Deliverable D1

Review of current procedures for assessing load carrying capacity

Status C

BRIME
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Project Co-ordinator: Dr R J Woodward, Transport Research Laboratory (TRL)

Partners: Bundesanstalt fuer Strassenwesen (BASt)

Centro de Estudios y Experimentacion de Obras Publicas (CEDEX)

Laboratoire Central des Ponts et Chaussées (LCPC)

Norwegian Public Roads Administration (NPRA)

Slovenian National Building and Civil Engineering Institute (ZAG)

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by R Kaschner, Bundesanstalt für Straßenwesen (BASt)

C Cremona, Laboratoire Central des Ponts et Chaussées (LCPC)

D Cullington, Transport Research Laboratory (TRL)

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EXECUTIVE SUMMARY

SCOPE

Europe has a large capital investment in the road network including bridges, which are the most vulnerable element. The network contains older bridges, built when traffic loading was lighter and before modern design standards were established. In some cases, therefore, their carrying capacity may be uncertain. Furthermore, as bridges grow older, deterioration caused by heavy traffic and an aggressive environment becomes increasingly significant resulting in a higher frequency of repairs and possibly a reduced load carrying capacity.

The purpose of the BRIME project is to develop a framework for the management of bridges on the European road network. This would enable bridges to be maintained at minimum overall cost, taking all factors into account including condition of the structure, load carrying capacity, rate of deterioration, effect on traffic, life of the repair and the residual life of the structure.

The objective of WP 2: ”Assessing the load carrying capacity of existing bridges” is to derive general guidelines for structural assessment. This report describes the first stage of the work in which detailed information on bridge assessment in the participating countries is collated. In the later stages of the work, guidelines can then be developed that reflect the best practices and yet allow for variations in national priorities as the process of harmonisation is pursued.

SUMMARY

This report describes the results of a review of current practices and procedures used in the participating countries based primarily on the results of a questionnaire.

As a first step the report presents general information related to the principles of assessment, including definitions, objectives, methodology and assessment stages. The main objective of structural assessment is to determine the traffic loading that the bridge can carry that is consistent with an appropriate level of structural safety. The level of safety achieved may be implicit in the specified analytical procedures or determined explicity by reliability calculations. Structural assessment may be required for a number of reasons, including change of conditions of use, presence of damage or deterioration, or if repairs were expected. It may also be required as part of a general bridge management system. Methods of evaluating the dafe carrying capacity of a bridge can be categorised into deterministic, semi-probabilistic and probabilistic methods. Response to the questionnaire showed that the procedures used for bridge assessment vary widely from country to country.

Chapter 3 covers the main statistical data relative to the national bridge stock in each of the participating countries. These statistics relate primarily to the structures on the motorways and national routes. This information provides the basis for the proposals for bridge assessment to be developed in WP 2, and for the development of a general model for traffic loads. Moreover significant types of damage and deterioration are combined and the influence of damage types on the development of design codes in the past are described for the participating countries.

In chapter 4, the existing basic rules and the procedures applied for the assessment of load carrying capacity of bridges are presented for the different countries. The procedures used show essential differences. In most of the countries covered by BRIME, design codes are used directly for assessment. In some countries, the design codes are adapted in some way, for example, by modifying the partial safety factors used. In Germany, structural assessment is, in most cases, performed using conservative standards taking a single global safety factor into account. On the other hand, the UK has formulated an extensive system of assessment codes which are contained in the Design Manual for Roads and Bridges. Depending on the specific requirements, the assessment procedure for an individual bridge can be performed at a different level of expertise and complexity.

In all cases recording and allowing for the current structural condition is important. Non-destructive test methods are used extensively for the determination of in-situ material properties, identification of existing structural condition and extent of damage. In general, load tests to evaluate load carrying capacity are performed only in exceptional circumstances.

In conclusion, it is proposed that a possible common framework for bridge assessment can be developed using a multi-level procedure similar to that used in the UK Highways Agency's standard BA 79/98. Such a framework would be flexible enough to cover the more simple as well as the complex probabilistic procedures for assessment.

IMPLEMENTATION

This report forms the basis for a subsequent discussion and evaluation of bridge assessment procedures which will ultimately lead to the development of proposals and guidelines. These proposals contribute to deliverables D5: ”Development of models (traffic and material strength)”, D6: ”Experimental methods and use of reliability techniques”, and D10: ”Guidelines for assessing load carrying capacity”.

The report also plays a fundamental part in defining the approach adopted in Workpackage 3: ”Modelling of deteriorated structures” and its deliverable D11: ”Assessment of deteriorated bridges”. In addition, structural safety is a significant parameter for priority ranking, as examined in Workpackage 6: ”Priority ranking and prioritisation” and the decision-making process which is being studied through Workpackage 5: ”Decision: repair, strengthening, replacement”. All of these components are fundamental to the development of an effective bridge management system which will be developed in Workpackage 7: ”Systems for bridge management”.

REVIEW OF CURRENT PROCEDURES FOR ASSESSING LOAD CARRYING CAPACITY

ABSTRACT

The present report covers the current practices and procedures for the evaluation of the load carrying capacity of bridges as used in the participating countries of BRIME. As a first step general information is given relating to the principles of assessment, i.e., definitions, objectives, applicable rules and assessment stages. The verification of structural safety in terms of the load that a structure can carry safely, is the main objective of structural assessment and is necessary if conditions of use have been changed. As well as examining individual structures, the function of bridge assessment might be to examine the performance of the bridge stock as a whole. Methods of evaluating structural safety can be separated into deterministic, semi-probabilistic and probabilistic methods. Results of the questionnaire devised as part of this study showed that the current application of these methods is different in the participating countries.

This report includes the main statistic data relating to the bridge stock on the highways and trunk roads, the significant types of damage and deterioration, and the influence of this damage on the development of design and assessment codes. This information will be used as a basis for the subsequent tasks.

The analysis of current procedures for structural assessment shows essential differences in the different countries. In most countries the design codes are used. Some are adapted in some way, for example, by modifying the partial safety factors used. In Germany, structural assessment is, in most cases, carried out using conservative standards taking one global safety factor into account. In comparison, there is an extensive system of assessment codes in the UK which are based on the relevant bridge design codes, but have been re-written specifically for the assessment of existing bridges. In all cases, recording and allowing for the current structural condition is important. In general, load tests are performed only in exceptional circumstances to evaluate load carrying capacity.

In summary, it can be concluded that a possible common framework for structural assessment can be represented by a multi-level procedure which covers simple deterministic approaches as well as complex probabilistic procedures.

1 INTRODUCTION

The objective of Workpackage 2: ”Assessing the load carrying capacity of existing bridges”, is to prepare basic guidelines for determining the load carrying capacity of existing road bridges. An initial step involves taking stock of the procedures and techniques currently used by countries participating in the EU Bridge Management in Europe (BRIME) project. On the basis of a survey carried out among the participating countries, fundamental information was first obtained on the types of structures found in the national bridges stocks, the structural condition and types of deterioration present, and the national codes (Standards, Advice Notes, Guidelines, etc) used for determining load carrying capacity. The survey included information on the tasks and objectives relating to the determination of load carrying capacity, as well as the principles and subsequent computation processes. In addition, clarification was required as to which experimental methods, including non-destructive testing (NDT) are employed on site and what laboratory tests are used to support the analytical processes. The questionnaire form used for this survey is included in Appendix 1.

The material gathered and supplied by the participating countries was evaluated and organised in terms of common features, differences, and national characteristics. A summary of the results is provided in the following chapter. The response to the questionnaire, its evaluation, and a comparison between the approaches adopted in the different countries form the basis for the subsequent discussions. The ultimate objective is to prepare proposals that define a consistent method of bridge assessment which can be used within the overall context of a bridge management system. The questionnaire will also be used as a basis for the other deliverables from Workpackage 2, i.e., D5: ”Development of models (traffic and material strength)”, D6: ”Experimental methods and use of reliability techniques”, and D10: ”Guidelines for assessing load carrying capacity”.

This report has an impact on the other components of BRIME. The review of current practice for assessing load carrying capacity will define the starting point for Workpackage 3: ”Modelling of deteriorated structures” and its deliverable D11: ”Assessment of deteriorated bridges”. Subsequently, the output from WP3 will be used in the final output from WP2. The assessment of bridge strength and calculation of structural safety is a significant parameter for priority ranking (as investigated by Workpackage 6: ”Priority ranking and prioritisation”) and the decision-making process (as investigated by Workpackage 5: ”Decision making, repair, strengthening, replacement”). Therefore the output of Workpackage 2 plays an important role in the development of an overall bridge management system (Workpackage 7: ”Systems for bridge management”).

2 PRINCIPLES OF ASSESSMENT

2.1 INTRODUCTION

This chapter describes the principles of bridge assessment and their application as understood by the three main participants in WP2. Note is taken of the current practices adopted in all the countries participating in BRIME as determined from the questionnaire. Chapter 4 elaborates on the questionnaire results and the current practices in all of the countries.

Bridge assessment consists of determining the load carrying capacity in relation to the specified highway loading. A bridge that ”passes” the assessment is one that can be shown, generally by calculation using normal analytical techniques, to be able to carry all combinations of the assessment live loading without distress. A bridge that is not able to carry these load combinations may be referred to as sub-standard.

When a bridge passes an assessment it means that it has been shown to possess an appropriate level of safety consistent with carrying the required traffic loading – either implicitly within the procedures given in the assessment rules, or explicitly by means of reliability calculations.

Bridge assessment is very similar to bridge design. The same basic principles lie at the heart of the process. An important difference lies in the fact that when a bridge is being designed, an element of conservatism is generally a good thing which can be obtained at very little additional cost. When a bridge is being assessed, it is important to avoid unnecessarily conservative measures because of the disruption and financial implications that may follow if a bridge is designated as sub-standard without good cause.

2.2 REASONS FOR ASSESSING A BRIDGE

Bridge assessment may be initiated for a variety of reasons involving a change of some kind, for example:

- where conditions of use are altered, for example general increases in the maximum permissible vehicle or axle weights;
- where individual bridges are modified, for example where the number of traffic lanes has increased or the deck is widened;
- where a structure has been damaged either by mechanical means, for example by vehicle impact, or by deterioration as a result of steel corrosion, ASR, sulphate attack etc;
- where repairs or alterations have been carried out which affect structural performance;

- where an exceptional load (not covered by the design loading) is to be carried by the bridge.

