Bridge Management and Assessment in the UK

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SYNOPSIS

What can be learned from the experience gained in the UK now that its 15-year national programme of assessment and strengthening has in principle come to an end? What sources of information and guidance are currently available to bridge engineers responsible for maintaining the bridge stock? The principle findings of audit reports on the assessment program and also on the implementation of guidance for the management of substandard bridges are presented along with specific procedures for improving our predictions of load carrying capacity. Recent initiatives in bridge management are outlined and questions raised relating to the fundamental assumptions underlying our current definition of failure. Finally, several new bridge-related developments are reviewed and possible areas for utilisation of emerging technologies are discussed.

1 DOCUMENTATION ON BRIDGE MANAGEMENT AND ASSESSMENT IN THE UK

In the UK there is a considerable amount of guidance on the design, management and assessment of bridge structures given in the *Design Manual for Roads and Bridges* (DMRB) (1), which has been developed by the Highways Agency (HA) in England, the Scottish Executive, the Welsh Assembly and the Department for Regional Development in Northern Ireland. This document is freely available and downloadable in pdf format from links on the Highways Agency (HA) website. It contains both standards (referred to as BD's for Bridge Departmental Standards) and also supporting guidance notes in the form of advisory notes (referred to as BA's for Bridge Advice Notes) for a wide range of bridge engineering activities covering design, inspection, assessment and maintenance. The standards are mandatory for any bridge related work on motorway and trunk road bridges in the United Kingdom however in practice most other bridge authorities have also adopted these standards and advice notes for use on bridges on the secondary road network as well.

The primary difference between these documents and many other codes around the world is the depth and breadth of coverage on bridge *assessment* as distinct from *design*. Many nations rely on the guidance in their national design codes when assessing the strength of their existing bridges. The UK recognised that substantial benefits could be gained from having an extensive set of codes specifically dedicated to assessment which recognise the substantial differences in both philosophy and the availability of information when evaluating existing structures as distinct to designing new structures. It is believed that this is probably the most extensive set of assessment codes in the world.

In Australia bridge assessment or *bridge rating* is covered in a cursory manner by Section 7 of the Austroads Bridge Code however much of what is done apparently relies upon guidance in the design sections of the code without specific modifications for the assessment of existing bridges.

AASHTO in the US has produced a guide specification for strength evaluation (2) but this is not as extensive as the UK codes on this topic. It would seem that even with this specification many states still rely heavily on the AASHTO bridge design code when assessing bridge strength.

An important more recent addition to the DMRB was the introduction in 1998 of advice note BA79 titled *The Management of Substandard Highway Structures* (3). This gives specific guidance on what to do when a bridge is deemed to fail a structural assessment. In particular it outlines 5 levels of progressively more detailed investigation that can be considered when evaluating a failed structure. Level 1 analysis is effectively a first simple elastic analysis using characteristic strengths and loads. Level 2 includes provision for a more refined structural model using for example yield line analysis when appropriate. Level 3 recommends including bridge specific loading and material strengths (from for example core testing). Level 4 includes some simplified reliability evaluation and level 5 suggests a full reliability analysis of the structure could be undertaken. In addition, and perhaps most importantly of all, it gives guidance on appropriate strategies for monitoring structures that had failed assessment in the interim until remedial action could be undertaken. It is this last provision that has been widely utilised by bridge authorities in the UK as a means of justifying the delay in strengthening to structures that fail assessment but are deemed suitable for monitoring. After monitoring, the second most used measure for managing substandard bridges is the use of "partially effective barriers" to protect non-carriageway parts of the structure (e.g. footpaths, parapets)

2 THE UK BRIDGE ASSESSMENT AND STRENTHENING PROGRAMME

The primary document for assessment in the DMRB is BD21 *The Assessment of Highway Bridges and Structures* (4), which was first published in 1987 just in time for the commencement of the UK's 15-year programme of bridge assessment and strengthening that was announced in November 1987. (The most recent edition was published in 2001.)

The aim of the assessment programme was to assess the strength of all motorway and trunk road bridges and upgrade them where necessary in time for the increase in the legal gross-vehicle weight for lorries from the then 38 tonnes to 40 tonnes in January 1999 which then brought the UK into line with the rest of the European Union.

It was recognised by bridge engineers that this increase to 40 tonnes would have little effect on the number of bridges that would pass an assessment. (It was only in May 1983 that the maximum gross-weight limit for lorries in the UK was raised from 32.5 tonnes to 38 tonnes). In practice it provided an excuse to undertake an extensive check on the actual capacity of the older bridges on the highway network, many of which had been designed to much lower load limits and for which no record of capacity was available. In addition, as a result of improvements in the understanding of shear behaviour in concrete structures, the concrete code was changed in 1972 to introduce more onerous criteria for shear reinforcement and concerns were raised that many of the existing bridge stock might well be inadequate under these new criteria.

