Proceedings of the Institution of Civil Engineers
Engineering History and Heritage 162
February 2009 Issue EH1
Pages 39–49
doi: 10.1680/ehh2009.162.1.39

Paper 800001
Received 1/04/2008
Accepted 15/07/2008

Keywords:
bridges/dangers & hazards/failures

Ron. J. Bridle
Former Chief Highway Engineer and Directer of TRRL, UK

Frank Sims
Former Executive Director of Engineering and Chief Officer of the West Yorkshire Metropolitan county council, UK

# The effect of bridge failures on UK technical policy and practice

R. J. Bridle FREng, FICE, FRSA and F. A. Sims OBE, FREng, FRSA, FICE

**The first part of this paper sets the scene for the growth of the road programme in the UK since 1950 and new additions to the existing stock of bridges. The second part describes the events that gave concern for the preservation of those bridges and the attention given to the policy and inspection procedures to safeguard the nation's existing stock. Tables describing the bridge stock, the principal factors influencing maintenance expenditure and the principal tasks are provided, together with concluding observations and acknowledgement of the great efforts of the bridge engineering community over the half-century covered.**

## 1. INTRODUCTION

In the late 1950s and the early 1960s the UK road and motorway programme commenced and accelerated. The annual value of highway structural works, within the trunk road and motorway programme, grew from £5 million in 1955 to over £100 million in 1972, based on rates pertaining at the time. Producing design, analysis, contract documents and work supervision stretched the available engineering resources beyond acceptable limits; it also pressurised management to the extent that problems sometimes fell below the management horizon and the 'urgent' overwhelmed the 'important'.

Both consulting engineering practices and county councils were anxious to expand the volume of work assigned to them. Checking was often the first casualty of an increasing workload. It was not until the formation of road construction units (RCUs), by Sir William Harris, in the late 1960s that attention was given to optimum resourcing and continuity of workload on a regional basis. The new structure also brought a balance in highway work awarded to consulting engineering firms, RCU sub-units, county and other highway authorities.

The institutions administered the qualification of engineers, but no thought was given to the training of the engineers necessary to staff the programme of major road and motorway building. Most training was by hands-on experience in the authorities, companies and organisations involved. One organisation, the Cement and Concrete Association (C&CA), took advantage of the void and from the early 1950s set up training and education courses in all aspects concerning concrete applications. The Association turned out a growing supply of bridge and highway engineers versed in the methods of analysis of concrete structures based on an extensive programme of research. The research was carried out at Wexham Springs, the C&CA headquarters, as well as at universities and at the Road Research Laboratory, as it was then called. The British Constructional Steelwork Association (BCSA) sustained no parallel effort until the formation of the Constructional Steel Research and Development Organisation (Constrado) in 1971. The British Welding Research Association and The Welding Institute were also involved in research, together with other trade organisations.

The consequence was inevitable. Concrete dominated the short- and medium-span market and shared in the larger span bridges, except for the very longest spans.

## 2. DESIGN GUIDANCE, CODES, STANDARDS AND RESEARCH—THE BEGINNINGS, A BRIEF MODERN HISTORY[1,2]

In the 1950s the guide to structural design was the Ministry of Transport's (MOT) memorandum number 577, first published in 1945 and reprinted in 1955. It was a simple but comprehensive document giving guidance on geometric standards, clearances, forms of construction and loadings. In general it relied on British standards and codes of practice for the fundamental requirements of steel and concrete. Of particular significance was the 1937 *Specification for Steel Girder Bridges BS 153 Part 3A Loads*, revised in 1954, which enabled early motorway bridges to take account of HB (MOT Loading for heavy load routes) loading.

