are used to check the structural response of the bridge.
Norway	A comparison is made between the expected and measured responses, and the latter is also compared to accepted performance criteria.
Poland	**Static loading test** The measured elastic deflection ≤ the calculated value The measured permanent deflection, as a proportion of the total deflection: ≤ 20% for reinforced concrete structures ≤ 10% for prestressed concrete structures. **Dynamic loading test** The deflection under the dynamic load should be less than that due to static or quasi-static load (that is, v = 0 or 10 km/h respectively) multiplied by a dynamic factor. The frequency of free vibrations and the damping properties of the structure are also calculated.
Slovenia	**Static loading test** • the measured elastic deflection ≤ the calculated value • the measured permanent deflection, as a proportion of the total deflection, should be: ≤ 25% for reinforced concrete structures ≤ 20% for prestressed concrete structures ≤ 15% for steel and composite structures. • the measured maximum crack width ≤ the design value • the maximum measured deflection should not affect the functionality or aesthetics of the bridge. **Dynamic loading test** • the measured dynamic coefficient should be less than or equal to the design value • the measured periods of free vibration should be about the same as the theoretical values the enforced vibrations should not be uncomfortable to users of the bridge.
Slovenia	Where the requirements for static loading are not met and the permanent deflection is 25% or more above the allowable values, the load test should be repeated. For the repeat

State	Analysis of results and assessment criteria
(cont.)	loading test, the permanent deflections must not be greater than: • 12.5% for reinforced concrete structures • 10% for prestressed concrete structures • 7.5% for steel and composite structures. If these requirements are not met, the structure should be re-analyzed and appropriate measures undertaken - amongst other issues to ensure the safety of users.
Spain	**Static loading test**: • measured elastic deflection ≤ 110% of the calculated deflection (prestressed concrete structures) • measured elastic deflection ≤ 110% of the calculated deflection (steel structures) • measured elastic deflection ≤ 115% of the calculated deflection (reinforced concrete structures) • permanent deflection ≤ 15% of the calculated deflection (prestressed concrete structures) • permanent deflection ≤ 10% of the calculated deflection (steel structures) • permanent deflection ≤ 20% of the calculated deflection (reinforced concrete structures)
Switzerland	A report is produced for each load test: this should compare the measured and calculated deflections (explaining any differences), evaluate the dynamic behaviour and provide conclusions on the response of the bridge.
United Kingdom	There are no set performance criteria. An analysis must be carried out as part of the load test and the applied load limited to ensure that no permanent deformation or damage occurs. The results of a load test are used to re-assess the performance of the structure using a more accurate model of structural behaviour.

Table AIV-9 Details of current research and development projects on loading tests

State	**Current research and development projects**
Czech Republic	Research underway to: • improve methods of measuring the response of a structure • better define the test load in terms of the design loads.
Germany	Load test procedures are the subject of research at various universities.
Poland	Investigations are underway to improve the methods of measuring the response of a bridge during a loading test, particularly at points on a bridge that have restricted and/or difficult access. Work is also underway to improve methods for analyzing and comparing the actual and predicted behaviour of a bridge to an applied load. Further work is required to determine the applied test load in terms of the design load and in-service live loads. Of current interest is a means of assessing the rate of loss of prestress in prestressed concrete structures.
Switzerland	The priority for load testing has declined for a number of reasons, such as: • a test does not provide information about the ULS • there are few practical options available when a structure does not fulfil its stated performance requirements. This decline may be reversed when the presence of defects/damage on a bridge can be identified through the measured ‘elastic’ behaviour of the bridge under a test load.
United Kingdom	The use of load testing for assessment is still being investigated: the role of proof load tests are of particular interest.