A survey published in January 1987 by the Department of Transport (5) considered a sample of 560 older short span (less than 50 m) bridges to see how many would fail the assessment code. The results indicated that around 10% of the masonry, 35% of the concrete and 66% of the metal bridges would not meet the required standards. (It is interesting to note that this survey indicated that for concrete bridges the most common mode of failure was likely to be in bending due to insufficient capacity in the tension reinforcement).

In addition, many of the nation's bridges have deteriorated significantly and it was recognised that the management of the bridge stock would require knowledge of the overall condition of the population of bridges. In another study, Wallbank (6) examined a random sample of 200 concrete bridges to evaluate their performance and maintenance requirements. Deterioration was identified in 144 (72%) of these bridges which raised concerns about the number of deteriorated structures in the population as a whole.

Since the UK does not have a national structures database it is notoriously difficult to obtain reliable figures on the number of bridges in the UK. It has been estimated that there are of the order of 160,000 bridges in total with the Highways Agency, which is responsible for motorway and trunk road bridges in England, having 10,000 structures, devolved governments in Scotland, Wales and Northern Ireland having around 7,000, local authorities having around 62,000 with the majority of the remainder being owned by Network Rail (the old British Rail), British Waterways and BRB (previously British Rail Property Board) (7). Again trying to get definitive information on the mix of bridge types in the bridge stock is difficult however the vast majority of the HA network comprises reinforced and, to a much lesser extent, prestressed concrete structures whilst the majority of the local authority, rail and waterway bridges are masonry structures.

By 2004, the majority of the bridges on the motorways and trunk roads have been assessed and, where deemed necessary, strengthened or replaced. However, in parallel with the assessment of the motorway and trunk road bridges, the local authorities also instigated a bridge assessment program for the bridges on the secondary road network and this has proved far more difficult and is indeed still far from complete despite the originally specified timetable of 15 years.

As of 1 April 2004 it has been estimated that 5500 bridges owned by, or which are the responsibility of local authorities require (and are still awaiting) strengthening at an estimated cost of £1.25 billion. In addition a further 3200 require major maintenance and 6700 require enhancement (e.g. upgraded parapets, widening) at an estimated cost of £430M. The maintenance backlog for local authority bridges alone is estimated at £590M (8). Such estimates are notoriously unreliable, particularly in view of the lack of a national bridges database. Nevertheless the overall picture is clear. There remain very large numbers of bridges that have been deemed to fail the assessment criteria for strength whilst many more require upgrading to meet current standards. In addition there is an enormous backlog of maintenance required on the bridge stock.

3 UK BRIDGE OWNERS FORUM

In November 2000 the Bridge Owners Forum (BOF) was established by representatives of all the major public and private bridge owning authorities in the UK. The terms of reference for the forum are primarily to identify research needs and priorities in bridge engineering but also to disseminate information and promote co-operation amongst the diverse range of owners managing the UK's bridge stock. This forum has proved highly effective and now advises government directly on what research needs to be commissioned. In reality, as the only grouping of all the bridge owners in the UK at the time, it became the defacto national bridge committee. More recently the UK Department for Transport (DfT) has set up a National Bridges Board which aims to develop the strategy and policy for the management of the bridge infrastructure in the UK although, unlike the Forum which covers the entire bridge stock, the Board's remit is somewhat restricted in that it is limited to public highway bridges in the UK and membership is thus somewhat narrower than the Forum which primarily deals with research.

3.1 BridgeForum website

The DfT has also funded the establishment of a BridgeForum website (www.bridgeforum.org) which provides an information portal to many aspects of bridge engineering and in particular bridge research developments.

3.2 Bridge Consultants Forum (BCF) and Bridge Researchers Forum (BRF)

As part of its remit, the Bridge Owners have held meetings with representatives of most of the major bridge consultancy firms in the UK at two Bridge Consultants Fora. The consultants were asked to identify and prioritise those bridge related topics that they believed require further research that would aid them in managing, designing and assessing bridges. The minutes of these meetings, and the list of topics identified, are available on the BridgeForum website.

In addition, a Bridge Researchers Forum was held to which academics from 18 Universities in the UK who are engaged in bridge related research were invited to present their work to the assembled owners. Again the minutes are available on the web. These give a concise overview of the bridge scene in UK universities. Although many interesting projects were presented it became clear that there was insufficient alignment between the research the academics wished to pursue and the needs of the bridge owners, with a number of projects being considered somewhat peripheral to the major problems faced by the profession. It was noted that there had been a substantial investment by the government's main funding body for university research in engineering, the Engineering and Physical Sciences Research Council (EPSRC) (which is the UK equivalent of the Australian Research Council) into research on new materials for civil engineering applications. In particular many Universities had active programs of research into the use of fibre-reinforced plastics (FRP's). The consensus amongst owners was that although this might be interesting from a research point of view this work would have minimal impact on the major problems they faced and would only really be applicable to a small number of highly specialised applications, for example, external bonding of FRP strips for flexural strengthening purposes. One leading academic expressed the view that FRP's were not viable as a direct replacement for steel reinforcement because the full capacity of the FRP's was not utilised unless high strains, and hence excessive deflection of the elements, occurred. As a result the most effective application of FRP materials was in prestressing. One interesting application of FRP's was to enhance the performance of reinforced concrete elements by providing confinement which improved ductility.