A *Specification for Road and Bridgeworks* was introduced by the Department of Transport (DOT) in 1951 as a first edition, which was constantly reviewed and updated thereafter. Since that time, overseeing design development has been the major part of the bridges engineering division's role. The pace at which advances in design knowledge and techniques were occurring brought about the necessity to review national codes of practice every four years and the recognition of the need for new codes. Many aspects of bridge design and construction were outside the ambit of national codes of practice, but nevertheless require codifying.[2]

In 1960 a bridge committee of the Road Research Board was constituted, which included representatives from local government, consultants, research organisations and the construction industry, to which any aspect of bridge design and construction could be referred. Sub-committees with wide representation, headed by leading experts in the bridge field, were formed to deal with individual subjects. For a great deal of the work it was essential to obtain the results of research, undertaken principally by the Road Research Laboratory, on which design codes could be based.[2]

The work of the DOT progressed. Memorandum 577 received various amendments, of which number 785 of 1961 was a major advance in its acceptance of high-yield steel reinforcement with permitted stresses up to 2109·7kg, subject to control of surface cracking by the use of appropriate bar diameters in accordance with a 'crack' formula. In the same year memorandum 771 confirmed the adoption of BS 153 loadings and introduced the concept of HB loading.

By the mid 1960s, with the increase in bridge construction and the innovation of new forms being sought by designers, the lack of an all-embracing bridge code became apparent. The British Standards Institution (BSI) set up a committee to prepare a standard code for steel, concrete and composite bridges.

Not surprisingly, many of the members of the bridge committee and others from the sub-committees were involved in the development of the national bridge code within—BS 5400. A study of the many documents issued by the Ministry's bridge division over the past 50 years reveals the extent of the work undertaken by (DOT) and its advisors in keeping practice up to date and taking advantage of innovation.

An important function of the bridges engineering division has been to ensure that the results of research and development are translated into departmental and national standards, design guidance advice notes and apecifications. Apart from the work of the bridge committee, the ministry has closely collaborated with research organisations and manufacturers of bridge components. In order to keep pace with developments, procedures were established, notably with the Building Research Station and the Road Research Laboratory, for the proof-acceptance of new materials and techniques. Procedures were also being adapted to suit the advent of the computer. Fundamental lessons learned from construction at that time had yet to be consolidated but the examination of the application of limit state philosophy to bridge design was underway.[2] BS 5400, when issued in 1978, became the first limit state code of practice for bridge design and construction in the world.

In 1964 the division approved 800 bridge designs, and 1000 in 1965.[2] Detailed arithmetic checking at these numbers became impossible with the staff employed and radical changes to approval procedures were needed. The efforts being made to keep up with the pace of innovation and the need for standards accentuated the difficulties, as will become clear later in this paper.

However, apart from dealing with new works, the bridges engineering division was also responsible to the secretary of state for the maintenance of the existing bridge stock, now Beginning to carry an increasing volume and weight of traffic.

## 3. OPERATION BRIDGEGUARD[1]

'Operation Bridgeguard' was introduced in 1967 to assess the load-carrying capacity and the state of the nation's bridges built before 1922. A meeting with county bridge engineers was held to discuss the timescale of completion of Bridgeguard. The ministry had wanted the trunk road bridges to be assessed within one or two years with other bridges to run in parallel. This timescale was considered unreasonable and concern was expressed at the 'throttling' effect it would have on county highways as weight restrictions became imposed on bridges considered to be weak. A more realistic programme was considered to be ten years. A major problem was the availability of the technical resources required in addition to financing the exercise. With little prospect of additional finance the crash programme had to be phased and work was still being undertaken several decades later and beyond.[1]

From the introduction of Operation Bridgeguard the assessment of the nation's bridges by the DOT, local highway authorities and other bridge owners, including bridges over railways and waterways, has become a continuing task. Consulting engineers have provided additional input. Bridges found to be weak have had weight restrictions imposed and in some cases with width restrictions to reduce loading until strengthening could be undertaken. Some bridges have been demolished and rebuilt. A large number of bridges have been strengthened or given added protection to meet revised impact criteria (see Figure 1).

Today many weight restrictions remain on local roads. The current assessment code is BD21/97, having superseded a revision of the code in 1993 and bridge assessments are still being undertaken.

By the end of the 1960s, given the history described above, the attention to standards and the research undertaken, some confidence might have been understandable, but as a consequence of the conditions described in the opening paragraphs, failures were to intrude into any complacency there might have been and these failures caused radical changes in procedures.