Annex V Evaluation of condition rating

AV.1 AUSTRIA

The general form of the function used to derive a condition rating (S) for a bridge is:

$$S = \sum_{1}^{32} G_i \times k_{1i} \times k_{2i} \times k_{3i} \times k_{4i}$$

where:

G_i - Type of damage. In all, 32 types of damage are defined. For each type, a description is given of its extent, intensity and the urgency of intervention work on a particular structural member. The value of G_i varies according to the severity of the damage: the values range from 1 to 5.

k_{1i} - Extent of damage. This characteristic is not quantified by measurements of length or area for example; rather it is expressed in simple broad terms - such as, sporadic, common, and widespread or extensive. The description usually refers to one or more bridge components, or to the entire structure. The value of this factor ranges between 0 and 1.

k_{2i} - Intensity of damage. As above, this characteristic is expressed in simple terms - for example, superficial, minor, significant and substantial. The term is usually associated with a particular type of damage, such as crack widths. The value of this factor ranges between 0 and 1.

k_{3i} - Importance of the structural component or member. Structural components/members are classified into primary, secondary, and others: their importance is defined, using this factor, over the range 0 to 1.

k_{4i} - Urgency of intervention. The value of this factor varies according to type, seriousness and risk of collapse of the structure or part of one: values range between 0 and 10.

As shown in Table AV-1, the condition rating classifies the level of damage on a bridge.

Table AV-1 Condition rating and damage classification system used in Austria

Damage class	Level of deterioration	Condition rating (S)
1	None or very little	0-3
2	Little	2-8
3	Medium to severe	6-13
4	Severe	10-25
5	Very severe	20-70 (with k_{4i} = 10)
6	Very severe or total	> 50 (with k_{4i} = 10)

AV.2 DENMARK

It is assumed that inspectors are able to identify those parts of a bridge that require close examination, and are also capable of assessing the level of deterioration.

For each structural component, an inspector is provided with:

- information on the typical types of damage that can occur
- a description of each type of damage - corresponding to a condition rating of 3 (see below)
- a description of minor maintenance and standard repair works for some types of damage.

The type of damage is assessed for each structural component. The extent of damage is estimated on site but, where possible, the geometric data stored in the inventory for the bridge are used to help derive the estimate. A rating is assigned to each component using the classification system defined in Table AV-2.

Table AV-2 Condition rating system used in Denmark

Category/rating	Description of condition and actions required
0	No significant damage
1	Little damage: remedial works not required other than routine maintenance
2	Little damage: component functioning as originally designed and repair to be undertaken when convenient
3	Significant damage: repair required as a matter of priority
4	Serious damage: repair required urgently
5	Complete degradation: failure or a high risk of failure of the component

Usually some form of remedial works would be required where the condition rating is 3 or higher. Information is available on standard methods of repair for typical types of damage.

The condition rating for a bridge is assessed according to the ratings given to its structural components, but it is not merely taken as the highest (that is, the most unfavourable) rating assigned to its components. Rather, the rating for a bridge takes account of:

- the position and structural importance of the damaged components
- the type and extent of damage(s)
- the likely change in the extent and intensity of damage with time
- the effect of damage on traffic flow and user safety.

In general, the condition rating for a bridge should not be higher than the rating assigned to the most deteriorated component, nor should it be lower than the rating assigned to any of its main components - such as abutments, piers, bearings, slabs and girders.

AV.3 FRANCE

Details of the condition rating system used in France are provided in Table AV-3.

Table AV-3 Condition rating system used in France

Condition Class	Description of condition and actions required
1	Bridge is in a good condition, and only requires routine maintenance as defined in 'Instruction techniques pour la surveillance et l'entretien des ouvrages d'art' [Instructions for bridge survey and maintenance].
	Bridge is in a good structural condition but has minor defects that require specialised maintenance works.
2	No urgent action required.
2E	Work required as a matter of urgency to prevent rapid growth/development of a structural deficiency. This condition class should be selected where existing defects could develop, within a relatively short period of time, into major ones such that the structure would then be assessed as Class 3.
	A structurally impaired bridge that requires repair works.
3	No urgent action required.
3U	Urgent action required: either the load-carrying capacity of the bridge is inadequate or will become so in the near future through the rapid growth/development of structural deficiencies.
NE	Not assessed.

The highest (most unfavourable) rating given for the range of defects found on a particular item (such as a structural component, protection barrier, or mechanical device) determines the condition class assigned to that item. Likewise, the worst condition class assigned to one of the constituent parts of a bridge governs the condition class of that bridge.

AV.4 GERMANY

To improve consistency in assessing the condition of highway structures, a new technique for evaluating condition was introduced in the 1998 version of R1-EBW-PRÜF whereby a qualified assessment is made of each defect or incidence of damage. Each occurrence must be evaluated according to its consequences for traffic safety, stability and durability, and also qualified using terms such as small, medium and large. From the matrices, as shown in Figure AV-1, the condition rating is evaluated for each classified damage with the respect to stability (**S**), traffic safety (**V**) and durability (**D**).