An International Bridge Forum (IBF) is now planned to which senior representatives of bridge authorities from around the world will be invited to the UK to share experiences on current needs and priorities in bridge research and any particular recent innovations and developments in their countries.

3.3 Best Practice Guides for Masonry and Steel Bridges and Dry Stone Walls

A number of important projects have already been initiated by the BOF. A "best practice guide" covering all aspects of the management, assessment and strengthening of masonry bridges is currently being prepared. This project, funded by the DfT, is being undertaken by consultant Mott Macdonald and managed by CIRIA on behalf of the BOF. A similar project to produce a "Best practice guide" for steel bridges has recently been approved and a contract will soon be let. Another major area of concern for bridge owners in the UK is the many thousands of kilometres of dry stone walling along the sides of roads and bridges and there exists very little published guidance on how to analyse, assess, maintain and manage these structures. Approval for funding of a "best practice guide" for these structures has also been received and this contract will be let shortly.

3.4 Contingency Margins for Live Loading

Having heard of similar studies undertaken in Australia, the Highways Agency, at the request of the BOF, commissioned a study titled "Contingency Margins for Live Loading" which examined the potential benefits of dramatically increasing the live load requirements for all future new bridge designs. This study, undertaken by Mott Macdonald, has only recently been completed and the report has not as yet been published (it will be made available on the BOF website when received). The key finding was that for a 3-4% premium on construction cost one could expect a 40 - 50% increase in live load capacity. In view of the enormous cost involved in both undertaking the strength assessment exercise and then carrying out the actual strengthening works there is a strong case for adopting such a load contingency policy to effectively remove live load capacity from the equation in any future strength assessment exercises. Since the introduction of the assessment program in 1987 the legal load limit in the UK has 'quietly' been increased to 41 tonnes. In fact there is a curious exemption that allows lorries up to 44 tonnes (6 axle vehicles) on key transport corridors linked to railheads. Exactly what routes this covers and how such a policy is enforced is not particularly clear. It should also be noted that some other European countries already allow significantly higher gross-vehicle and individual axle weights and the lobby to increase the current limits further is very strong.

3.5 Procurement of Design Services

Both Owners and Consultants have discussed various procurement options for design that would encourage and reward innovation and quality in engineering design and lead to improved performance and longevity in the structures that are built. One such proposal suggested that when designing new bridges to the given load criteria, the consultants could also submit their estimate of the additional cost required to attain specified increases in load carrying capacity above the minimum requirement. In this way owners would be encouraging an approach that rewarded innovative designs that optimised the increased load carrying capacity. This is in direct contrast to the current procedure that encourages the brightest minds to find ways of achieving the required strength with the absolute minimum of materials. Reinforced concrete designers aim to minimise the weight of steel in their designs. Similarly, steel fabricators do everything they can to shave even a millimetre off their weld runs to reduce costs and enhance the chance that their design will win a tender. In practice it may well be that, by way of example, adding a millimetre to all the welds might result in a 1% cost increase but a 10 % strength enhancement or perhaps an additional 20 years of life? Clients may well decide that such an investment would be a sensible insurance policy for the future.

4 AUDIT OF THE UK BRIDGE ASSESSMENT PROGRAMME

The Bridge Owners Forum considered it a high priority for the outcomes of the assessment program to be reviewed and, in particular, information gathered on the types of bridges that were failing assessment, the principle modes of failure identified and the effectiveness of the current approach to assessment. As a result consultant Parsons Brinckerhoff was appointed by the Highways Agency to conduct a review of the bridge assessment failures on the motorway and trunk road network. This contract report (9) should be compulsory reading for all bridge assessment engineers and is available on the BOF website. A sample of 294 bridges that had been assessed as sub-standard was audited to evaluate the effectiveness of the assessment programme. This audit found that by far the largest proportion of structures deemed to have failed assessment was made up of insitu reinforced concrete bridge decks (45%), followed by brick/masonry structures (15%), then insitu prestressed concrete (13%). (The structure material types in the audit sample were chosen to reflect the stock of structures assessed as substandard in each of the networks of England, Scotland, Wales and Northern Ireland. It must be remembered that since only motorway and trunk road bridges were considered the sample reviewed was biased towards reinforced and prestressed concrete structures and not other materials such as steel or masonry arch bridges). The most common structural form of substandard bridge was found to be the solid concrete slab, followed by beam and slab bridges and then box beams with cantilevers. The most common substandard elements were slabs, main beams and piers, followed by deck cantilevers and parapets.