## 4. BOX GIRDER FAILURE AND THE MERRISON COMMITTEE[3]

The failure of four steel box-girder bridges occurred during erection in the late 1960s and early 1970s. They were the Cleddau Bridge at Milford Haven in Wales, the West Gate Bridge across the River Yarra in Australia, the Koblenz Bridge in

Figure 1. Pier strengthening

Germany and a bridge over the Danube in Austria. Three of these bridges are illustrated in Figure 2.

These failures[3,4] were not due to lack of knowledge of plate buckling in steel box-girder behaviour, although that was not realised when the failures were first reported. Although certain shortcomings in the analysis became evident, as information was gathered, it became apparent that human error was the key constituent, especially in decisions made during construction, which fell below the attention given by the management at the design stage.

In the case of the Cleddau Bridge, failure occurred through buckling of the diaphragm above the pier as the box-sections were cantilevered out, over the river. Somehow or other the design thickness had become translated from ¾ in to $^3/_8$ in on the manufacturing drawings. How this happened was never established.

The Koblenz Bridge also failed during the cantilevering process. The contractor wished to make the transverse weld between the boxes automatically and, to achieve this, cut back the stiffeners on the bottom plate to allow for the welding process. The missing stiffener sections were replaced but were only welded to the ends of the existing stiffener and not welded to the bottom plate. Consequently, the unstiffened part of the plate buckled as the cantilever was extended and the load on the plate increased.

The Yarra Bridge was a failure of communication and supervision during erection. The two halves of the box were to be bolted together but buckles, owing to construction, made the task impossible. The resident engineer on the site directed the use of kentledge to press out the buckles, without consultation with the designers and with disastrous consequences.

The concerns of the British government were not only for the stock of British box-girder bridges but for the international reputation of British consulting engineers, as the Yarra Bridge was under the supervision of Freeman Fox and Partners, who were pre-eminent at the time.

The DOT planned to carry out a loading test on a box girder supporting a slip road on the Bidston Moss viaduct, in Liverpool, to demonstrate the adequacy of design and construction. However, the test was quickly cancelled when initial investigations cast doubt on the correlation between design assumptions and structural details.