An additional reason that, as yet, has not been applied generally in the participating countries is:

- where a bridge is of an older type built to outmoded design standards or loading and may have less reserves of strength than currently is the practice (i.e. may now be sub-standard).

In most of the participating countries, assessment is only carried out on specific structures that have been affected directly and significantly by one of the above changes in conditions. In the UK, it is the final reason that has predominated, largely in response to the revised European bridge loading specification that required an increase in gross vehicle weight from 38 to 40 tonnes. This along with concerns about the durability of bridges led to the initiation, in 1987, of a fifteen-year bridge programme of bridge assessment and rehabilitation. This has required all bridges in the country not known to have been designed to particular standards to undergo assessment to the revised loading specification.

One of the primary objectives of a bridge management system is to ensure that all bridges are maintained in a safe condition with respect to the loading they have to carry. To do this requires that the carrying capacity is known sufficiently well.

2.3 DEFINITIONS

The definitions and principles given in this section is as far as possible in accordance with the final draft of ISO 2394, with the draft N.9 of the ISO//WD 13822: Basis for design of structures: Assessment of existing structures, and other international standards.

The following general terms are defined for specific use in this report:

Structural assessment[1]:
The total set of activities performed in order to verify the reliability of an existing structure.

Damage:
An unfavourable change in the condition of a structure that adversely affects its structural performance.

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[1] This definition is made from the point of view of the reliability theory.

Deterioration:

A process that adversely affects structural performance over time due to one or more of the following:

- naturally occurring chemical, physical or biological processes;
- normal, extreme or accidental actions;
- normal, severe environmental conditions;
- wear due to use;
- improper use or maintenance.

Inspection:

On site examination to establish the present condition of the structure.

Investigation:

Collection and analysis of information through inspection, document search, load testing and other testing.

Limit states:

Undesirable states of the structure, generally classified as ultimate limit states (ULS) and serviceability limit states (SLS). For example, exceeding the capacity of a structural component or of the structure as a whole is classified as an ultimate limit state. Serviceability limit states may include:

- limited local structural damage;
- deformations which produce damage in non-structural elements or affect the use or appearance of structural or non-structural elements;
- vibrations resulting in discomfort, alarm or loss of ability to use the structure.

Load testing:

Examination of the structure or part thereof by loading to estimate its behaviour or properties, or to predict its load bearing capacity.

Maintenance:

Routine intervention to preserve the appropriate structural performance.

Material properties:

Mechanical, physical or chemical properties of materials used in the analysis of structural behaviour.

Rehabilitation:

Work required to restore, and possibly upgrade, the condition of an existing structure.

Reliability:

Covers aptitude to use and structural safety. The aptitude of use is related to the serviceability limit state while structural safety is related to the ultimate limit state.

Repair:

Improvement of the condition of a structure by restoring or replacing existing components that have been damaged.

Upgrading:

Modifications to an existing structure to improve structural performance.

2.4 OBJECTIVES

For the purposes of this project, assessment can be defined as a set of activities used to determine the safe load carrying capacity of an existing structure. Evaluation of load capacity can be carried out using a wide range of approaches depending on the level of information available and accuracy required. It involves comparing the existing capacity with the capacity required to resist the specified loading. The method used can be based on simple deterministic approaches, using global safety factors, semi-probabilistic methods using partial safety factors through to sophisticated reliability techniques. In most countries, semi-probabilistic methods are used although reliability techniques may be available or in the process of development.

One of the implied objectives of assessment is to estimate the structural reliability of the bridge. Reliability is a complex notion which introduces the following concepts and attempts to quantify them:

- fixed and random sets of information;
- quantification of the characteristics of these sets information based on existing knowledge in terms of statistical parameters;
- the reliability of these parameters.

When semi-probabilistic methods are used, reliability is not calculated explicitly: an appropriate level of reliability is achieved by ensuring that the factored resistances exceed the factored load effects. This has the advantage of relative simplicity, but results in some non-uniformity in the reliability achieved for different components and structures.

The continued use of existing structures is of great importance because the built infrastructure is a huge economic and political asset, growing larger every year. Structural assessment as part of an effective management process is therefore a major engineering task. The structural engineer is increasingly called upon to devise ways to extend the life of structures whilst observing tight cost constraints. Furthermore, the residual life of a structure can be an important consideration, the minimum level of which can be set by the owner.

The specific objectives of the assessment must be specified by the owner or the technical authority responsible for the structure. The objectives can be based on the following:

- safety performance level, which provides appropriate safety for the users of the structure;
- continued function performance level, which provides continued function in the event of an earthquake, impact or other foreseen hazard;
- special performance requirements of the owner or the authorities related to property protection (economic loss) or serviceability.

Different cases have to be distinguished. The structure can be:

- in good condition,
- not in good condition but public safety is not compromised;
- unfit for service.

Various options are available. The structure can be:

- retained as it is;
- modified (e.g. increased number of lanes);

The traffic load against which the assessment is made can be:

- an exceptional unique convoy;
- a limited number of exceptional convoys;
- normal traffic including specified exceptional loads;
- traffic loading with maximum loads to be determined and not restricted in time (such as a reduced load carrying capacity);
- a traffic with maximum loads restricted in time (such as a reduced load carrying capacity before rehabilitation).

According to the terminology introduced by international associations and standards (such as ISO 2384), reliability covers suitability for use and structural safety. The suitability for use is related to the serviceability limit states while structural safety is related to the ultimate limit states.

2.5 EXISTING ASSESSMENT RULES

Currently, the rules used in bridge assessment are provided mainly by design standards with additional standards relating to testing methods, including load testing. In some countries, the design standards used can be either the current standards, or those that were current at the time of construction. In others, only current design loading specifications can be used, although these can be modified specifically for assessment and can include a reduced load level based on restricted traffic conditions. Additional requirements can be given regarding exceptional traffic loading. Design standards are mainly based on two alternative approaches:

- allowable stress design as prescribed in German or Japanese codes;
- partial safety factor design as prescribed in the French, UK and Eurocode documents.

In the allowable stress design approach, the adopted safety principle consists in verifying that the maximum load effect S calculated in any section of any part of a structure, and under worst case loading, remains lower than a so-called allowable value $R_{allowable}$. This value is derived from the failure load effect R_f of the material divided by a safety factor K, set conventionally. The structural assessment aimed to verify:

$$S \leq R_{allowable} = \frac{R_f}{K} \qquad (1)$$

In a probabilistic approach, the stress S applied to a structural element, and the variable characteristic of the strength R of this element, are randomly described because their values are not perfectly known. If the verification of the criterion related to the limit state results in

$$R < S \qquad (2)$$

the limit state is exceeded. The probability P_f of the event $R < S$ will characterize the reliability level of the component with regard to the considered limit state:

$$P_f = \text{Prob}(R < S) \qquad (3)$$

The semi-probabilistic approach used in many design codes schematically replaces this probability calculation by the verification of a criterion involving characteristic values of R and S, noted R_d and S_d, and partial safety factors g_R and g_S which may be represented in the following form:

$$g_S S_d \leq \frac{R_d}{g_R} \qquad (4)$$

The partial safety approach is claimed to be semi-probabilistic, considering the application of statistics and probability in the evaluation of the input data, the formulation of assessment criteria, and the determination of load and resistance factors.

It is important to note that the rules set down in design codes constitute a set of prescribed rules that are only valid within a certain context. Thus, in order to be applicable, a bridge must conform to the design code in the following areas:

- the type of bridge
- the methods used in the structural analysis;
- the quality of construction materials and workmanship;
- the actual traffic loading on the bridge;
- the condition of the bridge;
- the detailing used.

For assessment, situations often exist which render design codes inapplicable either because of existing structural condition or because of the presence of non-conforming details. This is particularly in the case of older bridges and current design codes have to be interpreted carefully before being used.

The design codes present safety margins which, in general, exceed those that are reasonable to accept for the assessment of existing bridges. This is because the level of knowledge of existing structures and the actual traffic conditions can be determined to a greater degree of reliability, as they can be observed and/or measured. Thus partial safety factors can be reduced while maintaining the same level of structural reliability. Knowledge of the structures can be increased by further investigations and this can justify further reductions in partial safety factors. The partial safety factors take into account variabilities in structural behaviour and loading. The required safety margin is reduced with age. Finally, the optimum safety level in a new design is greater than in an existing bridge because of the large costs associated with rehabilitation.

The use of such principles leads to complexity in the assessment calculations. More importantly, however, is the selection of appropriate safety level which at present is very difficult because of the lack of rules on how such a choice is made. Selecting appropriate level of safety must include consideration of socio-economic conditions. In all cases, the numerical applications must take account of:

- the mode of construction: for concrete structures, detected unacceptable cracks are a hint to a potential deficiency in capacity of the structure. Thus, both serviceability and ultimate limit states must be considered. For steel bridges and reinforced bridges, the ultimate limit states will be essential. When repeated loading occurs, fatigue will depend on the mode of construction.
- the type of structure: imprecise aspects of the construction process and the probability of sudden failure or of re-distributing effects will be different according to the type of bridge;
- the part of the structure considered: the consequences of component failure can be great or small depending to the part of the structure and the limit state.

It is clear that the establishment of principles and procedures to be used for the assessment of existing bridges is needed because some aspects of assessment are based on an approach that is substantially different from new design, and requires knowledge beyond the scope of design codes. In addition, bridge assessment should be carried out in stages of increasing sophistication, aiming at greater precision at each higher level. In order to save structures from unnecessary rehabilitation or replacement (and therefore to reduce owners' expenditure), the engineer must use all the techniques, all the methods and all the information available in an efficient way. Simple analysis can be cost effective if it demonstrates that the bridge is satisfactory, but if it does not it can present major drawbacks regarding the bridge under study and advanced methods should be introduced as an option as far as possible. Reliability theory based on a probabilistic description of resistance and load variables is one such approach.

The modelling of uncertainty is required for a rational approach to the evaluation of structural safety. This has many advantages over more traditional deterministic techniques for the following reasons:

- the evolution of loads with time is not considered in deterministic methods;
- the properties of materials can be modified with time in an unfavourable way, e.g., through corrosion, loss of durability or fatigue;
- the combination of multi-component load effects is not properly considered (such as the combination of normal and moment effects);
- real elements are often different from the specimens on which design performance is measured;
- studies on sensitivity to errors in modelling the behaviour of structures are generally omitted;
- poor workmanship is unfortunately statistically inevitable;
- construction requirements discovered when the works are being carried out may lead to alternative solutions which bring about an overall behaviour of the structure slightly different from the one provided for in the design.