The most common modes of failure identified were longitudinal flexure, transverse flexure and general shear. Since the largest proportion of substandard structures was made up of solid concrete slabs, a more detailed examination of the modes of failure of these bridges was undertaken. This highlighted that the vast majority of slab failures could be attributed to either longitudinal flexure (40%), transverse flexure (24%) or general shear, which accounted for 23% of the slab failures. Local shear only accounted for 4% and anchorage failure 1%.

Thus we are faced with the scenario that the most common assessment failure was of short to medium span solid concrete slabs due to inadequate longitudinal or transverse flexural capacity. This must surely raise a lot of eyebrows as well as make all bridge engineers question the basis on which these structural assessments were made.

Importantly, the audit then goes on to examine the causes behind these theoretical failures. What is again very informative is the conclusion that the most common cause identified was not the increased loading or the changes in code rules or deterioration of the elements but what was deemed to be the use of overly conservative or inappropriate methods of analysis.

This directly leads one to the conclusion that a large number of bridges in the UK have been strengthened unnecessarily over the last 15 years and one can only surmise that, in reality, many are still being strengthened unnecessarily. The lessons of this exercise must be learned and procedures developed to reduce the likelihood of such an outcome in future assessment exercises that are an inevitable part of a bridge managers' remit these days. This report highlights the urgent need for bridge engineers to redefine assessment failure such that the current reliance on first yield of a single element based on a linear elastic analysis is replaced, in appropriate circumstances, by a more realistic estimate of ultimate capacity making allowance for redistribution of loads which is likely to occur in most typical bridge decks and particularly in solid concrete slabs which dominate the population of substandard bridges in the audit sample.

The other major problem identified in the audit was the lack of availability of information relating to the substandard bridges. For example, of the 294 failed bridges examined, the managing organizations were unable to produce any original design documentation for 89% of the structures. Similarly, they were unable to produce the AIP (Approval in Principle) document for 47% of the bridges. This document is supposedly completed and approved prior to an assessment being undertaken and outlines the assessment methodology to be employed and any key assumptions that will be made. Documentation summarising the load affects and resistances determined during the assessment was unavailable for 67% of the bridges. Even the assessment report itself, which in theory determines that the bridge is substandard, was not available for 18% of the bridges in the audit sample. This emphasises the need for not only a consistent approach to record keeping and documentation but also the requirement for some form of centralised national database of key information on the bridge infrastructure.

5 IMPROVED ANALYSIS OPTIONS FOR ASSESSMENT

The audit report on the assessment program highlights a number of specific approaches to assessment that substantially improve our ability to more realistically model ultimate strength. When adopted these have each resulted in very substantial savings to bridge owners.

5.1 Anchorage of longitudinal reinforcement near supports

A number of bridges were found to be substandard under the new assessment rules for shear that required sufficient anchorage of the longitudinal steel to permit the truss analogy to be valid. The existing code rules for determining the required anchorage length have been found to be very conservative. A research program at Bath University has developed a new methodology for determining the anchorage requirements of longitudinal steel near the supports (10). This in effect takes into account the fact that the confining pressure on the concrete and steel from the bearings at the supports provides an enhanced anchorage capability. This has been adopted by a number of organisations and should be included in an updated version of the UK assessment code.

5.2 Yield Line Analysis of Concrete Bridge Decks

The development of a generalised yield line analysis program COBRAS at Cambridge University (7) has made yield line analysis of slabs, and certain beam-and-slabs, a practical option and the more widespread adoption of this program has resulted in substantially increased load assessments of many of the bridges previously deemed sub-standard. This same program has in fact been used to varying extents by the Main Road authorities in Western Australia, New South Wales and South Australia.

5.3 Denton's Equations

An extremely useful computational tool that can potentially increase the assessed capacity of concrete bridge decks was recently developed by Denton (11). In the UK, the Wood-Armer equations are used extensively for the design of bridge decks since they produce an optimal reinforcement configuration. However these same design equations are also often used for determining the moment fields when assessing existing bridges. In cases where the reinforcement in the actual bridge is not optimally distributed the predicted capacity can be very conservative. Denton recognised this and derived modified equations that provide a better estimate of the load capacity of the bridge. These equations have been incorporated as a subroutine called RASSP in the SAM-LEAP5 structural analysis program that is one of those commonly used in the UK. An example is given in Denton's paper where an increased capacity rating of the order of 30% has been obtained by employing Denton's equations. This approach has now been adopted by a number of engineers in the UK and has resulted in very significant savings.