The condition rating of a structure (Z_{ges}) is determined via a 3-stage damage evaluation set: this uses the parameters S^V (for traffic safety), S^S (stability) and S^D (durability), takes account of a defined evaluation key as well as the total extent of damage (U) and the number of occurrences of damage (n). Thus:

$$Z_{ges} = f\,(S^V, S^S, S^D, U, n)$$

In evaluating the condition rating for component groups (Z_{BG}), a condition number Z_1 is ascertained for each incidence of damage. The value of Z_1 is adjusted by the factor ΔZ_1 which takes account of the total extent of the damage (U) as follows:

U = 'small' → $\Delta Z_1 = -\ 0.1$

U = 'medium' → $\Delta Z_1 = 0$

U = 'large' → $\Delta Z_1 = +\ 0.1$.

The condition rating of the component group Z_{BG} is based on the maximum value of Z_1 adjusted by the factor ΔZ_2 which takes account of the frequency of occurrence of damage (n) within the component group. The values of ΔZ_2 for the substructure component group are:

$n < 5$ → $\Delta Z_2 = -\ 0.1$

$5 \leq n \leq 15$ → $\Delta Z_2 = 0$

$n > 15$ → $\Delta Z_2 = +\ 0.1$.

And for all other component groups:

$n < 3$ → $\Delta Z_2 = -\ 0.1$

$3 \leq n \leq 5$ → $\Delta Z_2 = 0$

$n > 5$ → $\Delta Z_2 = +\ 0.1$.

The condition rating of the structure (Z_{ges}) is based on the highest condition rating of the various component groups ($_{max}Z_{BG}$) adjusted by ΔZ_3 which takes account of the extent of the damage to the various component groups:

for 1 to 3 damaged component groups → $\Delta Z_3 = -\ 0.1$

for 3 to 7 damaged component groups → $\Delta Z_3 = 0$

for more than 7 damaged component groups → $\Delta Z_3 = +\ 0.1$.

(Intermediate values of ΔZ_3 are linearly interpolated from the above.)

A description of the condition classes is given in Table AV-4.

D=0

S \ V	0	1	2	3	4
4	4,0	4,0	4,0	4,0	4,0
3	3,0	3,2	3,4	3,6	4,0
2	2,1	2,2	2,3	2,7	4,0
1	1,2	1,3	2,1	2,6	4,0
0	1,0	1,1	2,0	2,5	4,0

D=1

S \ V	0	1	2	3	4
4	4,0	4,0	4,0	4,0	4,0
3	3,1	3,3	3,5	3,6	4,0
2	2,2	2,3	2,4	2,8	4,0
1	1,5	1,7	2,2	2,7	4,0
0	1,1	1,3	2,1	2,6	4,0

D=2

S \ V	0	1	2	3	4
4	4,0	4,0	4,0	4,0	4,0
3	3,2	3,4	3,6	3,8	4,0
2	2,3	2,5	2,6	2,9	4,0
1	2,2	2,3	2,4	2,8	4,0
0	2,0	2,1	2,2	2,7	4,0

D=3

S \ V	0	1	2	3	4
4	4,0	4,0	4,0	4,0	4,0
3	3,3	3,5	3,7	3,9	4,0
2	2,8	3,0	3,1	3,2	4,0
1	2,7	2,8	2,9	3,0	4,0
0	2,5	2,6	2,7	2,8	4,0

D=4

S \ V	0	1	2	3	4
4	4,0	4,0	4,0	4,0	4,0
3	3,6	3,7	3,8	4,0	4,0
2	3,3	3,5	3,6	3,7	4,0
1	3,2	3,3	3,4	3,5	4,0
0	3,0	3,1	3,2	3,3	4,0