A method taking into account uncertainties in variables appears to be a realistic safety assessment criterion. Therefore, probabilistic methods today constitute an alternative to allowable stress design or partial safety factor approaches. They are based on:

- the identification of all variables influencing the expression of the limit state criterion;
- study of the statistical variability of each of these variables, often considered to be stochastically independent;
- derivation of probability functions for each variable;
- calculating the probability that the limit state criterion is not satisfied;

- comparing the probability obtained to a limit probability previously accepted.

Although extremely attractive, the probabilistic reliability theory is limited by many factors: some data are difficult to measure for the following reasons:

- the required statistical data often do not exist;
- probability calculations quickly become insurmountable.

These considerations are decisive for determining what may be expected from the limits of probabilistic theory. They imply in particular that the probabilities suffer from the fact that they are only estimates of frequencies (sometimes not observable) based upon an evolving set of partial data. They also result from hypotheses (e.g., choice of type of distribution) which make them conventional. Consequently, the outcome of a probabilistic approach depends strongly on the assumptions which are made about the uncertainties associated with the variables. If these assumptions are not founded on adequate data, estimates of safety will be misleading. Indeed, probabilistic methods are often abused when the variables are not carefully modelled. It is therefore essential that the quality of data and validity of assumptions are borne in mind when using a probabilistic approach to make decisions about the apparent safety of a structure. Figure 1 represents the basic approaches to reliability assessment.

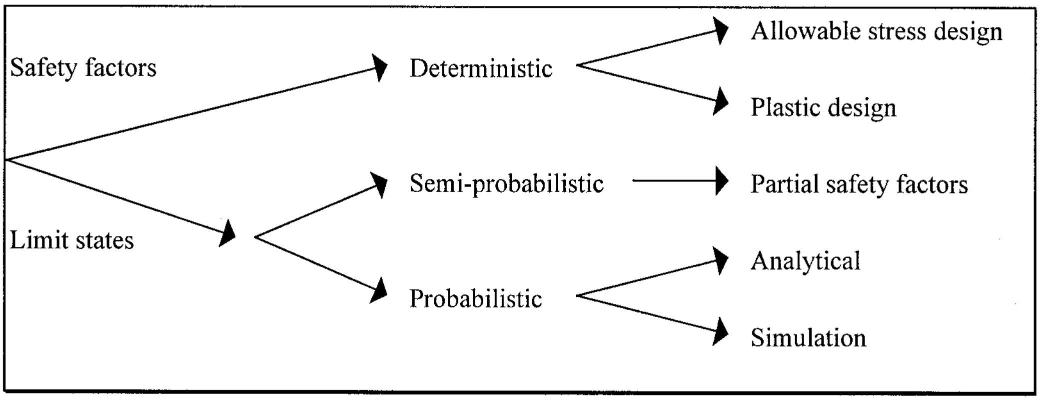


Figure 1: Basic approaches to structural reliability assessment.

2.6 ASSESSMENT STAGES

Bridge assessment normally incorporates an assessment of the condition of the structure followed by a structural assessment to determine load capacity. During the condition assessment, only the essential components of the structure are inspected in order to take safety measures if public safety is concerned (e.g., traffic restrictions or, in extreme cases, closure of the bridge). This condition assessment is very basic and consists of examining existing documents and visiting the bridge for a preliminary inspection. In many cases, this inspection may identify particular conditions which need to be investigated using more detailed methods in order to determine their cause, extent, etc, and consequently their effect on structural behaviour and carrying capacity.

All this information ultimately feeds into the structural assessment which consists of determining the strength of the bridge in relation to the loads which the bridge is expected to carry.

The following stages of bridge assessment can be identified:

Study of documents:
Design and inspection documents contain important information that is necessary for a thorough assessment of an existing bridge. These documents must be verified with respect to correctness and in particular whether they were updated after previous alternations to the structure.

Preliminary inspection:
A preliminary inspection is a quick and inexpensive inspection performed by a competent bridge engineer. The aim of a preliminary inspection is to identify the structural system and possible damage by visual observation using simple methods. The information collected is related to aspects such as surface characteristics, visible deformations, cracks, etc. The results of the preliminary inspection indicate in qualitative terms the condition of the bridge, e.g., no damage, minor damage, serious damage, etc.

The function of the preliminary inspection includes the identification of aspects related to the condition and safety of a structure. This may lead to further investigations, or special inspections, necessary to perform a precise diagnosis, to obtain a quantitative reliable assessment versus structural safety, or to propose a rehabilitation or repair programme.

Supplementary investigations:
Supplementary investigations can include:

- various inspection methods, including material sampling, non-destructive testing, etc;
- updating the drawings, section dimensions and details of the structure;
- assessing the materials properties.

Supplementary investigations can be initiated by reviewing the available documents:

- drawings, specifications, structural calculations, construction records, inspection and maintenance records, details of modification;
- regulations and by-laws, codes of practice which were used for construction;
- topography, subsoil conditions, groundwater level at site.

The details and dimensions of a structure, as well as characteristic values of material properties, can be obtained from design documents, provided the documents exist and the information is reliable. Where any of the essential information is in doubt, details and dimensions of components and properties of materials assumed for the analysis should be determined from a detailed inspection and materials testing. The planning of such an investigation is based on information that is already available. One of the major problems is the way in which this additional information is used. It is necessary to check the real geometry of the bridge, especially the width of some structural parts. For older bridges, documents are often not available and it is therefore useful to proceed to a full geometry study based on numerical analysis of photographs.

Structural assessment:
Assessment must take account of the condition of the structure by making due allowance for the loss of resistance as appropriate. For example, the cross-section of members in steel bridges should be reduced if significant corrosion is present. Similarly, concrete can suffer loss of resistance loss due to chemical attack. Important cracking can modify the sectional rigidity and therefore the influence the distribution of load through a bridge deck. The position of reinforcement inside the concrete can differ from the design.

Structural condition should be determined by analysis or measurements. Static or dynamic testing on the structure can be used to characterise the structural behaviour and/or to predict a load capacity when other approaches such as detailed structural analysis or inspection alone do not provide clear information or have failed to demonstrate adequate structural reliability. Supplementary investigations provide additional information which can be used to improve the structural assessment.

Structural assessment must be carried out with care because during the design stage, little information is available regarding the load which the bridge will ultimately carry. Very often, the assessment must take account of the fact that structure was designed using old standards.

The structural analysis can be carried out using basic principles of structural behaviour, or by more sophisticated methods such as finite element analysis. In general, the mathematical models used are linear and elastic. In order to make it representative, the structural assessment must include the true geometry of the structure, the real construction process and, if appropriate, the loss of resistance of the materials. Non-linear models can be used to provide further information for explaining local phenomena. Other problems (cracks, damage models, etc) require special models or repair programme.

At the end of this stage, the need for repair, rehabilitation, etc, will be identified. The conclusions should be supported by a technical and economical study for the different alternatives to helps the owner make the decision on the available options.

2.7 EXPERIMENTAL TECHNIQUES AS PART OF ASSESSMENT

Experimental measurements made as part of a site investigation can be categorised as follows:

- testing to determine unknown dimensions and quantities, e.g., size and depth of reinforcement;
- material testing using extracted samples or non-destructive tests to determine material properties or presence and extent of deterioration;
- long-term monitoring of structural behaviour, e.g., structural deformation, temperature, crack width, prestress force, etc;
- dynamic measurements, e.g., from wind or traffic loading;
- laboratory tests on components;
- on-site load testing.

In some cases, it is necessary to determine the size and position of reinforcement, prestressing elements, concrete cover, etc. Non-destructive testing methods are particularly suitable for such investigations. In general, however, it is evident that non-destructive material testing is not in widespread use across Europe in spite of the rapid advancements of processes during the last few years. Material tests form an important prerequisite for an effective structural assessment. Such investigations are geared towards acquiring reliable information on the characteristic condition of the materials used. With the help of material samples obtained at non-critical points, physical and chemical laboratory analysis can be used to determine:

- Strength of concrete, steel, reinforced concrete, prestressed concrete;
- Condition of concrete, e.g., depth of carbonation, depth and extend of chloride penetration, presence of ASR, etc;
- Corrosion of steel components and reinforcement.

For the determination of carrying capacity, non-destructive testing can provide useful information on presence and extent of defects, e.g.:

- Determination of loss of prestressing force;
- Determination of rupture in prestressing tendons;
- Detection and quantification of corrosion in reinforcement
- Detection and quantification of fatigue cracks in steel members
- Determination of crack depth and geometry in concrete.

A further benefit of these techniques is that they can formulate a methodology to help avoid additional weakening of the structure already exhibiting signs of damage. A list of techniques used on site and in the laboratory is included in Appendix 3.

Structural measurements in the form of load tests for determining carrying capacity are used very rarely, usually as supplements to analytical calculations to determine actual structural behaviour. Depending on the required function and scope of the measurement variables involved, automatic online recording and evaluation systems can be used.

3 BRIDGE INVENTORY

3.1 EXISTING BRIDGE STOCK

The bridge inventory across Europe forms the objective basis for developing relevant techniques for structural assessment which can be standardised for future implementation on an international scale. It is expected that the different climate, environmental effects, construction practices, etc, in the different countries will give rise to different problems which will have an effect on how bridges are managed. It is useful therefore to examine information on the composition of the bridge stock, and the condition of the bridges in terms structure type, geometric relationships such as spans and bridge areas, age, etc. The data listed in table 1 refer in general to the nation-wide highway and trunk road network. It should be noted, however, that in most cases this is only a small proportion of the overall bridge stock, as bridges managed by local authorities are not included. In the UK, for instance, there are approximately 150,000 bridges. Of these, only about 13,000 are owned directly by the government, the remainder being the responsibility of local authorities and private owners such as Railtrack, London Underground and British Waterways. The government owned bridges are further split between Highways Agency bridges (i.e., those in England), and those owned by the Scottish Office, Welsh Office and the Northern Ireland Department of the Environment. Thus the statistics in table 1 are heavily biased towards to more recent, long span bridges.

Country	France	Germany	Norway	Slovenia	Spain	UK
Number	21549	34824	9163	1761	3911 1)	9515 2)
Area [1000m²]	7878	24349	2300	660	N/A	5708 2)

Table 1: Bridge stock of national highway networks in the participating countries.