5.4 Inappropriate Downgrading of Strength by Condition Factors

Another factor that has been inappropriately applied in bridge assessment is the so-called condition factor. During an inspection of a bridge the inspector makes a general assessment of bridge condition and then specifies a condition factor that is applicable to the bridge as a whole. For example a structure with extensive evidence of cracking may be given a condition factor of, say, 0.9. During the assessment it was found that many engineers were factoring down the final resistance of the structure by this factor in the belief that this would somehow reflect the effect of deterioration on strength. In practice this generalisation may not in any way reflect an actual reduction in capacity. For this reason it has been recommended that general condition factors be removed when assessing structural capacity. If deterioration of an element or components is an issue then the actual specific decrease in strength of this element should be determined and included in the assessment.

5.5 Cracked Stiffness for Grillage Analysis

Although not a new concept it was found that exploitation of the lower bound theorem by modifying the stiffness of transverse members in grillage analysis was surprisingly rarely employed and most seemed to rely on using gross section properties in analysis, even in cases where very low transverse steel inevitably would result in bending failure in such an analysis. Again there is considerable scope for reassessment of bridges that have been analysed in this way.

6 AUDIT ON THE MANAGEMENT OF SUBSTANDARD BRIDGES (BA79)

In addition to the review of the assessment program, the Highways Agency also commissioned Parsons Brinckerhoff to "review the use of BA79, the advice note on the Management of Sub-standard Bridges, and to identify anomalies and deficiencies within the current system to ensure that the continuing operation and management of substandard highway structures is carried out in a safe manner." The final report (12), dated December 2003, is also freely available on the BOF website and again should be compulsory reading for all bridge assessment engineers. It concludes that "there was significant variability in the level of implementation of BA79 throughout the bridge owners audited and there were an appreciable number of sub-standard structures for which there was no evidence of them being managed either in strict compliance with or in the spirit of the advice note. A number of these structures were being managed by organizations where its use would appear to be mandatory."

The response from organizations that had used BA79 to the Level 4 and 5 assessment procedure, which included reliability analyses, ranged from neutral to negative. Only one structure is known to have been assessed to either level 4 or level 5 and the results of that assessment did not appear to come to any firm conclusions. It is likely that these provisions for reliability analysis will be removed in any future revision of this advice note.

Perhaps the most sobering aspect of this report, which was also identified as a major issue in the audit of the assessment program, was the lack of documentation and a consistent database with records relating to each of the individual bridges being managed and assessed. In one notable example quoted in the report, one organization supplied a list of 171 sub-standard structures for which it was responsible. It was subsequently found that of these, 54 were no longer managed by the organization, another 28 were no longer sub-standard having been strengthened or replaced, but a further 42 new structures not on the original list were identified as sub-standard in their place.

The audit report concludes, "it appears that the greatest level of risk in the management of substandard structures stems from this lack of consistency and limited application of the document (BA79), and the quality of the records on which the management processes are based, rather than the technical quality of its application."

One recommendation from this review was that a structure file containing all the relevant documentation should be mandatory. It is disconcerting to find that such a file wasn't being maintained all along. The report highlights the manner in which the day-to-day management of the bridge infrastructure has changed dramatically in recent years. One contractor might be responsible for the management of a regions' bridges for, say, a five-year period and then a competitor might win the follow-on contract. At present this private contractor is responsible for maintaining the relevant records for each structure and these, in theory at least, get passed on to the company that takes over the management of the structures. However there has been insufficient attention paid to the transfer of all the relevant records between contracts and it is clear that a great deal of information gets lost. The days of the wily old bridge engineer who has worked with the same bridge stock over a career and has intimate knowledge of all are well and truly gone. Many of the paper records are now destroyed after they are converted into electronic form by third party subcontractors. In many instances, these subcontractors may have no technical knowledge at all and, as a result, frequent mistakes and errors in data entry and filing were found. This again highlights the necessity for a consistent structure file for all bridges, not just failed ones. It is hoped that the scene in Australia does not reflect the UK scene in this regard. This audit report highlights some of the detrimental consequences that have arisen from the privatisation and outsourcing of much of the management of the bridge stock.

7 CURRENT DEVELOPMENTS IN BRIDGE MANAGEMENT IN THE UK

There are a number of new initiatives underway in the UK that are defining how bridges are currently managed and indicate the way in which bridge management is moving forward.

7.1 SMIS

The Highways Agency is currently developing a comprehensive Structures Information Management System (SMIS). Parts of this system have already been implemented and are being used by the agents who maintain the highway bridge stock in England on behalf of the Highways Agency. For example, inspection reports of HA bridges are entered directly into SMIS at remote terminals in the offices of the maintaining agents. This computerised system aims to provide a database of core information as well as a comprehensive decision support tool for bridge managers. It includes modules for recording basic inventory data, bridge condition, inspection and testing data and maintenance scheduling. It is also being expanded to incorporate information from which the value of the assets can be determined, performance indicators evaluated and condition indicators determined.

As with any major computerised database and management tool there are some good and bad aspects of this system. Only time will tell whether this indeed fulfils its intended role. One of the major expenses involves populating of the database with the required information. This is being done progressively as each major inspection or assessment of a bridge is undertaken.