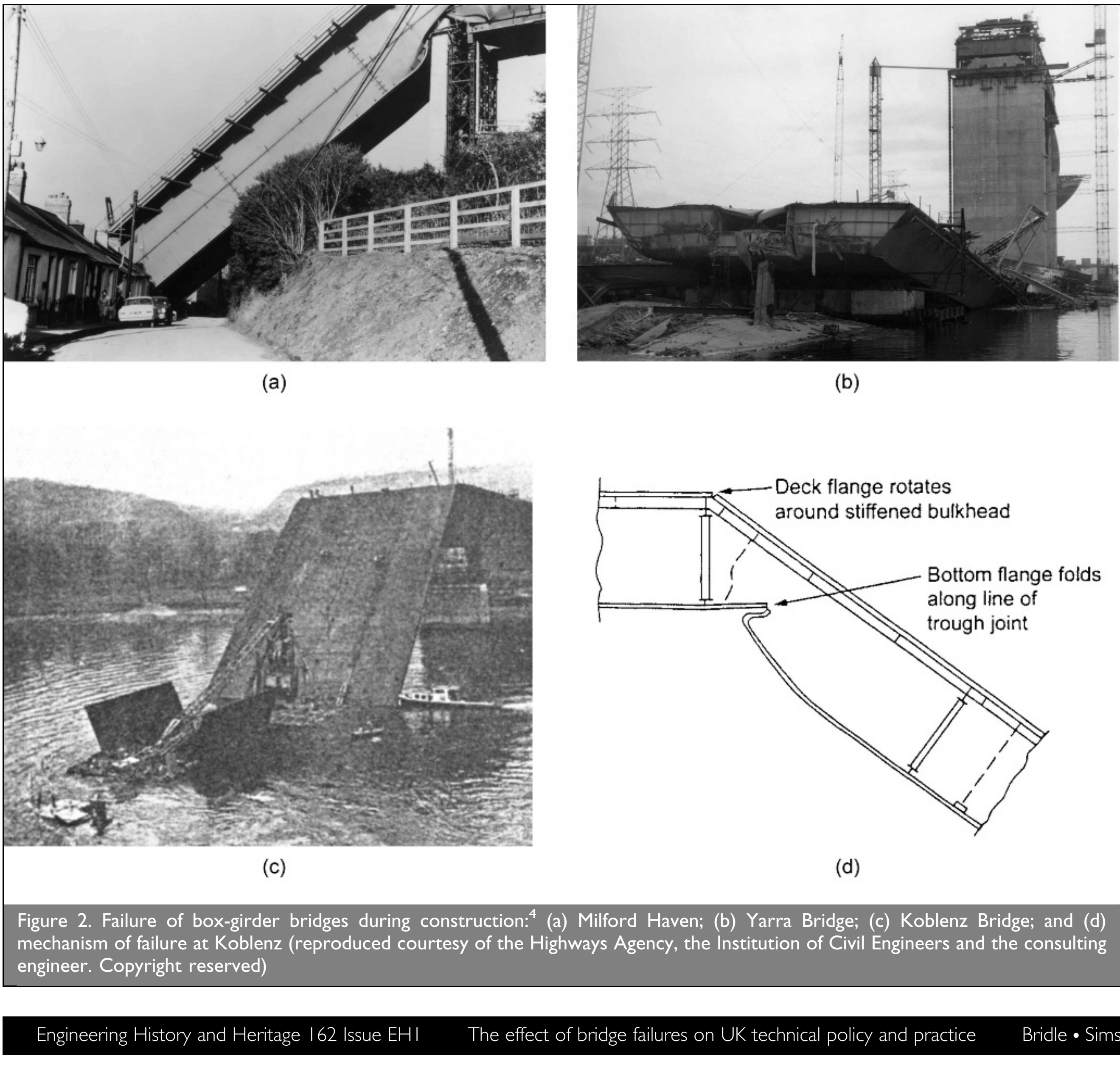


Figure 2. Failure of box-girder bridges during construction:[4] (a) Milford Haven; (b) Yarra Bridge; (c) Koblenz Bridge; and (d) mechanism of failure at Koblenz (reproduced courtesy of the Highways Agency, the Institution of Civil Engineers and the consulting engineer. Copyright reserved)

The secretary of state, Peter Walker, now Lord Walker, had in mind to close all box-girder bridges. Following discussion, he was persuaded to close only the outside lanes of these decks, confining traffic to the central lane, so avoiding traffic chaos until investigation could reveal the issues and remedies.

The secretary of state, in conjunction with the secretaries of Scotland and Wales, appointed an independent committee of investigation chaired by Dr Merrison, as he was then, vice Chancellor of Bristol University, supported by a noted panel of specialists. Their mission was to consider what lessons were to be learned from the accidents and produce recommendations for the design rules and procedures to be adopted in the design and erection of major steel box-girder bridges.

The terms of reference were[3]

(*a*) to consider whether the collapses at Milford Haven (UK) and Yarra (Australia) necessitated reconsideration of the design and method of erection for every major box-girder bridge about to be erected in the UK
(*b*) to examine the design rules and methods of analysis used in steel box-girder deck structures for large bridges and to draw up an interim technical memorandum for the guidance of bridge engineers, prescribing rules and methods to be adopted in the design and erection of such bridges, the limits within which such designs may be accepted and any special matters affecting contract procedures
(*c*) to recommend what further research and development should be undertaken into this type of construction.

At the time of setting up the committee, 49 steel box-girder bridges had been completed or were under construction, with a further 30 in an advanced stage of design.

The committee, in reaching its findings considered two basic questions: (*a*) whether fundamental knowledge of structural mechanics available to the engineer had reached a stage at which it was reasonable to undertake, with confidence, the design of thin plate box-girder bridges; and (*b*) whether guidance in the detailed application of the fundamental knowledge was accessible to the engineer.

The committee was surprised at the paucity of research effort that had been put into examining the behaviour of steel box girders and found that a great deal of work had to be done to answer the questions that the enquiry was discovering. Fundamental questions were raised about the co-ordination of research and its direction towards solving the problems faced by designers. Although the knowledge was available, it was not generally in a form readily usable by the practising engineer. This was owing to a communication gap between the academic and the design office engineer.