1) Number of bridges recorded until 1996
2) Bridge owned by the Highways Agency, i.e., in England only

Tables 2 to 5 and figures 2 to 5 contain data supplied by the participating countries on bridge type and condition. The following categories are used in accordance with the main structural material used:

- Steel (and iron) [ST]
- Composite steel [ST-COMP]
- Stone [S]
- Concrete [C]
- Reinforced concrete [RC]
- Prestressed concrete [PC]

These categories are country specific in that country defines bridge type in slightly different ways. Thus in the following tables, some of the above categories are grouped together. They nevertheless allow evaluation and comparison in general terms.

In France and Germany, there is a predominance of reinforced concrete over prestressed concrete as far the number of structures is concerned, although this order is reversed when it comes to bridge areas. This is because the longer span concrete structures tend to be prestressed. The bridges built from concrete, reinforced concrete and prestressed concrete are summarised for the other countries. The proportion of steel and steel composite bridges in all countries is notably lower: Norway exhibits by far the largest proportion with roughly 23 per cent (quantity) and 29 per cent (area) of its bridge stock in this category (see tables 2 and 3).

Three classes were formed for determining the age structure, i.e., less than 20 years, 20 to 40 years, and more than 40 years. Based on these categories, an evaluation of the number of structures showed that less than 20 years old bridges predominate except in the UK. With the exception of Slovenia, bridge more than 40 years old are rarest (see table 4). It should be remembered that only the highway and trunk road bridges are included here. Thus the numerous older short span bridges common on rural and urban roads are not considered.

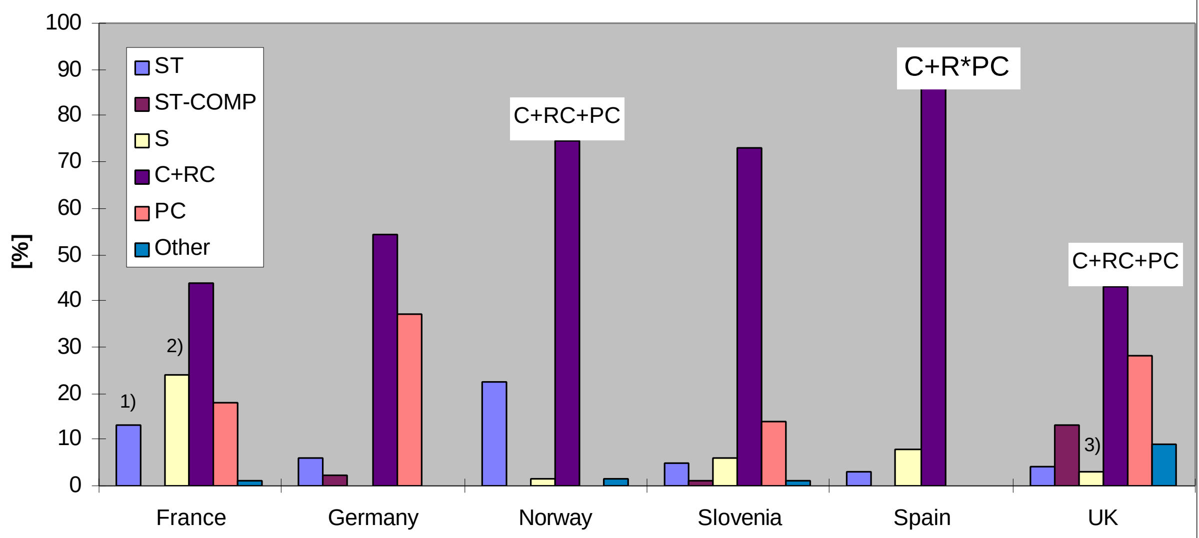
Division in accordance with bridge length (between the abutments) reveals a nearly equal distribution among all countries. The proportion is more than 80 per cent for lengths of up to 50m, and considerably more than 90 per cent for lengths of up to 100m (see table 5). These common features prove favourable for determining marginal conditions and the scope of validity of the traffic load simulation model to be developed in Workpackage 3: ”Traffic loads”. More information will be given in deliverable D5: ”Development of models (traffic and material strength)”.

Country	Year	ST	ST-COMP	S	C + RC	PC	Other
France	1996	4 + 9 1)		24 2)	44	18	1
Germany	1997	6,1	2,3	54,4		37,2	-
Norway	1996	22,5		1,3	74,6		1,6
Slovenia	1998	5	1	6	73	14	1
Spain	1996	3		8	89		-
UK	1997	4	13	3 3)	43	28	9

Table 2: Different bridge types as a proportion of total bridge stock (%).

1) Steel-construction and metal culvert
2) Masonry
3) Arch

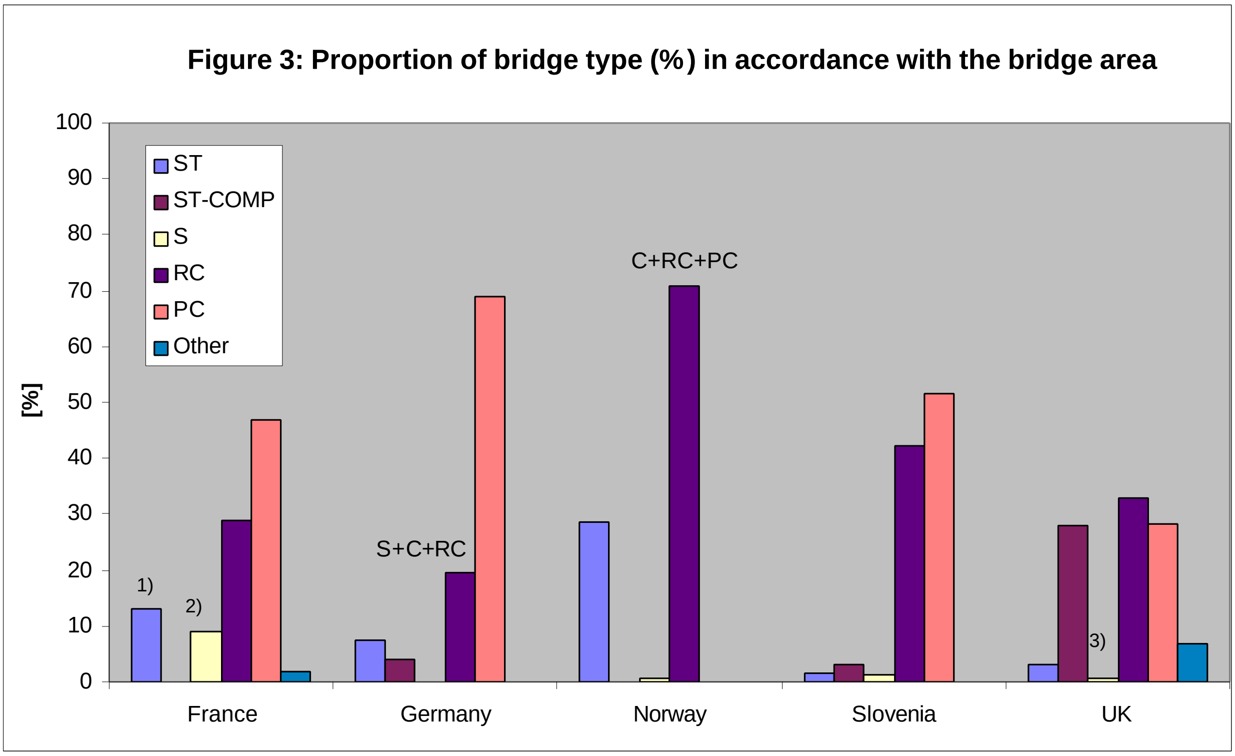
Figure 2: Different bridge type as a proportion of total bridge stock (%)



Country	Year	ST	ST-COMP	S	C + RC	PC	Other
France	1996	9 + 4 [1)]		9 [2)]	29	47	2
Germany	1997	7,5	4,0	19,5		69,0	-
Norway	1996	28,6		0,6	70,8		-
Slovenia	1998	1,6	3,2	1,3	42,3	51,5	0,1
UK	1996	3,1	28,1	0,7[3)]	32,9	28,3	6,9

Table 3: Proportion of bridge type (%) in accordance with the bridge area.

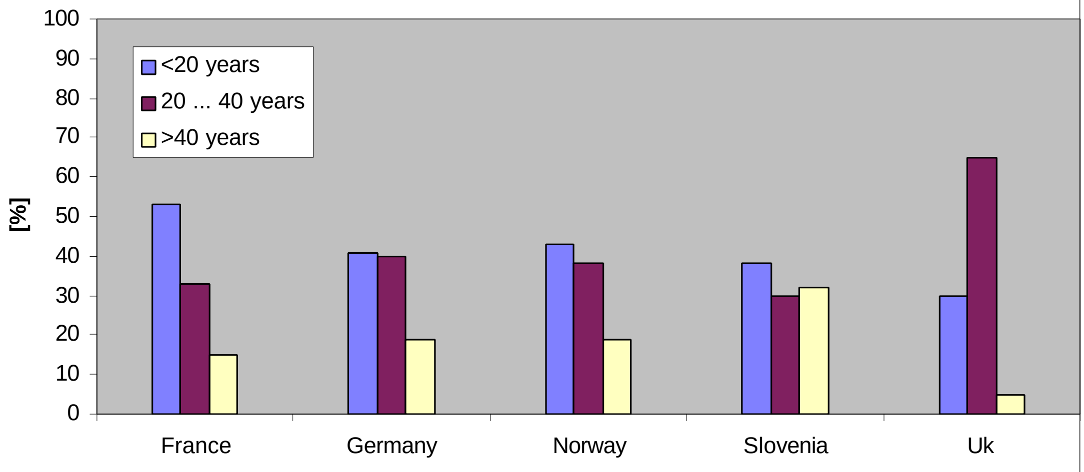
1) Steel-construction and metal culvert
2) Masonry
3) Arch



Country	Year	< 20 years	20 ... 40 years	> 40 years
France	1996	53	33	15
Germany	1997	41	40	19
Norway	1996	43	38	19
Slovenia	1998	38	30	32
UK	1997	30	65	5

Table 4: Age distribution (%) in accordance with the number of structures.