This system is not a national bridges database and there are no plans at present to develop one. Thus the majority of structures in the UK, which are not managed by the Highways Agency, will not be entered into SMIS. Other bridge authorities tend to have their own in house system but there would still appear to be a need for a common core format for these databases so that information can be collated and exchanged to assist in formulating policy at a national level. The author still believes that such a national database, as has been developed in the US, is an essential requirement for the effective longer-term management of the bridge stock in the UK.

7.2 BIM

A new, comprehensive two-volume Bridge Inspection Manual (BIM) for the motorway and trunk roads bridges of the UK is in the final stages of production although it has still, as yet, not been released. Volume 1 is a compendium of inspection procedures for different structure types and Volume 2 is a loose-leaf folder. A new bridge inspection standard, BD63, will be added to the DMRB as an implementation document for this manual.

7.3 Code of Practice for Bridge Management

A contract to develop a Code of Practice for the Inspection and Maintenance Management of Bridges and Other Highway Structures has been let by the National Bridges Board to consultant engineering firm Atkins. This code aims to harmonise procedures and result in a more consistent approach to bridge management across the various bridge authorities including the counties, Highways Agency, regional government assemblies (Scotland, Northern Ireland, Wales), Network Rail, BRB Ltd (British Rail Property Board) and British Waterways. The goal is not to produce a software package rather it aims to produce a framework for a Bridge Management System outlining what core elements would be included.

7.4 Key Performance Indicators (KPI’s)

Key Performance Indicators are being developed for the Highways Agency to demonstrate the effectiveness of maintenance, safety and availability of the bridge stock. A contract to produce these has been awarded to Atkins. The brief covers both HA and local authority bridges. The following Performance Indicators have been proposed by the contractor.

7.4.1 Condition Indicator

This is being developed under a separate contract on behalf of the local authorities, again having been awarded to Atkins. The Highways Agency plans to adapt this indicator to reflect the availability functionality in its own SMIS Structures Management Information System. This indicator aims to measure the physical condition of the elements in a bridge as compared with their new condition. The aim is to produce a measure that will allow managers to monitor the progressive deterioration of a structure with time and quantify the effect of any maintenance or rehabilitation that is undertaken.

7.4.2 Reliability Indicator

This aims to measure the reliability (or safety) of the structure in supporting traffic loads. This will be a function of the probability of structural failure and consequences of failure. The probability of failure will be based on the assessed live load capacity but modified to take account of in-service factors. The consequences of failure will include the costs of traffic accidents, costs of casualties, environmental and socio-economic costs.

7.4.3 Availability Indicator

This indicator gives a measure of the availability of the structure for its required purpose/function. The aim is to provide a means of measuring the impact of long-term restrictions for weight, height and width (volume of traffic) on the network. This PI will be a function of the traffic delay costs, increased cost of traffic accidents, environmental and socio-economic considerations.

7.4.4 Outstanding Maintenance Indicator

The Outstanding Maintenance Indicator aims to quantify the backlog of work identified from inspections but not planned for execution in the next financial year.

It can be seen that consultant Atkins has won most of the key contracts for developing the different components of the overall bridge management system that is being adopted in the UK. Information on the documentation being prepared is available at the dedicated Atkins website https://pronet.wsatkins.co.uk/bridgecop

7.5 Welsh Bridge Management System

In addition to the above projects, Atkins are also developing a separate Bridge Management System specifically for the Welsh Assembly. The Welsh differ somewhat in their outlook on the key requirements for a management system. In particular they argue that for their bridge stock they wish to be able to measure functionality criteria and residual life rather than the indicators referred to above. In particular it has been pointed out that condition indices allow for the measurement of condition but do not indicate criticality or when a structure is no longer serviceable/performing its function.

8 OTHER RECENT DEVELOPMENTS IN BRIDGE ENGINEERING

8.1 Eurocodes

The Eurocodes are slowly being introduced into the UK in a piecemeal manner. The original timetable for completion of the different parts of the Eurocodes relating to bridges has slipped by a number of years in most cases although some parts are now complete. These codes will be mandatory and will replace the current British Standards over the next few years. However the manner in which each code is applied to the motorway and trunk road bridge stock in the UK is defined by an implementation standard in the DMRB. For example the current British Standard for concrete bridges, BS5400 Part 4, is implemented by BD24. (The Eurocodes come as standard documents for all countries but each is supplemented by an accompanying National Application Document (NAD) which modifies the Eurocode to suit individual national circumstances). The experience in the bridge community in the UK at present is that there is very little adoption of Eurocodes in design and there seems to be very little interest in them despite the fact that they will have to be applied shortly when the British Standards are withdrawn. At present the current British loading code is due to be replaced by Eurocode 1 (EN1991) by 2008, the concrete code by Eurocode 2 (EN1992) by 2006, the steel code by Eurocode 3 (EN1993) by 2007 and the composite code by Eurocode 4 (EN1994) by 2006. Information on the implementation of Eurocodes in the UK is available on the internet at www.eurocodes.co.uk.