Figure AV-1 Details of condition rating system used in Germany

Table AV-4 Condition rating system used in Germany

Rating	Description of condition and actions required
1.0 – 1.4	Very good structural condition. The stability, durability and safe use of the structure are assured. Routine maintenance is required.
1.5 – 1.9	Good structural condition. The stability and safe use of the structure are assured. The durability of the structure might be impaired slightly in the long-term. Routine maintenance is required.
2.0 – 2.4	Satisfactory structural condition. The stability and safe use of the structure are assured. The durability of the structure may be impaired considerably in the long-term. It is possible that the proliferation of damage or the occurrence of consequential damage will, in the long-term, lead to a considerable reduction in stability and/or safety or structural condition. Routine maintenance is required. Repair work is required in the medium-term. Reconstruction works and/or the installation of warning signs to help maintain user safety might be necessary in the short-term.
2.5 – 2.9	Temporarily satisfactory structural condition. The stability of the structure is assured. Traffic safety may be impaired. The durability of the structure might be impaired considerably. It can be expected that the proliferation of damage or the occurrence of consequential damage will, in the long-term, lead to a considerable reduction in stability and/or safety or structural condition. Routine maintenance is required. Repair work is required in the short-term. Reconstruction works and/or the installation of warning signs to help maintain user safety might be necessary in the short-term.
3.0 – 3.4	Critical structural condition. The stability and/or user safety of the structure are impaired. The durability of the structure might no longer be assured. The proliferation of damage or the occurrence of consequential damage may reduce stability and/or user safety in the short-term. Routine maintenance is required. Repair work is required immediately. Reconstruction works and/or the installation of warning signs to help maintain user traffic safety and/or restrictions on use may be required as a matter of urgency.
3.5 - 4.0	Inadequate structural condition. The stability and/or user safety of the structure are considerably impaired or threatened. The durability of the structure might no longer be assured. The proliferation of damage or the occurrence of consequential damage may threaten stability and/or user safety in the short term, or lead to irreversible deterioration of the structure. Routine maintenance is required. Repair work or replacement is required immediately. Reconstruction works, the installation of warning signs to help maintain user safety and/or restrictions on use may be necessary as a matter of priority.

AV.5 NORWAY

The degree of damage is expressed on a numerical scale - as reproduced in Table AV-5 - and this is used to assess whether maintenance and/or repair works are required and when such works should be undertaken.

Table AV-5 Condition rating system used in Norway

Code	Description of condition and action required
1	Slight damage/deficiency; no action required
2	Medium damage/deficiency; action required within next 4 to 10 years
3	Serious damage/deficiency; action required within next 1 to 3 years
4	Critical damage/deficiency; action required immediately or within next 6 months at the latest
9	Not inspected

The impact of the damage/deficiency is assessed according to the consequences that it may have on the bridge, its users and the environment. The assessment system is reproduced in Table AV-6.

Table AV-6 Structural deficiency system used in Norway

Code	Description of consequence
B	Damage/deficiency threatening load-carrying capacity
T	Damage/deficiency threatening user (traffic) safety
V	Damage/deficiency that may increase maintenance costs
M	Damage/deficiency that may affect the environment and/or aesthetics

The results of an inspection along with measurements of, for example, material properties form the basis for establishing the degree of damage and its potential consequences. The codes for the degree and the consequence are used in conjunction: for example, 3B represents serious damage or a deficiency that, if left untreated for more than 1 to 3 years, could reduce the loading-carrying capacity of the bridge.

For each type of damage, the activating condition is described in ‘Inspections handbook for bridges’: the term ‘activating condition’ means that a structure, or an element of one, has been damaged or has faults or deficiencies that require maintenance in the near future. This condition must be determined at the time of the inspection and is indicated as follows:

degree of damage 1: condition may be accepted without action

degree of damage 2 - 4: condition will require action at some time or other (short or long-term) within the next 10 years.

AV.6 SLOVENIA

The condition rating (R) of a bridge and/or its components is derived from the following function:

$$R = \sum V_D = \sum B_i \times K_{1i} \times K_{2i} \times K_{3i} \times K_{4i}$$

where:

V_D - rating value for the type of damage.

B_i - the value of this factor reflects the potential effect of a particular type of damage (i) on the safety and/or durability of the affected structural element. The values of B_i range from 1 to 4.

K_{1i} - the value of this factor, which ranges from 0 to 1, describes the extent of damage. In the field, the extent of damage on the affected component or structure is not quantified (for example, in terms of affected length or area), rather it is classified as A, B or C according to the percentage of the elements or the surface area affected. For A up to 30% is affected, for B between 30 and 60%, and for C more than 60%. Usually the value of the factor is assigned to one or more components of the bridge or to the whole bridge.