Interim rules in a document SBG6A were issued in May 1971. They were basically an abstraction and correlation of all relevant theoretical work available together with recommendations as to where and how these rules should be applied and the value of parameters to be used in their application.

In October 1973, following the completion of the programme of recommended research, and the work of the Merrison committee BE 6/73 was issued on the application of the committee's *Interim Design and Workmanship Rules for Steel Box Girder Bridges*,[3] which became the basis for both box- and plate-girder design until the introduction of BS 5400. This document was in force until the issue of BD 13 in 1982.

A programme of strengthening the bridges in question was implemented with rigour. The majority of box-girder bridges were checked and strengthened in two or three years but some took much longer. The last bridge to be completed and recorded was the Erskine Bridge in 1985.

Despite the aim to retain the use of the box-girder form, subsequent to the above exercise, its use diminished in favour of the plate girder. The main changes rested in the ratio of workmanship to material costs, which tilted the balance in favour of the I-section form. Attempting to meet the required new workmanship standards in welded stiffened thin plates also contributed to the economic decline of the steel box girder.

A full account of the findings of the Merrison committee is given in volume 2,[4] chapter 6 of the series of books produced by the Motorway Archive Trust, describing the history of motorway planning, design and construction.

The Committee regarded four requirements as indispensable to a sound procedure for constructing large steel box-girder bridges

(*a*) an independent check of the engineer's permanent design
(*b*) an independent check of the method of erection and the design of the temporary works adopted by the contractor
(*c*) the clear allocation of responsibility between the engineer and the contractor
(*d*) provision by the engineer and the contractor of adequately qualified supervisory staff on site, with their tasks and functions clearly distinguished.

DOT implemented these recommendations through the issue of technical memorandum BE 4/73 and also applied them in extending the procedures to other structures and highway components. There were later amendments to this document.

## 5. CERTIFICATION[3,5,6]

DOT's system of certification of bridges was based on the Merrison report but extended beyond it. The advent of the technical approval procedures constituted a radical change in the philosophy governing bridge engineering. The local authority associations and the Association of Consulting Engineers were consulted. The important changes are listed below.

(*a*) DOT would continue to examine the design criteria and methods, but not computations, and would stipulate client requirements.
(*b*) The requirement, by DOT, for the engineer to provide an independent check of the design and computations.
(*c*) The application of an 'approval in principle' stage for all but minor structures. This would cover the selection of bridge type, the materials for construction and the methods of analysis and design to be adopted.

The bridges engineering division was thus relieved of the impossible task of checking detail while concentrating on the features of design and construction not covered by existing codes and standards. This task has since provided useful feedback in drawing up research and development programmes in conjunction with the Transport and Road Research Laboratory (TRRL), and others, with the aim of making subsequent amendments to DOT's standards for implementation before inclusion in British standards.

The key changes have been set out here, but there is a host of detail involved in the legal and financial arrangements, which are included in volume 2,[4] quoted above. The main aim achieved by the certification procedures was to reduce the risk and the economic consequences of structural failure to an acceptable minimum value. This can be expressed mathematically, but is not generally applied. Nevertheless, such philosophy does guide experience in making choices.

In broad terms it is possible to consider what would happen if things go wrong and a structure fails,[5,6] or in the event of alternative scenarios such as a system breaks down, or a careless driver brakes too quickly on an icy road. Local and central government carry their own insurance, but it is possible to assess the cost of insurance if the risk and economic consequences are known. The economic consequences resulting from a bridge failure are

(*a*) injury and loss of life
(*b*) loss of utility
(*c*) replacement cost
(*d*) costs of public overreaction.

The present value of the insurance (PVI) is the sum, over 30 years, of the risk the event will occur multiplied by both the discount factor and the economic consequences borne. It can be seen that it is worth investing resources in reducing the PVI, through additional checking or strengthening, until the last increment of resource is equal to the decrement it creates in the PVI.