8.2 Uncertainty in Inspection and Testing

An important issue, which has not really been addressed to date, is the unreliability of the visual inspection reports undertaken as part of the normal inspection procedures. When determining the condition of a bridge, and in particular, evaluating any evidence of distress or deterioration, one relies heavily on the reports by the site inspectors who are required to report in detail on any deficiencies observed on the structure. A recent study by Moore et al. (13) of the inspection process undertaken in the US, in which 49 experienced bridge inspectors were asked to inspect 5 test bridge structures, showed that there was a very significant likelihood that major defects would not be picked up. For example, although most inspectors would detect general defects such as defective painting or general corrosion, important strength related defects such as weld cracks were detected by less than 7% of the inspectors and other defects such as missing rivet heads by only 5%. Very simple measures, which with the benefit of hindsight seem obvious, were identified to improve the performance of inspectors. Compulsory eye tests for all inspectors were suggested as one such measure. Other important factors influencing the performance of inspectors were psychological conditions such as a fear of heights or fear of traffic. It was also shown that the quality of the inspection was strongly correlated with the formal qualification level of the inspectors. Finally it was shown that a rigorous audit system to maintain the quality of the system was essential.

The Highways Agency and consultant Babtie are funding a research project which goes beyond inspection to also look at the uncertainty involved in NDT testing used in concrete bridge assessment and inspection. This project, which is near completion, has highlighted the high degree of variability in the test data received by bridge engineers and the factors that influence the results. This work is again essential reading by all bridge engineers and raises very serious questions indeed about the usefulness and effectiveness of much of the standard testing currently undertaken as part of the bridge management process (14).

8.3 Reinforced concrete bridge cantilevers

One of the most common forms of failure identified in the audit of the UK bridge assessment program was of concrete bridge side cantilevers. The current assessment code has quite onerous loading criteria for checking for the case of accidental loading due to errant lorries leaving the carriageway and riding up onto footpaths and verges. This has resulted in a substantial number of bridges being rated substandard. Many of these have been analysed using simplified hand methods which assume a somewhat arbitrary distribution of loading from the wheel loads to the cantilever root, or Pucher charts or elastic finite element methods. Again all assume failure occurs when first yield is reached at a single location. A recently completed PhD project at Cambridge University has investigated this problem and produced guidance on the actual distribution of loading along the cantilever root and also undertaken an experimental program to identify the range of parameters which govern whether the likely mode of failure will be in shear of flexure. This is an example of problem driven applied research responding to the needs of the profession and should result in substantial savings to the bridge assessment community (15).

8.4 The strength of reinforced concrete voided slab bridge deck

The Welsh Assembly has a number of strategically important voided slab bridges that had been found to be substandard in flexure, based on a conventional elastic analysis. In response to this, Cambridge University was commissioned to develop an extension to the COBRAS yield line analysis program for assessing concrete voided slab bridges. It is interesting to note that voided slab bridges make up around 10% of the bridge stock of the motorways and trunk roads of England and yet there is hardly anything at all in the literature examining their behaviour and the likely modes of failure at the ultimate limit state. The theoretical and programming work, which has resulted in this new module for voided slabs, has now been completed. However to validate the theory an experimental research project has been initiated at Cambridge to identify the parameters which define the mode of failure of such bridges and the validity of using yield line (or any other) form of analysis for assessing strength.

9 EYE TO THE FUTURE

Here the author speculates on some new developments and technologies that may be adapted in bridge management and assessment in the future.

9.1 Wireless Sensor Technology

One exciting development that may well dictate how we manage our structures in the future has been the revolution in sensor and remote monitoring technology over the last few years. There are several research projects in the UK and overseas which are utilising miniaturised sensors, such as MEMS (micro-electrical mechanical systems), with in-built wireless communications facilities to measure key parameters such as deformation and acceleration of a structure in real time. This information can be sent directly to the bridge manager's computer and allows continuous monitoring and rapid identification of potential problems. It would seem likely that future bridges will have various sensors inbuilt at the time of construction. One example of long-term thinking is demonstrated by the Stoerbelt bridge and tunnel project. Here the designers have inbuilt the necessary electrical connections in each tunnel segment to allow cathodic protection to be installed at some future date if steel corrosion is identified by the inspection programme.