K_{2i} - the value of this factor, which ranges from 0 to 1, reflects the intensity of the damage. However, in the field, the intensity of damage is classified into one of four grades: I - light, II - medium, III - severe, IV - very severe. Usually the value of the factor is assigned to a particular type of damage - such as the width of cracks and the thickness of delaminations.

K_{3i} - this factor defines the importance of the structural component or member to the safety of the entire structure. The values of K_{3i} range from 0 to 1.

K_{4i} - the value of this factor reflects the urgency of intervention work: the values range between 0 and 10. The value thus depends of the type of structure, and the risk and consequences of collapse of a bridge or parts of one.

The condition of a bridge is classified, as shown in Table AV-7, according to the value of R. And on this basis, the supervising bridge inspector will decide the global condition class of the bridge structure.

Table AV-7 Condition rating system used in Slovenia

Condition class	Description of condition	Condition rating (R)
1	Critical	>20
2	Bad	14-22
3	Satisfactory	8-17
4	Good	3-12
5	Very good	0-5

AV.7 SPAIN

A condition index for a bridge is derived from the rated condition of its elements as assessed through an inspection. A Condition Mark (CM_{el}) - on a scale of 0 to 5 - is derived for each structural element according to the nature, degree and extent of damage on the element, and the effect of the damage on the functioning of the element and of any other elements.

For each incidence of damage, a rating is given by an inspector for the following three factors:

- Damage - a rating (from 0 to 3) is the sum of the values awarded for the following sub-factors:
    - nature - values of 0 and 1 are given, respectively, for ‘harmless’ and ‘harmful’ damage
    - degree - values of 0 and 1 are given, respectively, where the damage has developed to a ‘low level’ and a ‘high level’

    (The basis of assigning values for the nature and degree of a wide range of damage types is provided in detail in the published ‘Catalogue of damages’.)

    - extent - a value of 0 is awarded where less than 50% of the element (based on surface area, for example) that could be affected by the damage is affected, a value of 1 is given where more than 50% is affected.

    (The criteria for determining the possible extent of damage are a function of the nature and type of damage; for example, shear cracks only occur near bearings whilst flexural cracks on the lower parts of a deck occur at mid-span.)
- Function - ratings of 0 or 1 are awarded, respectively, where the damaged element can or cannot continue to fulfil its function.
- Implication - ratings of 0 or 1 are given, respectively, where damage of the element has or has not led to damage on other elements.

The Condition Mark (CM) for each incidence of damage is the sum of the above ratings. The value ranges from 0 to 5: the higher the value the more serious the damage. However, the scale is not linear: for example, a change of CM from 1 to 2 is not equivalent to a change from 3 to 4. Thus the CM value is expressed as an index through the Transformed Condition Mark (where $TCM = 2^{CM}$) to account for this non-linear variation in safety.

The Condition Mark (CM_{el}) for a particular element is simply the maximum CM of all the types of damage affecting it. The Condition Index of a bridge element (CI_{el}) is then derived as the product of CM_{el} and a weighting factor (γ_{el}): the value of the latter reflects the importance of the structural element to the whole bridge.

The condition index (CI) of a bridge is simply the maximum CI of its elements. A priority index (PI) of a bridge is derived as the product of CI and a weighting factor (γ_{bridge}): the value of the latter reflects the importance of the structure to the road network. Thus:

$$PI = \gamma_{bridge} \times \max(\gamma_{el} \times 2^{CM_{\max}})$$

AV.8 SWEDEN

The functional condition of a bridge is classified according to the extent that its structural members satisfy the specified design requirements. In total, 14 different members are considered: these are; the foundation, earthwork slopes, supports, abutment and wing walls, bearings, primary load-bearing elements, other load-bearing elements, bridge deck, edge beams, waterproofing, surfacing, parapet, expansion joints, and the drainage system. The condition classes for these are:

- 3 - which denotes that the function was impaired at the time of the inspection
- 2 - indicating that a defect was likely to arise within 3 years following the inspection
- 1 - indicating that a defect was likely to arise within 3 to 10 years following the inspection
- 0 - which denotes that there was no damage at the time of inspection.

