New strategies for bridge assessment

M. J. Baker, BSc(Hons), DIC, CEng, MIStructE, MICE

C. J. Burgoyne, BA, MSc, PhD, CEng, MICE

Professor P. J. Dowling, BE, DIC, PhD, FEng, FIStructE

Imperial College of Science & Technology, London

SUMMARY

This paper discusses a number of concepts which together could form the basis for a new approach to bridge assessment. In particular, attention is paid to the need for different safety factors when assessing as opposed to designing structures, the effect of redundancy, the problems of localised failure mechanisms and the use of reliability analysis.

INTRODUCTION

The problems of bridge assessment and the need for their repair, strengthening and replacement are issues which have become increasingly important in the 1980's, not only in the UK, but in other countries as well. The need for bridge strengthening and replacement has come about not only because of damage and deterioration caused by environmental effects, but also because of an increase in highway bridge loading. In addition to increases (and probable further increases) in maximum permissible vehicle weight, there have been significant changes in the proportion of fully laden vehicles, especially on some routes and especially at times of day when other traffic is light.

It is ironic, however, that the general view held by many engineers is that structural assessment is a more difficult task than initial design. Yet in the former case, the structure physically exists and is available for study, testing and measurement, whereas in the case of a new design the structure exists only in the form of drawings, calculations and specifications. This view, if correct, highlights some of the inadequacies of current design procedures, which in theory should provide a more challenging task than assessment, since less information is available. The explanation lies, of course, in the fact that the structural designer can generally use codified values for loads and material properties, whereas the engineer assessing an existing structure has the problem of determining what is really there, before undertaking an analysis.

This paper discusses various aspects of bridge assessment and proposes a number of alternative solutions.

IMPORTANT CONCEPTS IN BRIDGE ASSESSMENT

Basic Differences between Design and Assessment

The design of new bridge structures is to a very large extent controlled by Codes of Practice, of which BS5400: Part 4 [1] is an important example. Since the advent of limit state concepts, the levels of safety against collapse (i.e. the ultimate limit state) have been set by a process of calibrating a representative range of designs to each new code against the sub-set of designs to the previous code which have been shown by experience to give adequate performance. This process of calibration has differed somewhat between codes. For example, the partial factors in CP110 [2], BS8110 [3] and BS5950 [4] were determined by deterministic calibration over a range of structures; whereas in BS5400: Part 3 [5] a fully probabilistic procedure using reliability theory was adopted [6]. A similar exercise is currently being carried out for BS5400: Part 4 to determine the need for any adjustments to the partial safety factors (subsequently referred to simply as partial factors) originally proposed.

Regardless of whether design codes are based on limit state or permissible stress principles, or whether single or partial factors are used in the design process, the real levels of safety (and serviceability) depend on:

- the relationship of actual peak loads in service to the ultimate (service) loads assumed, implicitly or explicitly, in the design
- the relationship of actual material properties to those assumed in design
- the extent to which all the potential failure modes (serviceability criteria) can be modelled by suitable mathematical relationships, i.e. suitable design equations.

In general, none of the above can be predicted with complete accuracy. The differences may be thought of as 'uncertainties', and represent lack of knowledge by the designer at the time he/she needs to make a design decision.

In the current generation of codes which use partial factors, it is convenient to associate the magnitudes of these 'uncertainties' with the values of the partial factors needed. However, there is no simple relationship between the two because different design variables may have differing degrees of influence on failure under different circumstances. For example, in 'under-reinforced' concrete members in bending the sensitivity to concrete strength is low and even though the material may exhibit high variability there is no need for a high partial factor (to reduce the 'design value' of this quantity in relation to the specified strength). Conversely, for a concrete member highly stressed in shear or compression, the concrete strength is more important and a higher partial factor is required for a given level of uncertainty, or material variability.

The safety factors given in design codes have to be selected so that structures with acceptable, but below average, strength properties which are subsequently subjected to loads which are exceptionally severe remain safe and, if possible, serviceable during their design lives. For this reason, structures which, by chance, end up with higher than average strength properties may have more than adequate reserves of strength.

Changes in information with time. Since the uncertainties mentioned above correspond to lack of knowledge by the designer or engineer, it is clear that as more information is gained uncertainties are reduced. However, distinction must be made between:

- quantities which are essentially fixed in value, but are not known precisely – e.g. the mechanical properties of reinforcing steel once it has been placed in a structure (neglecting for a moment the effects of corrosion, fire, etc.), and

- quantities which are essentially time dependent (stochastic) and can never be known until after the event – e.g. the maximum live load on a structure in the next 20-year period; or the length of the most severe fatigue crack after a similar length of time.

In the case of quantities which *do not vary with time* it is clear that all knowledge gained, after the structure has passed through the initial design phase, serves to decrease the corresponding uncertainty. For example, with reinforcing steels, knowledge of the mechanical properties will increase progressively with:

- knowledge of the steel supplier (previous test records are likely to be reasonably representative of future supplies)

- the availability of test certificates for the reinforcement actually supplied for the bridge

- any additional mechanical tests that are carried out either during construction or subsequently.