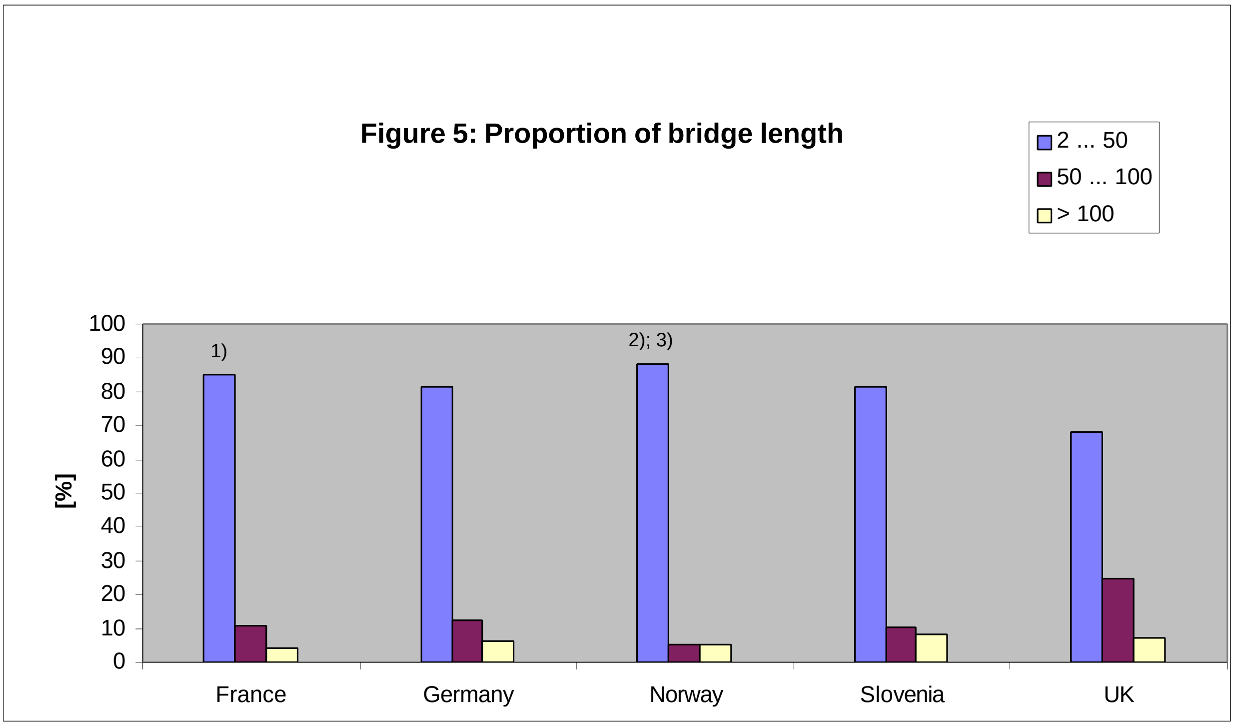
Figure 4: Age distribution (%) in accordance with the number of structures



Country	Year	2 ... 50m	50 ... 100m	> 100m
France	1996	84,7 [1)]	10,6	4,1
Germany	1997	81,5	12,5	6,0
Norway	1996	88,2 [2), 3)]	5,4	5,1
Slovenia	1998	81,2	10,4	8,4
UK	1998	68	25	7

Table 5: Proportion of bridge length [%].

1) 0,6% < 2,0m
2) 2,5 ... 50m
3) 1,3% : Lengths unknown



3.2 SIGNIFICANT STRUCTURAL DAMAGE

The basis of all maintenance strategies is the acquisition of information on the current condition of the structures. For this purpose, structures are inspected in accordance with specific standards at regular intervals. The occurrence of damage and defects is used to determine deterioration rates which, in turn, serve as criteria for making decisions concerning maintenance and rehabilitation measures.

For the purpose of avoiding damage, however, it is even more important to obtain conclusions concerning the causes of different types of deterioration. These findings can be used to updated and supplement existing sets of technical rules for design, construction, repair and rehabilitation of brides. For example, in the UK, a detailed survey was carried out on a representative sample of 200 bridges to determine the type, extent and causes of deterioration, and attempted to determine the costs associated with rehabilitating the bridge to ideal condition. The survey is reported in /12 /. Subsequently, standards for the design of durable bridges were produced. Similarly Documents relating to the deterioration of bridges and other engineered structures /1,2/ were prepared in 1982 and 1994 by the German Ministry of Transport. The types of deterioration described in these documents do not form part of a statistical survey of the existing inventory of bridges. Rather, the documents provide examples of significant types of deterioration as well as appropriate techniques producing durable bridges. The documents draw the attention of all involved parties, road construction authorities, engineering agencies, manufacturers of building materials and construction companies, to this problem.

Deterioration can be subdivided into 3 different types:

- Deterioration arising from faults in design, building materials or components;
- Defects due to the construction method or occurring during the production process;
- Deterioration caused by external influences.

Table 6 gives an overview of the major types of damage or deterioration which may influence load carrying capacity of a structure or components. This is only a first view on the problem of deteriorated bridges which will be dealt with in more detail in Workpackage 3: ”Modelling of deteriorated structures”. Information on the effect of deterioration on strength and how it can be taken into account in assessment will be presented in deliverable D11: ”Assessment of deteriorated bridges”.

Cause	**Affected component**
Structural damage	
Foundation, soil pressure	Foundation
Design, calculation	Whole structure
Construction	Concrete or masonry structure Prestressed concrete structures in general Prestressing technique Steel and composite steel structures Bridge cables and cable components
Pavement and waterproofing	Bridge deck, substructure
Inadequate protection against de-icing agents and other aggressive substances	Concrete structures
Inadequate protection against corrosion	Concrete structures Steel structures
Inadequate components	Bearings Expansion joints Water drainage Others
Inadequate inspection and maintenance	Whole structure
Accidents	
Excavations and foundations Scaffolds Construction techniques	Structure
Averages	
Overloading Vibration, explosion, impact Fire, flooding Environmental factors, not known during design Mining Inadequate reconstruction or maintenance measures	Structure

Table 6: Overview of bridge damage.

Many types of deterioration are present in the European bridge stock and these are similar form and extent in the countries covered by the consortium. These are listed here

General:

- ASR (reinforced and prestressed concrete structures)
- Carbonation (reinforced and prestressed concrete structures)
- Ingress of chloride (reinforced and prestressed concrete structures)
- Inadequate freezing resistance (reinforced and prestressed concrete structures, masonry)
- Inadequate waterproofing
- Inadequate surface drainage
- Faulty bearings and expansion joints
- Damage resulting from overload and a rise in traffic flow
- Reinforced concrete structures:
- Deficiencies in reinforcement techniques
- Corrosion of reinforcement elements due to an inadequate concrete cover
- Inadequate concrete quality

Prestressed concrete structures:

- Corrosion of prestressing elements
- Inadequate injection grouting
- Shrinkage and creep
- Formation of cracks

Steel structures:

- Inadequate corrosion protection systems
- Corrosion as a result of insufficient maintenance
- Material fatigue

Arches made of brick and natural stone:

- Splintering of joint mortar
- Damage to parapets
- Damage to seals / damage resulting from frost

- Brick and arch ring separation
- Settlements

Special aspects related to individual countries exist in addition to these generally types of damage:

France:

- In the case of cable and suspension bridges, corrosion and fatigue of steel cables and embrittlement of old cable structures.

Germany:

- Cracks in the coupling joints of box girders made of prestressed concrete.
- Crack corrosion in the case of old prestressed steel elements.
- Poor condition of old structures in the new federal states resulting from the inadequate maintenance in the former German Democratic Republic.

Norway:

- Exposure to sea water (corrosion by chloride)

Slovenia:

- Severe damage caused by de-icing agents on prefabricated elements made of prestressed concrete, accompanied by a complete failure of prestressing elements in some cases.
- Inadequate maintenance of wooden components.

UK:

The main causes of deterioration have been found to be:

- Corrosion of steel;
- Alkali-silica reaction;
- Concrete carbonation;
- Frost damage;
- Sulphate attack;
- Conversion of high alumina cement concrete;
- Structural damage from vehicle impact.

The most common defects found in highway bridges are cracking, staining and spalling of concrete resulting from the corrosion of the reinforcing steel. These can occur even in areas that appear to be protected from detrimental environmental conditions. The absence, or failure, of waterproofing membrane may allow the migration of salt-laden water to even the most protected areas. Spray from passing vehicles can result in deterioration of bridge elements well above the road surface. Bridge movement joints contribute seriously to the problem, particularly where poor detailing, inadequate joints or lack of proper maintenance allows the run-off to flow over the sub-structure. As a result, few bridge components are safe from chloride attack. A particular problem has been the corrosion of prestressing tendons in post-tensioned structures and a programme of detailed inspections is being carried out. This has been largely solved for new construction following the publication of improved grouting specifications.

Other types of deterioration have been found in UK bridges but not on a wide scale.

3.3 THE INFLUENCE OF SIGNIFICANT TYPES OF DAMAGE ON THE DEVELOPMENT OF DESIGN CODES

The influence which the identification of structural deterioration has on the development of design codes differs among the various countries involved in the project. One of the objectives of updating the codes is to improve structures in terms of robustness, durability and maintenance requirements. In view of the diversity of the measures involved, in terms of dimensioning, design, as well as material quality, some typical examples, most of which are applicable to all countries, are provided. These include rules:

- for increasing the **concrete cover** for more reliable corrosion protection of reinforcement against carbonation of concrete and the ingress of chloride ions;
- for restricting the **crack width** for increased durability of concrete structures through the introduction of appropriate verification techniques and limitation of reinforcement diameters;
- for **minimum content of reinforcement** to make allowances for tensile stresses, i.e., resulting from shrinkage and temperature deformations in surface near sections of reinforced concrete structures;
- for **minimum dimensions** related to (usually secondary) structural elements with the aim of producing robust structures with low maintenance requirements;
- for **producing, processing and quality assurance of concrete**, i.e., for concrete composition to avoid ASR; additives for increasing freeze-thaw-resistance; surface protecting systems;
- for the **corrosion protection** of steel structures, i.e., development of improved corrosion protection systems.

The following country-specific developments and special aspects, which do not necessarily provide a complete picture, also deserve mention.

France:

- Updating and improvement of national codes for reinforced concrete, steel and prestressed concrete bridges;
- ASR recommendation in 1994;
- Introduction of a technical directive by SETRA (1975) for considering the influences of temperature, contractions and creeping, local effects, etc;
- Improvement of shrinkage and creep laws considered in design codes for prestressed concrete bridges;
- Inclusion of fatigue verification based on EC 3 in the national code for steel bridges;
- Structural modification of pavement plates on composite steel bridges;
- Replacement of steel cables susceptible to tension cracks;
- Implementation of a new cable technology.