9.2 Computer Vision Applications for Bridge Engineering

One of the limitations of existing bridge databases is the manner in which bridge geometry is typically represented by a very restricted number of prescribed text fields which specify, for example, span, carriageway width, verge or footpath width, structural depth etc. As a result the original raw data, i.e. the view of the structure itself, is no longer available for verifying, nor can other alternative dimensions on the structure that have not been measured on the original measure-up be derived. Even if a collection of photos of the structure are taken and stored on the database, the exact positions from which these photos have been taken are rarely specified. One possible way forward here is to employ recent developments from the computer vision field that enable three dimensional solid models of structures to be generated directly from a selection of photographs of the structure. Such technology is being tested in a project at Cambridge University at the moment and could potentially revolutionise the collection of inspection data. The longer-term goal is to allow specific test and inspection data of selected areas of the structure to be superimposed on the global 3D computer graphics model of the structure so that a visual dimensionally rigorous record of the structure itself can be interrogated by the assessing engineer at any time.

9.3 Material Testing Technology

The flexural strength of concrete bridges, which has been highlighted in this paper as being a primary form of failure in bridge assessment in the UK, is highly sensitive to the tensile capacity of the primary longitudinal reinforcing steel. Although in many insitu test program information on concrete strength is collected from cores, collection of test data on insitu steel strength is more problematic, not least because of the difficulty in exposing a length of sample sufficiently long for testing and also because of the highly variable results that can be obtained depending upon the degree of work hardening experienced by the bar during extraction and the preparation of the tensile specimen itself. A reliable insitu test technique for establishing the yield strength of reinforcing bar with the minimum invasiveness would be an extremely valuable addition to the assessing engineers armoury. Various measuring techniques have been proposed but none seem to have gained acceptance in the bridge profession as yet. A research program at Cambridge University is investigating techniques for measuring yield strength of small specimens of reinforcing bar. If successful, this procedure would allow more realistic evaluation of the existing strength of concrete bridges.

10 CONCLUSIONS

The primary sources of information that provide guidance for assessing and managing the highway bridge stock in the UK are presented. The role of the newly formed Bridge Owners Forum is outlined and several of the initiatives instigated by the Forum are discussed. One of these projects was an audit of the national assessment program in the UK which revealed that the use of overly conservative or inappropriate analysis methods was the primary reason for the large number of bridges on the motorway and trunk road network that were found to be substandard during the recent bridge assessment programme. This was in contrast to the expectation that most failures would result from either changes in the shear rules introduced in 1972, increases in the legal loading compared with the loading specified at the time the bridges were originally designed or reduced resistances due to deterioration.

The necessity for assessing engineers to be familiar with options for more realistically predicting the load capacity of bridges is essential and some specific techniques to assist with this goal are presented. The primary lesson is that adopting appropriate methods of analysis would probably make the most significant contribution to improving bridge ratings rather than undertaking more detailed site inspections and testing or investing in the development of probabilistic reliability analysis techniques to try to justify passing bridges, particularly if these are based on the same overly conservative analysis failure criteria and structural analysis techniques. In concrete structures, which form the majority of the bridge stock on the major roads in the UK, the use of methods that allow for plastic redistribution of loading, such as yield line analysis, would substantially improve our load predictions.

A separate audit on the implementation of the advice note for the management of substandard bridges found that, despite the detailed guidance given for dealing with failed structures, this document was not widely used nor complied with. This was somewhat surprising considering that the procedures in this document would appear to be mandatory for a number of the bridges reviewed. The second major issue identified by this audit was the lack of records covering the various management activities that would define the bridges capacity and performance.

Key features of the new code of practice for bridge management, soon to be introduced in the UK, are outlined. This code will encompass key performance indicators that are aimed at allowing bridge managers to measure the overall performance of the bridge stock in maintaining the functionality and value of the bridge assets in a way that can be reported to the politicians who control the budgets.

A new structures management information system has been implemented and is slowly evolving into the overriding bridge management tool for the motorway and trunk road bridges in England however this has not been adopted universally as a national tool.

The entire inspection and testing regime in the UK is currently being questioned in the light of an extensive study undertaken in the UK that highlights the variability and uncertainty in these procedures. There is a strong case for more rigorous formal training of inspectors and a rationalisation of the NDT testing techniques. Bridge engineers should undertake specific sensitivity studies to identify the key parameter values needed before ordering site testing.

The Bridge Forum has facilitated owners, consultants and researchers meeting to identify research needs and priorities in the bridge engineering field. This has highlighted the many areas where further research is necessary to provide the tools needed by today’s bridge managers. The primary subject areas where improved knowledge and procedures were sought included effective bridge management systems and databases, the evaluation of shear strength in concrete structures, the modelling of deterioration in concrete structures and the effective inspection of bridge structures.

Bridge engineers are faced with many challenges to efficiently and safely manage our existing infrastructure. There is considerable scope for improving current practice as well as opportunities for researchers to solve the many problems still facing the profession. Most importantly we need to be prepared to review and audit our current activities, disseminate the knowledge gained from these audits and modify our procedures accordingly.

11 DISCLAIMER

The opinions and interpretations presented in this paper are those of the author alone and do not necessarily reflect the views of any other individuals or organizations mentioned or members of the Bridge Owners Forum.

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