An overall condition class is derived for a bridge with regard to its load-carrying capacity, safety (traffic users) and durability. The classification is based on the condition classes of the members making up the bridge. As shown in Table AV-8, different weightings are used for the various members.

Table AV-8 Weightings applied to structural members

Function	Member number	Structural member	Weighting
BC	1	Foundations	4
BC	2	Earthwork slopes	3
BC	3	Supports	4
BC	4	Abutment and wing walls	3
BC	5	Bearings	4
BC	6	Primary load-bearing elements	4
BC	7	Other load-bearing elements	4
BC	8	Bridge deck	4
BC,S	9	Edge beam	4
D	10	Waterproofing	1
D	11	Surfacing	1
S	12	Parapet	2
D	13	Expansion joints	1
D	14	Drainage system	1

BC - Load-carrying capacity S - Safety (traffic users) D - Durability

Where one or more of the structural members with a rating of 4 (that is, 1, 3, 5, 6, 7, 8, and 9) is assigned to condition class 3, the bridge is also assigned an overall condition class of 3. And where any of these same structural members is assigned to condition class 2, the condition class of the bridge will be 2 or (depending on the classes and weightings) 3.

At the time of a Major Inspection, an assessment will be made as to whether or not the structure will attain the service life assumed in design.

AV.9 SWITZERLAND

In Switzerland, the same condition rating system is used for bridges as for their structural members: details of the system are provided in Table AV-9.

Table AV-9 Condition rating system used in Switzerland

Category	Description of condition	Description of damage and action required
1	Good	None, or minor
2	Acceptable	Insignificant
3	Defective	Considerable
4	Bad	Serious
5	Alarming	Safety endangered Remedial works required prior to next Principal Inspection, and/or action required as a matter of urgency
6	Not checkable	Components that cannot be inspected

AV.10 UNITED KINGDOM

The following applies to most National Roads in England.

At the first Principal Inspection of a structure, information on each observed defect on the structure (that is the type, extent and severity of the defect, and any proposed remedial action) is recorded directly onto the Highways Agency's Structures Management Information System (SMIS). Each defect is given an extent and severity rating by the inspector, who may also indicate if emergency action is needed and add any comments and proposed actions. The SMIS database contains a comprehensive list of over 100 defect types which are grouped into the following four categories:

- Damage Causing
- Appearance Related
- Paint/Protective Systems
- Affecting Adjoining Areas

Each of the categories has its own severity definitions: the definitions for the first two categories in the list are given in Table AV-10 and Table AV-11, whilst the ratings for the extent of damage are given in Table AV-12.

Table AV-10 Severity definitions for 'Damage Causing' defects

Code	**Full definition**
D1	Defect is definitely not causing damage to element or structure
D2	Minor – Defect is unlikely to be causing damage to the element or structure now or is unlikely to result in damage in near future
D3	Moderate – Defect is probably causing damage to element or structure, or is likely to do so in near future.
D3S	Moderate – Defect may present a danger to the public in the near future
D4	Severe – Defect is clearly causing damage to element or structure.
D4S	Severe - Defect is presenting a danger to the public.
D5	Defect is causing element to be non-functional.

Table AV-11 Severity definitions for 'Appearance Related' defects

Code	Full definition
A1	Defect in tolerable condition
A2	Defect in low tolerability condition
A3	Defect in unacceptable condition.
A4	Defect in offensive condition[1].

Table AV-12 Extent ratings for damage

Code	Full definition
SB	Defect present in less than 5% of area or length of Element
SC	Defect present in 5% up to 20% of area or length of Element
SD	Defect present in over 20% up to 50% of area or length of Element
SE	Defect present in over 50% of area or length of Element

The data required for determining the condition of a structure are obtained from a careful visual inspection. Testing techniques can then be used to supplement visual inspections and provide more detailed information, and to detect the presence of defects that might not be observed during a visual inspection. The results of the tests are interpreted to determine the implications for the structure.

SMIS provides a means of integrating the engineer's maintenance cycle with the Highways Agency's business processes. Once defects have been assigned to individual elements[2], Maintaining Agent's engineers can use SMIS to plan remedial works by assigning a *Maintenance Action* to each defect. These can then be grouped together (which may or may not be structure specific) to form *Projects*. Projects can be bid for and taken through the Highways Agency's continuous value management process. Once Projects have been completed the Maintenance Actions (and any changes to the structure inventory) are revised and the maintenance cycle begins again.