Germany:

- Regular updating of basic standards, for reinforced concrete and prestressed concrete as well as standards for concrete bridges and steel bridges, also in accordance with the above-mentioned regulations;
- Development and systematic updating of ”Additional Technical Contractual Conditions”; ”Additional Technical Contractual Conditions for Engineering Structures”.
- For example, a rise in the occurrence of cracks in the joints of tendons of continuously prestressed concrete segmental superstructures led to changes in DIN 4227 and the ”Additional Technical Contractual Conditions for Engineered Structures”;
- Publication of ”Guidelines for the design of structures”;
- Preparation and continuous updating of a set of standard drawings for construction details, taking into account aspects relating to inspection and maintenance;
- Preparation of a catalogue titled ”Immediate Maintenance of Bridges” for structures in the five new federal states, in order to quickly offset maintenance deficits.

Norway:

- Prohibition of the use of sea water in concrete;
- Improvements in design for the purpose of increasing durability, i.e., functional and effective surface drainage systems, simpler detailing of steel bridges in terms of more reliable corrosion protection, aeration systems in box girders made of steel and design-related measures for bridge inspections and maintenance.

Slovenia:

- In the past, the influence of findings concerning bridge damage on the development of codes for bridge design has not been as strong as in other countries. At present, Euro codes are being introduced in order to eliminate deficits.

Spain:

- As part of updating sets of codes, particular attention has been paid to aspects relating to durability through appropriate supplements.

UK:

- The design guidelines contained in British standards and in the National Standards have been revised from the perspective of different types of damage. For example, particular emphasis has been placed on a concrete quality assurance and surface protection to prevent corrosion. Testing techniques for aggregates are being employed to prevent ASR, and sulphate-resistant cement is used wherever the indications for this exist. To increase freeze-thaw-resistance, air-entrained concrete is used for surfaces exposed to this factor;
- A document entitled ”Design for durability” was produced to avoid future maintenance problems.

4 BRIDGE ASSESSMENT IN THE COUNTRIES PARTICIPATING IN BRIME

4.1 ASSESSMENT STANDARDS

The UK is the only one of the countries participating in BRIME to have an established procedure for bridge assessment supported by a comprehensive set of documents. Elsewhere, the load carrying capacity of existing road bridges is normally assessed using design rules. In many cases, where the bridge in question does not comply exactly with the design rules, engineering judgement must be exercised by the engineer in charge of the assessment drawing on his experience to interpret the rules and to reach a sensible conclusion. The extent to which engineering judgement is permitted varies between the countries.

Among the assessment documents available in countries other than the UK, the following have been identified.

In **Germany** in 1990, following German reunification, differences in design loading between east and west made it necessary to reassign 5600 bridges to load classes in accordance with DIN 1072 in the federal road network of the former East German states. To support road building administration in the former East German states, special guidelines /3/ for the assessment of bridges were prepared for the first time. These guidelines contain details on standards, principles of design, evaluation of structural condition and the rating technique. The appendices to the guidelines contain examples of application.

In **Norway**, rating procedures for existing bridges are described in the manual titled "Bridge classification". A new edition is currently being prepared. It contains five chapters dealing with the following topics:

- Service loads subdivided into four load levels, three levels of exceptional heavy transports also being defined.
- Material properties, taking into account the age of the bridge, load and material factors.
- Sample calculations.
- Design loads, used for public road bridge construction through the years.
- A presentation of standardised (normalised) bridge design drawings used in public road bridge construction for the period 1912 - 1958.

In **Slovenia**, a technique for evaluating the safety of existing bridges was developed in the mid-Nineties; however, this technique has not yet been introduced as an obligatory measure as part of assessment guidelines.

The main documents currently used for bridge assessment in the **UK** are listed in Appendix 2. and are contained in the Design Manual for Roads and Bridges. They cover assessment loading, a definition of which bridges have to be assessed, methods for assessing outmoded types of bridge, the effect of deterioration, and the actions to be taken if the ability of a bridge to carry full assessment loading cannot be demonstrated. Separate assessment standards are available for steel, concrete and composite-steel bridges. They are based on the corresponding design standards but contain numerous changes to reflect the difference between design and assessment. Engineering judgement may still be exercised subject to the agreement of the Technical Approval Authority, but many difficult assessment problems are now covered explicitly in the documents.

It should be noted that Standards, identified by the letters BD, are mandatory and Advice Notes, identified by the letters BA contain background information and recommendations, but are not mandatory.

4.2 ASSESSMENT PRINCIPLES AND METHODOLOGY

Chapter 2 discusses the principles of bridge assessment and their application. In Chapter 4, the principles and methodology as currently adopted in the individual countries participating in BRIME are described.

France

The basis of assessment calculations in France is the same as for the design of new bridges. The assessment is performed for bridges in a poor condition and with potential problems. Structural analysis may be carried out using elastic, plastic or non-linear methods. In general, the Ultimate Limit State is used for reinforced concrete, the Service Limit State for prestressed concrete, and a calculation based on a failure criteria is applied to masonry bridges. There are no particular rules applied to specific types of structures and no official rules for assessment.

Safety coefficients may be reduced, for example, for materials or dead loads. Structural models used for assessment may be more detailed or closer to reality. The actual behaviour of the structure may be taken into account with the help of laboratory investigations and measurements.

Germany

- In Germany, the standards and other regulations used in the design of new bridges apply equally to the assessment of existing structures. No reduction is permitted in the specified safety levels for assessment compared with design.
- Assessment is normally restricted to calculations at the ULS using a standard, general safety factor of

  $\gamma = 1.75$ in the case of structural failure with advance warning and

  $\gamma = 2.1$ in the case of structural failure without advance warning.

  This is in accordance with the conservative design standards DIN 1045 (for concrete and reinforced concrete) and DIN 4227 (for prestressed concrete). In the case of prestressed concrete structures, an additional assessment must be performed for stress at working loads. The use of the partial safety method in accordance with the principles of the Euro code is allowed for assessing the carrying capacity of existing road bridges, but still constitutes an exception.
- Current practice takes into consideration local overloads resulting from a redistribution of forces in the structure, for example, peak loads in the zone of obtuse angle of slab bridges, as well as a distribution of cracks in reinforced concrete during the determination of bending moments and shear forces. The competence, knowledge

and experience of the engineer in charge of the analysis are therefore of particular importance in this case.

Instructions are contained in /3,5/ for the evaluation of structural condition. In accordance with these instructions, engineers must verify the validity of the cross-section measurements and material characteristics underlying the analysis of the load effect present at critical points, taking into account any signs of damage or deterioration detected on the structure. This evaluation must consider the present condition and the durability, taking into account the expected progression of damage or deterioration. If required, instructions must be issued to specify the conditions under which the assessed capacity will be determined in future, and whether further tests are necessary.

In the states of former East Germany, regulations /6,7,8/ for assessing existing bridges were prepared to serve as aids for engineers; these regulations have proven themselves in practice. In the absence of any other regulations at present, they are therefore still used by the five new federal states when evaluating the carrying capacity of existing bridges, for example, for filler beam deck bridges. Principles for simplifying the assessment were formulated in /3,5/. The following provisions are included:

- Assessment has to be performed for components and cross-sections that determine the carrying capacity in perfect condition, as well as those exhibiting damage or deterioration which may impair the carrying capacity.
- Consideration is given to unexpected displacements and rotations at bearing positions and the interaction of sub-structures and super-structures in the case of statically indeterminate systems.
- Procedures are given for cases where bridge records are available and where they are not.
- Instructions are given for taking structural condition into consideration.
- In cases of good structural condition, simplified assessment techniques are given; i.e. assessment is restricted to the "primary loads" load case.

Fatigue assessments are not performed very often as the loading history usually unknown.

Norway

In Norway there are generally no fundamental differences between the original design calculations and the assessment of existing structures, apart from the magnitude of the traffic loads.

Up to 1998, structural assessment was based primarily on the philosophy of the elastic behaviour of materials. The ultimate limit state method, introduced in 1973 for design and now also the only accepted method for assessment, allows for non-linear behaviour. Normally this is restricted to the cross section and member levels. In normal circumstances, structural analysis is still based on linear elastic behaviour. Plastic design (yield line or plastic hinge approaches) has to some extent been used as a supplement to these methods where a high level of loading, close to the assessed capacity, is being called for.

From 1912 to 1957 the design loads consisted of axle loads and configurations just covering the actions from the heaviest permissible ”normal” vehicles. Subsequently, designs have adopted equivalent live loads as a standard. Usually the load level is somewhat greater than actual traffic load at time of construction. Consequently the latter type at loading has a built-in safety factor against overloading and enables the bridge to carry heavier exceptional traffic loads.

Generally, the condition of the bridge and how it affects the calculation procedure, is very much governed by the importance of structural element in question and the consequences of failure.

In general all types of construction are rated according to the ULS method. However, in steel structures containing welded elements and details prone to fatigue, the fatigue life is considered if:

- Live load / dead load ratio is high.
- Traffic intensity is high and / or having a high percentage of heavy vehicles.
- Overloading is expected.

Fatigue calculations apply mainly to welded plate girders, stiffening beams and cross girders, hangers of suspension bridges, high tensile bolts and tendons, so on so forth. However, unknown load history is a major problem in old bridges where the chance of severe overloads is likely to have occurred. In recent years new concrete bridges are also checked against crack width criteria in SLS.

Slovenia

The general principles of the assessment methods are the appraisal of the present condition of the structure or its part and its influence on the safety and/or durability of the whole structure or its part.

In most cases elastic analysis is performed. In addition, a procedure for safety assessment of existing bridges has been developed. For the time being safety aspect is taken into account only in some exceptional cases. Two types of safety calculation are used: the probabilistic *safety index* ***b*** and the deterministic *rating factor RF*.

The procedures are described in /9/, /10/.

Spain

As a rule, ULS is used to determine the carrying capacity of existing road bridges; SLS is also used in some cases though; fatigue limit state constitutes an exception. However, no special regulation exists.

UK

The underlying principles for bridge assessment in the UK are consistent with those for design as set out in British Standard BS5400. This has been the case since the assessment standard BD21 was first issued in 1984. In general, structures are assessed by the application of limit state principles using appropriate partial factors for load, load effects and member resistance (i.e. a semi-probabilistic approach).

Since then, research into assessment has led to a great many improvements in the assessment documents. The primary aims have been to respond to the differences between new design and assessment, to raise the assessed capacity of bridges as much as possible, without a reduction in the level of safety, and to allow bridges to remain in unrestricted service without strengthening as far as possible.