For bridge certification the risk of human error cannot be precisely quantified, although loading and material risks can. Certification, however, reduces the risk of human error through requiring second opinion at three levels of rigour. DOT, the technical approval authority (TAA, which also included the former RCU headquarters), assigns the highest category, category 3, to bridges of high complexity and high economic importance. For this category the engineer must appoint an independent checking office, which only receives a copy of the contract drawings. A certificate is demanded of both offices that the structure is in accordance with the standards and requirements laid down by the client. Where there is disagreement, DOT acts as arbiter or gives a ruling on interpretation in writing. For category 2 bridges the independent checking team may be in the office of the appointed engineer but separate from the design team. Only for category 1 structures, which are of the simplest kind, is the checking carried out within the design team.

The system has been in use for over 30 years without any bridge structure collapsing and it is worth quoting the Merrison committee's comment on DOT's technical approval system: 'We are satisfied that the new system will serve to expose any serious defects in the structures to which it is applied.'

## 6. LODDEN BRIDGE AND THE BRAGG COMMITTEE[4,7]

Despite the effect of the certification on the industry some temporary works escaped the rigour of the system. The supervision of temporary works was given the searching glare of publicity as a result of the collapse of the Lodden Bridge during construction (see Figure 3).

Once again the ramifications led to a new procedure governing the design and erection of temporary works and the oversight of construction processes. The collapse occurred on 24 October 1972[4] when falsework supporting a span of the A329 dual-carriageway viaduct over the River Lodden, near Reading, failed while a load of concrete was being poured.

The temporary structure consisted of steel trestles resting on horizontal beams on the permanent pier foundations supporting steel trusses. The steel trusses carried the shuttering within which the permanent deck would be cast. Both piers and trusses were commercially produced products.

Once the span had been cast the intention was to slide the beams supporting the falsework sideways into position over the top of the towers so that the second span could be cast. The first span was completed without any apparent problems and the beams were moved to the second span and the falsework erected (see Figure 3).

The particular fixing used to connect the beam to the tower is shown in Figure 3 and was used at both ends of the span. Neither of the pins was located on the neutral axis of the structure. The beam was unable to slide at either end of the span, which meant that horizontal forces were induced at the pinned ends. Whether these were calculated remains open to doubt.

About 30 men were at work on the span at the time of collapse. They reported a downward movement of about 152·4 mm and a few seconds later the structure collapsed into the water, falling along the line of skew. The chaos can be imagined. The shortcomings that led to the disaster, and the deaths and injuries, were not simply attributable to the way that the falsework had been designed and constructed, but also to the general inadequacies of the processes by which most temporary works schemes were undertaken.

Despite the Merrison recommendations, temporary works were generally regarded as the contractor's responsibility and the engineer felt he should isolate himself from attracting any responsibility that would lead to additional costs. This was not uniformly the case but sufficiently prevalent to give cause for concern as revealed in the investigation into the collapse of the Lodden Bridge.

Nothing now remaining on file gives a specific explanation of the failure and that shown in Figure 3 is the speculation of the bridges engineering division. G. Baker, who led the investigation for HM Factory Inspectorate, said that it may never be possible to establish the precise order of events but pointed to the grillage and its immediate supports as triggering successive failure in the structure as a whole.