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[1] Socially unacceptable graffiti such as racist, blasphemous or foul language which must be removed immediately.

[2] SMIS holds a detailed structural inventory that allows individual structural elements to be defined. In SMIS, therefore, defects can be assigned to individual (or groups) of elements (e.g. "West Pier Bearing No 3"). This differs from the previous paper based inspections (BE11/94 forms) that only allowed defects to be assigned to generic elements types (e.g. Bearings).

AV.11 UNITED STATES

For every element of a structural component, the type, extent, quantity and severity of each form of deterioration and deficiency must be described by an inspector. From this, the inspector assigns a qualitative rating to the condition of each element using the system described in Table AV-13.

Table AV-13 Descriptive condition rating system as used in the United States

Condition rating	Description
Good	Element has only minor problems
Fair	Structural capacity of element is unaffected by low level of deterioration
Poor	Structural capacity of element is affected or jeopardized by advanced deterioration

A condition rating is assigned to a structural component using the system described in Table AV-14: the rating should express the general condition of the entire component.

Table AV-14 Condition rating system used in the United States

Condition rating	Description of condition and actions required
N	Not applicable
9	Excellent condition
8	Very good condition - no problems noted
7	Good condition - some minor problems
6	Satisfactory condition - structural elements show minor deterioration
5	Fair condition - all primary structural elements are sound but there may be some small loss of section, cracking, spalling, or scour
4	Poor condition - substantial loss in section, deterioration, spalling, or scour
3	Serious condition - loss of section, deterioration, spalling or scour have seriously affected primary structural elements. Local failures are possible. Fatigue cracks in steel, or shear cracks in concrete may be present.
2	Critical condition - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present, or scour may have undermined the substructure. Unless the bridge is closely monitored it may be necessary to close it until corrective action is taken.
1	Imminent failure condition - major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic, but corrective action may allow it to be put back into (restrictive) service.
0	Failed condition - out of service; beyond corrective action.

AV.11.1 California

The State highway authority in California (Caltrans) has developed a Health Index system for managing its bridge stock. A Health Index rating (HI), on a scale of 0 to 100, is derived from the assessed condition of the elements of a bridge and the asset value of the bridge or network of bridges. The premise of the system is that each element of a bridge has an initial asset value and deterioration reduces this value.

The HI rating is calculated from the following:

$$HI = \left(\frac{\sum CEV}{\sum TEV} \right) \times 100$$

where: $$CEV = \sum (QCS_i \times WF_i) \times FC$$

$$WF = \left[1 - (ConditionState\# - 1) \times (I / StateCount - 1) \right]$$

$$TEV = TEQ \times FC$$

and

TEV = Total Element Value

CEV = Current Element Value

TEQ = Total Element Quantity

FC = Failure Cost of element

QCS = Quantity in a Condition State

WF = Weighting Factor for the condition state

Annex VI Consolidated listing of recommendations

Recommendation 1

Key design assumptions should be defined in the inventory of the asset management system. Where possible, the system should require these assumptions to be checked by an inspector.

Recommendation 2

A best practice guide for assessing highway structures should be established. Such a guide may lead to the development of national assessment codes in States where they do not already exist, but it would seem more productive to develop European-wide documents covering the assessment of highway structures.

Recommendation 3

Specific loading rules for assessing in-service structures should be devised. The first priority is the development of a new code for traffic loading that takes account of local conditions, remaining service life, and supplementary safety measures such as monitoring and controlling traffic flows. There is benefit in considering a European-wide approach to the development of such codes.

Recommendation 4

Information on actions that have been investigated in some depth should be disseminated and compared. Relevant documents should be translated into English.

Recommendation 5

Methods and techniques should be available for assessing the condition of all types of highway structure. As a starting point those developed for bridges can be adopted to other highway structures, but the evaluation of defects for other structures must be determined with respect to the nature and type of loading acting on them.

Recommendation 6

A range of new materials is now being promoted for the construction and repair of bridges but, at present, their long-term durability has only been assessed from laboratory tests. It is essential to observe the in-service performance of these new materials, and continuous performance records should be established for them as a matter of course. Appropriate equipment should be developed for detecting and monitoring deterioration processes.