Assessment is carried out primarily at the ultimate limit state using assessment loads and material properties with partial factors as specified in the assessment Standard BD 21. Provided the structure shows no significant signs of distress, the serviceability limit state is deemed to have been satisfied by the previous in-service behaviour of the structure and is not checked by calculation unless this is specifically required by the Technical Approval Authority. (The Technical Approval Authority is, for example, the Highways Agency for national roads in England and local authorities for local roads).

The rules for assessment are given in detail in the assessment Standard BD 21 and Advice Note BA 16. These documents cover the general principles to be adopted and specify methods of analysis for load effects and member resistance for some outmoded forms of construction. Separate documents are available for determining the resistance of steel (BD56, BA56), concrete (BD 44, BA44) and composite (BD61, BA61) bridges and components (see Appendix 2). The assessment documents are issued by the Highways Agency for England and in most cases by similar bodies in the other territories of Scotland, Wales and Northern Ireland) that comprise the UK.

Cast iron structures are assessed using permissible stress calculations as defined in BD 21, using special partial factors and restricting stresses to levels that would exclude the risk of fatigue failure. In other metal structures fatigue is assessed where appropriate.

Masonry arch bridges can be assessed at the ultimate limit state. However, unless a suitable rigorous analysis is used, they are assessed using a simplified analysis (termed modified MEXE) which is presented in the assessment Advice Note BA 16.

Elastic methods of analysis are acceptable as lower bound solutions for the ultimate limit state. For some outmoded forms of bridge deck, simplified methods of analysis are given in BA16, the choice of which depends on the structural form and the required degree of accuracy. Non-linear and plastic methods of analysis can be used provided a number of conditions are satisfied: for example, there is an adequate plateau of resistance, plastic bending does not cause reduction in shear capacity, supports can withstand elastic loads, and changes in geometry due to deflections are taken into account;

The assessment standards for each type of structure are based on the corresponding design codes for steel, concrete and composite bridges. This achieves a degree of uniformity in the techniques being applied and makes it easy for engineers familiar with the design documents to carry out assessments. The principles are identical, except that the bridge engineer can expect to be able to produce a more realistic strength evaluation by taking advantage of information available to him which was not available at the design stage. Many conservative measures built into the design codes have been modified for assessment purposes. These are as follows:

- *Specified design loading:*

  Bridge design loading takes account of all possible uses of the bridge, irrespective of local conditions and includes the effects of impact, lateral bunching of traffic, over-loaded vehicles and various load combinations. It also includes an allowance for future development and an increase in vehicle weights. For assessment this allowance is not applied. In addition bridge-specific loading can be used as defined in BD21 which allows reductions in loading for low traffic flow and good road surface condition. To take advantage of this provision, road surface and traffic conditions must be determined.

- *Partial safety factors for loads:*

  Permanent loads and super-imposed dead loads can be determined by site inspection and measurement, so that partial safety factors can be reduced to more appropriate values.

- *Material strength and partial safety factors:*

  Initially, assessment is carried out using the characteristic values of material strength used in design or found in construction records with design partial safety factors. If the calculated bridge strength is insufficient in-situ material strengths are obtained (by testing) which may be used with reduced partial safety factors as defined in the assessment standards.

- *Limits on material strength:*

  It is normal practice to place limits on the material strengths used in resistance formulae. This is sometimes a result of limitations on the range of test results available at publication of the code. The result is that very often the assessment engineer cannot make use of a high in-situ material strength where this is present in a bridge structure. In some cases, testing has shown that such limits can be removed or relaxed, leading to less conservative strength evaluation. In the UK, these limits were removed in devising the assessment documents where experimental data were available.

- *Conservative assumptions in design methods:*

  Many of the design equations for the determination of member resistance are based on experimental evidence which have been interpreted, rounded off, or simplified in a conservative manner. This approach has been adopted so that a safe design is produced. For assessment, these conservatisms have been removed on the basis of experimental evidence to provide a more accurate strength evaluation.

- *Unquantifiable reserves of strength:*

  In many bridge types, particularly older short span bridges, there are reserves of strength which are not taken into account in conventional analysis. Load testing for research purposes has demonstrated that there can be significant reserves of strength arising from a number of physical actions. This is an area where load testing can be used to identify potential reserves of strength and to quantify the additional strength for use in the assessment calculations.

- *Non-compliant details:*

  Design codes contain many restrictions on detailing – for instance on the anchorage length of reinforcing bars in tension. To a first approximation, any non-compliant detail constitutes an assessment failure, or at least a drastic reduction in strength. Where data can be provided to calculate the resistance of such details, the value calculated may be low but still sufficient for the purpose.

- *Weakness:*

  The above points concentrate on areas where bridge strength might be higher than the calculations suggest. Even more importantly, there are areas where potential weaknesses might exist which, if not identified, can produce an unsafe strength assessment. Examples are design faults, bad detailing, impact damage, deterioration from corrosion or normal wear and tear, quality of construction materials, etc. The assessment documents specify that these must be taken into account in determining load carrying capacity (see below).

The condition of the structure must be taken into account in determining capacity. Specific documents have been formulated which give advice on how the structural effects of different forms of deterioration can be taken into account, e.g. BA51: The assessment of concrete structures affected by steel corrosion; BA52: The assessment of concrete structures affected by alkali-silica reaction.

Where the form of deterioration is not covered, engineering judgement should be used to determine the effect on strength. The allowance for future deterioration should also be taken into account where appropriate.

4.3 EXPERIMENTAL TECHNIQUES

In the UK, the standard BD54/1994 titled "Load Testing for Bridge Assessment" is used to specify details and limits pertaining to load experiments. A bridge census and sample survey in the year 1987 predicted that a lot of older bridges would be found to be substandard when assessed using the standard calculation methods. In BD 54 it is pointed out that methods used for calculating the resistance model for assessment purposes are generally conservative. Against that load testing can be used advantageously to identify the hidden reserve strength of individual bridges.

In BD 54 a list of bridge types is given, for which load testing my be usefully employed:

- Small span bridges where either a single axle or a two-axle bogie could simulate the required traffic effects.
- Older bridges, of construction types now mainly unused, for which structural idealisation is particularly difficult.
- In general, bridges without internal structural complexities such as transverse girders.
- In general, bridges which can be termed as simply-supported.

Failure due to inadequacy with respect to shear can be sudden and hence it is not envisaged that load tests will be used for aiding assessment of bridges for which inadequacy in shear is suspected from preliminary assessment, unless the load levels can be kept sufficiently low and extra care is taken during the tests.

In Germany, a research project titled EXTRA II and intended for an experimental evaluation of the support safety of bridges is being implemented on-location by a co-operative venture comprising the universities of Bremen, Leipzig, Dresden and Weimar under the commission of the Federal Ministry for Education, Sciences, Research and Technology. Following completion of this research project in 1998, its results are to be made available for practical use through the preparation and introduction of corresponding guidelines. In Germany, load tests of bridges are only performed in individual cases. The use of bridges in the trunk road network has been regulated since 1994 by the ordinance of the Federal Ministry of Traffic titled "Experimental Evaluation of the Support Safety of Structures".

In summary, it can be established that the results of experimental testing of structures for an analysis of carrying capacity can be used for a more precise evaluation of the behaviour of structures, for example, through a comparison between the calculated and measured deformation/strain values or reaction forces. A modification of the selected static model which takes into account support conditions and rigidity distribution and the use of strength characteristics determined through material testing provides an improved picture of real conditions. During such investigations, however, a reasonable balance should be ensured between efforts put in and benefits derived.

4.4 STAGES IN ASSESSMENT

In most of the participating countries, an assessment is initiated primarily if an inspection shows that the condition of the bridge has deteriorated to the point that the carrying capacity needs to be checked. On other occasions the need for assessment may arise if there is expected to be a change in loading – for instance if more lanes are required on the bridge deck or the passage of an exceptionally high load is expected.

The main exception to this is the UK which is currently in the later stages of a 15-year programme of bridge rehabilitation and strengthening that was initiated in 1987. In this programme, all bridges that were not know to have been designed to certain specified standards were to be assessed and appropriate action taken thereafter depending on the assessed capacity. In all cases, the assessments have been preceded by an inspection to check the condition, but the assessment has proceeded even when the condition is perfect. It is proposed in the UK to adopt a management system in which the primary need for maintenance, strengthening or replacement is the level of safety remaining in the structure following an inspection and an assessment.

At another level, the stages in assessment depend on the results obtained for the bridge. If it is shown to have a satisfactory capacity there may be nothing remaining to do – apart, perhaps, for preventative maintenance.

When the assessed capacity is not satisfactory, further action is required.

When, on the completion of an assessment in the UK, the bridge in question is shown to be sub-standard in its load-carrying capacity, BD 21 defines various actions that may be taken including strengthening and restricting the use of the bridge to lighter classes of goods vehicles. One option is to try to raise the assessed capacity by refining the assessment, improving knowledge of the in-situ material properties and re-examining the loading. This process takes time, and one of the issues whether to leave the bridge in unrestricted service during the processes of re-assessment and strengthening.

In 1998, a new Advice Note was issued in the UK (BA 79) that seeks to regularise these procedures. There are two provisions in the Advice Note. The first defines five levels of assessment of increasing complexity that may be used in an attempt to prove that the bridge is not sub-standard – the assumption being that the assessment will commence at a simple level and progress further if necessary. The second provision consists of recommendations for actions in the meantime, while the structure is still provisionally sub-standard. In the case of a bridge defined as presenting an ”immediate risk”, actions to secure safety must be put in place without delay. In other cases the bridge may be left in service with monitoring provided it falls within a class of bridge defined as ”monitoring appropriate”.

The five levels of assessment are defined as follows:

Level 1: Assessment using simple analysis and codified requirements and methods.

This is the simplest level of assessment. Simple structural analysis is applied and partial factors are the same as in the design code. In some respects, therefore, this corresponds to what is done today in the other participating countries. The main differences from design are that the loading is changed from design loading to assessment loading, assessment documents are used which contain numerous relaxations with respect to calculated member resistance and outmoded forms of construction are dealt with adequately.

Level 2: Assessment using more refined analysis

If level 1 leads to unsatisfactory results, more refined structural analysis can be performed (better structural modelling). Records of material strengths are used but the safety factors from the design codes are used as in Level 1.