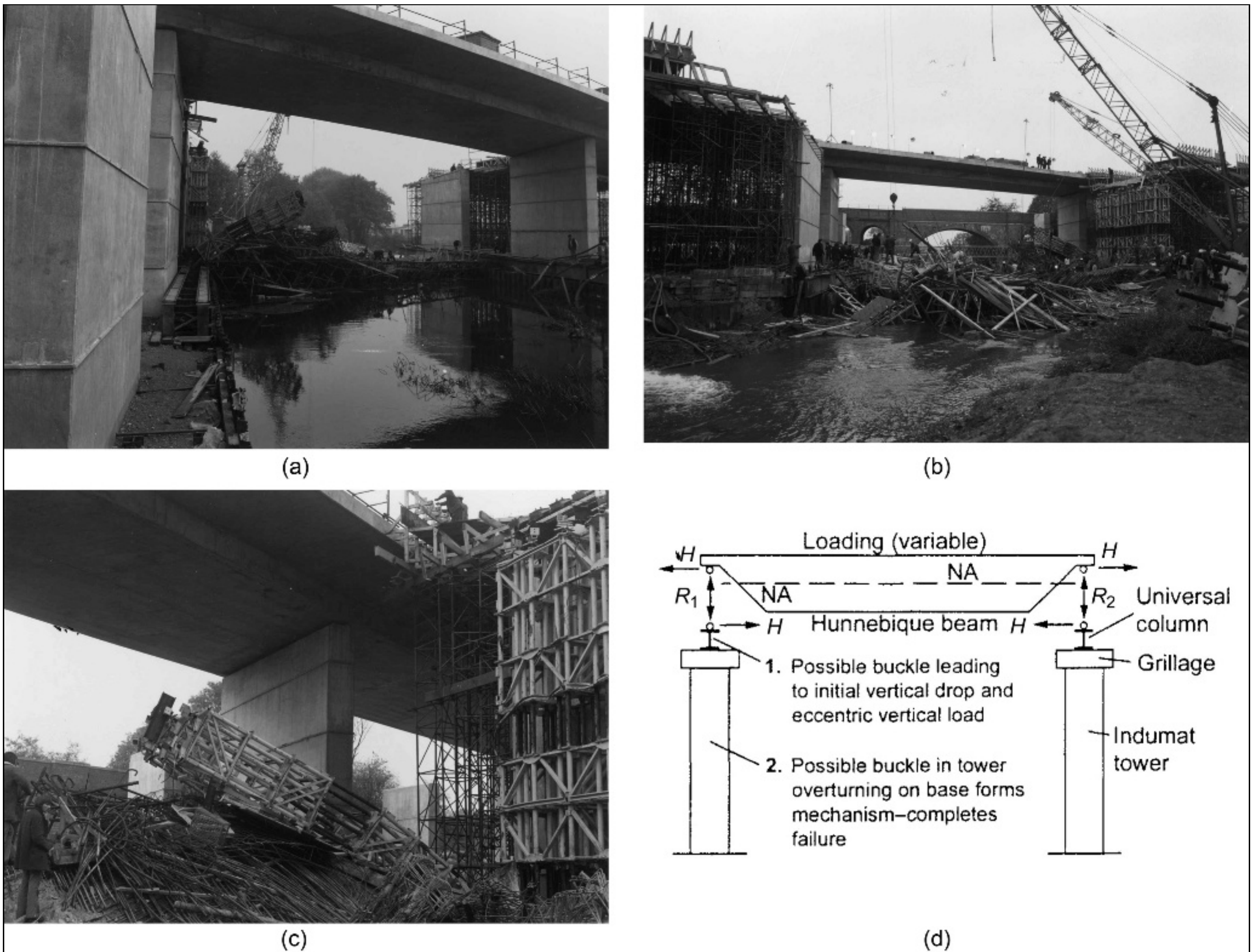


Figure 3. Collapse during construction of Lodden Bridge:[4] (a) failure looking upstream; (b) failure looking downstream; (c) the Indumat tower after the failure; (d) speculation on the mechanism of failure (reproduced courtesy of the Highways Agency. Copyright reserved)

An interdepartmental working party was appointed, which disclosed many inadequacies. Key deficiencies were established. Some resident engineers were unaware of the action they should take when proposals for temporary works were submitted to them as required under the contract. Some failed to ensure that the works could be built safely, in accordance with the drawings, and did not offend any of the assumptions made in the design. They were also unaware of their responsibilities in respect of maintenance and inspection when falsework was being constructed, especially the possibilities of buckling as a result of misalignment and other defects.

These inadequacies led the working party to recommend that a committee be appointed to advise the secretaries of state for both Environment and Employment on the action necessary to minimise the risk of falsework collapse. In the interim the committee proposed stopgap measures. It was also recommended that the independent chairman should be a member of the legal profession because of the legal and procedural issues that were involved. Part of the stopgap measures was to remind local authorities of their legal responsibilities under various Acts of Parliament. The committee also proposed the encouragement of the intention of the BSI to produce a code of practice on falsework. The committee was to report in two years with an interim report in six months.