Recommendation 7

Long-term studies should be undertaken to track the initiation and propagation of defects and deterioration processes. Such studies should cover a range of structural types, and both ageing and new structures.

Recommendation 8

Inspection procedures should be reviewed to determine where improvements in current practice can be made. Issues of particular interest are:

- defining the objectives of an inspection
- integration of the inspection process into the management of structures
- economic, environmental, safety and social implications
- determining the level of detail required in an inspection
- setting the frequency for the different types of inspection, but allowing flexibility according to the type of structure and what is being inspected.

Recommendation 9

The usefulness of the standard inspection report forms and the information provided to an inspector should be reviewed. Consideration should be given to the use of purpose-designed forms for each type of structure.

Recommendation 10

Consideration should be given to the establishment of a register or log for each highway structure. Such a document could contain details of its design and construction, inspection reports and details of any remedial works.

Recommendation 11

The factors that pose the greatest risk to the stability of a structure should be identified and included as part of the inspection process. Such factors may include:

- traffic accidents - thus there may be a need to check road alignment, visibility, lane markings, and signs for speed, weight restrictions and clearances
- seismic activity, subsidence and settlement - some elements are more at risk than others
- erosion and scour.

Recommendation 12

The methods of procurement and the specifications used for testing highway structures should be reviewed. From this, model contract documents should be established to suit various requirements for testing.

Recommendation 13

Advice or guidance notes on various NDT methods are required to extend the ranges of application, to encourage consistent and appropriate usage, and to improve the interpretation and application of the test data in assessing the condition of a structure. Such notes should include detailed information from case studies.

Recommendation 14

Research should be directed at producing cheaper, more reliable and user-friendly NDT equipment. Emphasis should be given to improving the signal processing equipment used for radar and ultrasonic surveys.

Recommendation 15

The use of load tests for assessment purposes should be reviewed: this should cover cost-effectiveness, instrumentation, and data collection and analysis.

Recommendation 16

It is recommended that loading tests are undertaken on novel or prototype structures.

Recommendation 17

In-service structures should be monitored as a matter of routine. Advice or guidance notes should be produced to encourage such exercises: these should cover the planning of such work; data collection, analysis and application to whole-life cost models; measurement techniques and equipment; and personnel qualifications. Where possible, they should also include information from case studies.

Recommendation 18

The data obtained from monitoring exercises should be held centrally, and in a form that makes them easy to retrieve and interrogate.

Recommendation 19

The methods used to collect and record the data obtained from inspections of highway structures should be reviewed. This should cover the use of photographic techniques, including stereo-photogrammetry and video recording.

Recommendation 20

The type and amount of data collected, archived and analysed from inspections should be reviewed periodically to ensure that they meet the requirements of the management system.

Recommendation 21

The extent to which the type, quality and quantity of data from an inspection satisfies the requirements of a condition assessment should be reviewed periodically. And, where necessary, work should be directed at improving or developing investigatory techniques, instruments, and the collection and analysis of site data.

Recommendation 22

Further work should be directed at improving the methods used to identify and rank the importance of defects with regard to the safety, durability and cost of maintaining highway structures.

Recommendation 23

Methods for deriving an adequacy rating or priority ranking of structures should be investigated. This should include a review of the potential of new mathematical techniques, such as fuzzy set theory and neural networks.

Recommendation 24

Taking the methods used for bridges as a starting point, methods for assessing the condition of earth retaining walls and buried structures should be established.

Recommendation 25

Long-term monitoring works should be undertaken as a matter of course, and the results of such case studies made available for reference purposes.

Recommendation 26

Work should be directed at improving the methods used to inspect and monitor the condition of in-service structures, the methods used to analyse the data from such exercises, and the quality of inspection reports.

Recommendation 27

As a matter or priority, work should be undertaken to develop and implement a certification scheme for inspectors. This should include attendance at training/educational courses, and checks on the competence of prospective candidates and inspectors. This work should be undertaken on a pan-European basis.

Recommendation 28

Work should be undertaken to check the consistency and reliability of structural assessments. It would also seem necessary to introduce a certification scheme for assessors: again, there is merit in a pan-European approach.