In the case of quantities which *vary with time*, e.g. traffic loading, the uncertainties in prediction are likely to increase with the length of the time interval between the time at which the prediction is made and the time when the predicted event takes place. For example, based on available data for traffic flows, the prediction of the maximum loading on a bridge during the next 12 months is likely to be more accurate than a prediction for the annual maximum traffic load on the same bridge in 10 year's time. Formally, this may be analysed in terms of the auto-correlation function for the loading process.

Comparison between design and assessment. In terms of the uncertainties mentioned above, the differences between design and assessment are clear. In design, the engineer is working with mathematical models which are reasonably representative of all bridges of the same size and type simply because he/she has no specific data. In the case of assessment, some of the quantities are fixed and the problem lies in devising a suitable sampling/testing scheme to obtain the specific data required. However, the information will never be precise and some uncertainty will remain, since the tests cannot be totally representative and the results will always be subject to some testing error, especially in the case of non-destructive examination methods.

It is also clear that the partial factors used in design are generally inappropriate for use in assessment. This problem is discussed more fully in the section of this paper on reliability methods.

Types of Failure Mode

In the assessment of bridge structures careful consideration must be given to all the types of failure mode that can be envisaged. These can broadly be classified as:

- failure modes against which the structure was originally designed (or would be designed if it were to be constructed today); for example, exceedance of the ultimate capacity of a major structural member, or a series of secondary members, as a result of high levels of superimposed loads or a combination of loads

- failure modes resulting from the localised, and often undetected, deterioration of critical components; for example, a fatigue failure, or the localised corrosion of a prestressing cable, or failure of a foundation by scour.

The main distinction between these modes of failure is that, whereas in the former case failure is prevented by a quantitative analysis and the use of sufficiently large safety factors, in the latter, failure is avoided by non-quantitative measures such as ensuring adequate corrosion protection. The assessment of structures with the aim of predicting or preventing this second type of failure mode is typically much more difficult than the assessment of structures against failure by overloading. A significant number of failures have been caused by neglecting these possibilities, either at the design stage or in the planning of routine inspection, a recent example being the failure of the Ynys-y-Gwas bridge in South Wales [7].

Failures triggered by localised effects can be prevented only by using the knowledge gained from previous failures to improve inspection strategies. This important problem will not be discussed further here.

THE USE OF RELIABILITY METHODS

The last decade has seen a dramatic increase not only in the capabilities of methods of structural reliability analysis, for example [8], but in the number of serious applications of these theories. To date, the main emphasis has been on the rational selection of partial factors for design codes – the probabilistic calibration of BS5400 Parts 3 and 4 being just two. However, much effort is now being placed in the use of structural reliability theory for the assessment of damaged structures, particularly offshore, where the inspection and maintenance costs are extremely high and considerable benefit can be gained from eliminating any unnecessary repair work. It is clear that similar possibilities exist for bridge structures.

In the choice of partial factors for BS5400:Part 3, a decision was made to have approximately constant reliability levels for the different structural components of a bridge, *at the design stage.* In general, this does not mean equal partial factors, nor does it imply that similar components will have the same risk of failure when constructed, since these risks will be affected by any differences in the material properties in the actual structure. These differences are generally not investigated, but the means of doing this has been discussed above.

Thus, in terms of reliability theory, it is clear that the uncertainties in the material properties of the completed structure can be very much less than for the same structure at the design stage. This means that for structures with average and above average material properties, the nominal capacity to carry imposed traffic loads will be higher than at the design stage, at a given level of reliability. It should be noted at this point that the reliability of a unique structure depends not only on the actual properties of the structure, but also on the state of knowledge of those properties.

From the above it can be concluded that if the same standards of reliability are applied during the re-assessment of a bridge as were applied at the design stage, many bridges can be safely expected to carry heavier traffic loads.

Systems Effects and Redundancy

In determining the partial factors for BS5400:Part 3, the standards of safety were related to single structural components, for two main reasons. First, although the designer has to undertake a global structural analysis, structural members are generally designed as discrete components. Second, methods of structural system reliability analysis were only poorly developed in the late 1970's when this work was carried out. A decade later, the capabilities of the reliability analyst in studying the progressive collapse of structural systems is considerably improved.

Bridge structures having moderate or high degrees of redundancy are generally thought of as having additional load paths in the event of some local component failure. Often in bridge structures the degree of redundancy in primary structural members is rather low, but not uncommonly a more complex three-dimensional idealisation of the structure provides justification for assuming higher margins of safety when the structure is considered as a system.

In the context of reliability theory, high structural redundancy corresponds to large differences between the risk of an initial local failure and the risk of total collapse. Studies of fixed offshore structures have shown that these differences can be considerable. One of the reasons for this is that the total collapse often involves failure in many regions of the structure at the same time and it is clear that occasional weak cross-sections are compensated for by other components which are stronger.

These findings have also been confirmed by tests to failure on full-scale structures, where the collapse loads have often been found to be much higher than those predicted by simple theory.

Similar arguments can be used in assessing the probable load-carrying capacity of reinforced and pre-stressed concrete components which contain a moderate or large number of separate reinforcing bars or pre-stressing cables. The strength of the cross-section is often closely related to the average yield strength of the bars, the variability of which is typically much less than that of the individual bars themselves. This effect is never considered in normal design. The analysis of this problem is reasonably complex as it involves the identification of the various components of variance in the material properties (see for example [9]). Nevertheless, in the assessment of a critical bridge structure this could be worthwhile.

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