Level 3: Assessment using better estimates of bridge load and resistance values

Bridge specific loading may be used and in-situ material strengths may be combined with specified reductions in partial safety factors in calculating member resistance.

Level 4: Assessment using specific target reliability

Load and resistance criteria and the associated partial factors may be modified where it is believed that the average criteria used for assessment and applicable to the bulk of bridges may be over-conservative. This may be done through a reliability study or by judgemental changes. Further advice is expected to be issued in due course.

Level 5: Assessment using a full probabilistic reliability analysis

If this form of analysis is used, the Technical Approval Authority should be consulted on the methods and criteria to be used.

5. CONCLUSION

It has been established that bridge assessment among the different partners of the BRIME project is mainly based on design standards and codes. The exceptions are the UK which has a well-developed, formal approach to bridge assessment and Slovenia which is taking some tentative steps towards using reliability theory. All the other countries use standard prescribed design rules and safety factors (partial safety factors or allowable stress factors). Such an approach in the assessment process is not only restricted to the BRIME partners, and numerous other countries are doing the same. Outside Europe, Canada and the USA have already established procedures for assessment that differ from design. For instance, in the USA, different target reliabilities may be used in the two cases.

The question which arises from the study of the different practices can be stated as it follows: is it possible to promote a new assessment procedure which will constitute a general framework flexible enough to allow the use of different ways to assess reliability according to given sophistication levels? The answer is probably yes provided that the framework is presented as guidelines that can be adopted progressively.

It is clear that the principles for the assessment of existing bridges have to be based on an approach that is substantially different from design, and which requires knowledge beyond the scope of design codes. Bridge assessment must be carried out, provided the means are available, in stages of increasing sophistication, aiming at greater precision at each higher level. In order to save structures and to reduce owners' expenditure, the engineer must use all the techniques, all the methods and all the information available in an efficient way. Simple methods are inexpensive and adequate if they show a bridge to have an acceptable load carrying capacity. Advanced methods have to be introduced where simple methods are too conservative.

It has to be said that the problems faced in the context of a bridge rehabilitation programme and of managing bridge stocks require a critical examination of the current assessment rules and procedures. Considerable advances have to be made in the way road bridges are assessed in Europe. To carry out assessments at levels of increasing sophistication seems today an attractive approach that can reconcile the national requirements without excluding advanced techniques. Such a methodology will be developed in a more general matter in deliverable D10. One possible proposal is to use a multilevel procedure as adopted in the UK.

6. SUMMARY

The main objective of WP 2: ”Assessing the load carrying capacity of existing bridges”, is to derive general guidelines for structural assessment. Initially, therefore, detailed information was obtained on current practices and procedures used in different countries by means of questionnaire.

As a first step the report presents general information relating to the principles of assessment, including definitions, objectives, current rules and assessment stages. The verification of the structural safety of a bridge is the main objective of a structural assessment. This may be an explicit process, as for a reliability approach, or an implicit process as for a semi-probabilistic approach. A bridge assessment would be necessary if the conditions of use were modified, if deterioration or damage was detected, or repairs were expected. Bridge assessments might also be required generally, as part of a bridge management system. Methods for bridge assessment can be divided into deterministic, semi-probabilistic and probabilistic methods. Response to the questionnaire showed that the procedures used for bridge assessment vary from country to country.

Chapter 3 covers the main statistical data relative to the national bridge stock in each of the participating countries. These statistics relate primarily to the structures on the motorways and national routes only. This information provides the basis for the proposals for bridge assessment to be developed in WP 2, and for the development of a general model for traffic loads.

In chapter 4, the existing basic rules and the procedures applied for the assessment of load carrying capacity of bridges are presented for the different countries. The procedures used show essential differences. In most of the countries covered by BRIME, design codes are used directly for assessment. In some countries, the design codes adapted in some way, for example, by modifying the partial safety factors used. In Germany, structural assessment is, in most cases, performed using conservative standards taking a single global safety factor into account. On the other hand, the UK has formulated an extensive system of assessment codes which are contained in the Design Manual for Roads and Bridges. Depending on the specific requirements, the assessment procedure for an individual bridge can be performed at a different level of expertise and complexity.

In summary, it can be concluded that a possible common framework for structural assessment can be represented by a multi-level procedure which covers simple deterministic approaches as well as complex probabilistic procedure. This similar to the concepts described in the UK document BA 79/98.

7. REFERENCES

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APPENDIX 1: QUESTIONNAIRE

1. Fundamental information

1.1 Please describe characteristics of existing structures.

A. Bridge stock data (age distribution)

B. Relevant construction types

1.2 Deterioration

1.2.1 What are the significant types of deterioration, e.g. with regard to materials, construction, design calculation procedures?

1.2.2 How was the development of guidelines for design influenced by different deterioration types?

1.3 Please list the usual rules, guidelines or codes for assessment procedures.

1.4. What is the need for assessment, what are the objectives? Please describe fields of application.

1.5 What kind of actions are carried out and in which sequence? Please describe the assessment process.

1.6 Please give additional notes if necessary.

2. Procedures of structural assessment

2.1 General principles of structural assessment

2.1.1 What are the general principles of assessment methods (limit state, serviceability, fatigue limit state)?

2.1.2 Please describe dependencies to different construction types.

2.2 Please summarise indication rules, which are used in structural assessment (assessment of elements and/or the complete structural system, consideration of material properties, uncertainties, load models).

2.3 Calculation procedures

2.3.1 Please describe the basis of calculation procedures for structural assessment (e.g. elastic, plastic, non-linear, safety aspect).

2.3.2 What are the differences between design calculation and analysis of existing structures?

2.3.3 How are condition aspects considered?

2.4 Please give additional notes if necessary (e.g. information on probabilistic procedures, consideration of construction history).

3. Test methods

3.1 Please list usual test methods in the frame of structural assessment:

A. Structural testing (e.g. load, vibration, laboratory testing, monitoring, measurement techniques)

B. Materials testing (e.g. physical, chemical, electrochemical tests)

3.2 How are the test results considered in the frame of analytical structural assessment?

3.3 What is the role and significance of non destructive testing (NDT) for the assessment of bridges?

3.4 Please give additional notes if necessary.

4. Results of structural assessment

Please describe the influence of results of structural assessment on the outcome of alternative strategies.

APPENDIX 2: BRITISH STANDARDS FOR ASSESSMENT

Document Reference	Title	Date of Issue
STANDARDS - BRIDGES AND STRUCTURES (BD SERIES)		
BD 21/97	The Assessment of Highway Bridges and Structures Amendment No. 1	Feb 1997 Aug 1997
BD 34/90	Technical Requirements for the Assessment and Strengthening Programme for Highway Structures Stage 1 – Older Short Span Bridges and Retaining Structures	Sep 1990
BD 37/88	Loads for Highway Bridges	Aug 1989
BD 44/95	The Assessment of Concrete Highway Bridges and Structures	Jan 1995
BD 46/92	Technical Requirements for the Assessment and Strengthening Progr. for Highw. Struct. Stage 2 – Modern Short Span Bridges	Aug 1992
BD 48/93	The Assessment and Strengthening of Highway Bridge Supports	Jun 1993
BD 50/92	Technical Requirements for the Assessment and Strengthening Programme for Highway Struct. Stage 3 - Long Span Bridges	Dec 1992
BD 56/96	The Assessment of Steel Highway Bridges and Structures	Nov 1996
BD 61/96	The Assessment of Composite Highway Bridges	Nov 1996
ADVICE NOTES - BRIDGES AND STRUCTURES (BA SERIES)		
BA 16/97	The Assessment of Highway Bridges and Structures Amendment No. 1	May 1997 Nov 1997
BA 34/90	Technical Requirements for the Assessment and Strengthening Programme for Highway Structures Stage 1 - Older Short Span Bridges and Retaining Structures	Sep 1990
BA 38/93	Ass. of the Fatigue Life of Corroded or Damaged Reinf. Bars	Oct 1990
BA 39/93	Assessment of Reinforced Concrete Half-joints	Apr 1993
BA 44/96	Assessment of Concrete Highway Bridges and Structures	Nov 1996
BA 51/95	The Assessment of Concrete Structures Affected by Steel Corrosion	Feb 1995
BA 52/94	The Assessment of Concrete Highway Structures Affected by Alkali Silica Reaction	Nov 1994
BA 54/94	Load Testing for Bridge Assessment	Apr 1994
BA 56/96	The Assessment of Steel Highway Bridges and Structures	Nov 1996
BA 61/96	The Assessment of Composite Highway Bridges	Nov 1996
BA 79/98	The Management of Sub-standard Highway Structures	Aug 1998

APPENDIX 3: NON-DESTRUCTIVE TEST PROCEDURES FOR CONCRETE BRIDGES

Application	Procedure	Status	Application	Procedure	Status
Concrete strength	Ultrasonic	P	Concrete thickness	Radiometry	P
	Schmidt hammer	P	Concrete quality	Ultrasonic	P
	Ball impact experiment	P		Schmidt hammer	P
	Bolt-firing tool	P		Rebound hammer	P
	Extraction test	P		Irradiation	P
	Shearing test	P		Permeability test	P
Detection and observation	Ultrasonic	(P)	Reinforcement positions	Reinforcement testing device	P
of cracks	Optical waveguide	P		Radiography	P
	Sound emission	P		Radar	P
	Moiré photography	P		Induction-thermography	P
	Holography	(P)			
Corrosion of	Potential technique	P	Corrosion of	Endoscopy	P
Reinforcements	Irradiation	P	tendons and	Radiography	P
			Ducts	Sound technique	(P)
Defective spots	Radiography	P	Pressure points	Endoscopy	P
in concrete	Ultrasonic	(P)	and defective	Radiography	P
	Radar	P	spots on ducts	Sound technique	(P)
Prestress	Core-drill samples	P	Moisture	Microwaves	(P)
and stress	Flat-Jack	P	Measurement	Resistance	P
Measurements	Thermo-elastic stress	L		measurements	
	analysis			Neutron probe	L
	Micro-magnetic	L		Irradiation with	P
	prestress measurement			neutrons	
Detachment zones	Sound technique	P	Permeability	Liquid penetration test	P
in the case of conc.	Ultrasonic	P	Measurements	Pressure gas technique	P
Carriageways	Radar	P		Vacuum technique	P
Monitoring	Vibration analyses	P			
of structures	Sound emission analyses	(P)			
	Measurements of deformation	P			

P Procedure is implemented under operational conditions
(P) Procedure was tested under operational conditions
L Only laboratory applications so far