The committee was set up with Stephen Bragg, vice chancellor of Brunel University, as chairman and in due course made principal recommendations in six parts.[7]

(*a*) part 1: details of collapses the committee studied
(*b*) part 2: commonest technical faults
(*c*) part 3: common inadequacies in procedure
(*d*) part 4: ways in which technical faults may be avoided
(*e*) part 5: procedures to correct the inadequacies in part 3
(*f*) part 6: practical training courses in falsework.

Generally the Bragg committee accepted the earlier findings of the working party and also leant on DOT's certification procedures used in the design of permanent structures. Responsibilities were clearly defined and a falsework engineer was nominated on the site. The role of the resident engineer in ensuring the safety of the permanent works was defined and regular inspection established. The BSI code of practice was put in hand. As with certification procedures the better performance and economic gain is testimony to their need.

BSI finally published the Code of Practice BS 5957 *Falsework* in April 1982, a further demonstration of how long it takes to make a new code.

## 7. THE POST-TENSIONING PROBLEM[8,9]

British engineers were first alerted to potential problems with the grouting of post-tensioned prestressing tendons in the late 1970s when a bridge on the continent was found to have cables that had completely disintegrated owing to lack of grout protection; the bridge had to be demolished.

In 1985 at the instigation of the MOT following the collapse of the Ynys-y-Gwas Bridge, which failed through corrosion of prestressing cables at joints in beams of segmental construction, a rigorous inspection of post-tensioned bridges was undertaken through its agent authorities and consulting engineers. In addition research work started at the TRRL into methods of ensuring complete grouting and the development of inspection, testing and appraisal techniques.

The findings of lack of grouting and consequential corrosion were so alarming that in September 1992 a temporary ban was placed on grouted post-tensioned construction for DOT's new bridges. Most other bridge owners followed suit.

It was thought that 3000 of the stock of over 100 000 bridges in the UK were of grouted post-tensioned construction. DOT owned 600 of them and the rest were shared among the local highway authorities, British Rail, British Waterways and London Underground.[8]

DOT, as a 'client' organisation, regarded the concrete industry as primarily responsible and it had to find a solution. In response to the urgency of the situation the Concrete Society, together with the newly formed Concrete Bridge Development Group (CBDG) set up a joint working party in June 1992 to study the problem and make recommendations, acting as the single focal point. DOT was a member.

A working group was also set up under BS 525/10, the bridge code committee, to examine all existing information in order to review the existing BS 5400 code provisions covering post-tensioned bridges and to be involved in the coordination of work being undertaken in this area.

The working party had to address two different problems. First, what could be done for those structures which were currently being designed or constructed by this method? Second, how could design and construction methods be improved to give confidence of adequate durability?

A specification was issued with the intention that experience gained from the application would contribute to its continued development. It was applied in a series of monitored trials on a number of bridge contracts and also adopted in other countries. It raised considerable interest in the USA.

In September 1996, on the basis of the work undertaken by the Concrete Society, the CBDG, research at TRL, field trials and work by the industry, the final report 47—*Durable Post-tensioned Concrete Bridges*[9] was presented to the FIP conference in London.

At the conference it was announced that the Highways Agency had lifted the ban on post-tensioned bridge construction, but excluded grouted segmental structures owing to the need for further work on continuity of ducts and construction joints. This restriction was to be lifted later.

Regrettably a number of motorway and other post-tensioned bridges had to be demolished and replaced. It is significant that steel composite construction has been favoured as a replacement.

Yet another problem was to become the concern of bridges engineering in the 1980s—the alkali–silica reaction (ASR).

## 8. ALKALI–SILICA REACTION[10,11]

The phenomenon known as ASR was first identified in the USA in the 1940s and was found to occur in concrete when certain siliceous minerals in the aggregate react with alkaline pore solution in the cement matrix. As a result of the reaction expansive forces are generated sufficient to crack the concrete of structural members and reduce their load-carrying capacity (see Figure 4). From 1946 and through the 1950s research work was carried out at the Building Research Station, which led to the mistaken conclusion that the UK was unlikely to be affected. Thus when the early motorways were constructed, ASR had not been classified as a problem, but in the late 1970s an increased number of instances were identified in bridges and other structures.

Although it is a maintenance problem for those bridges

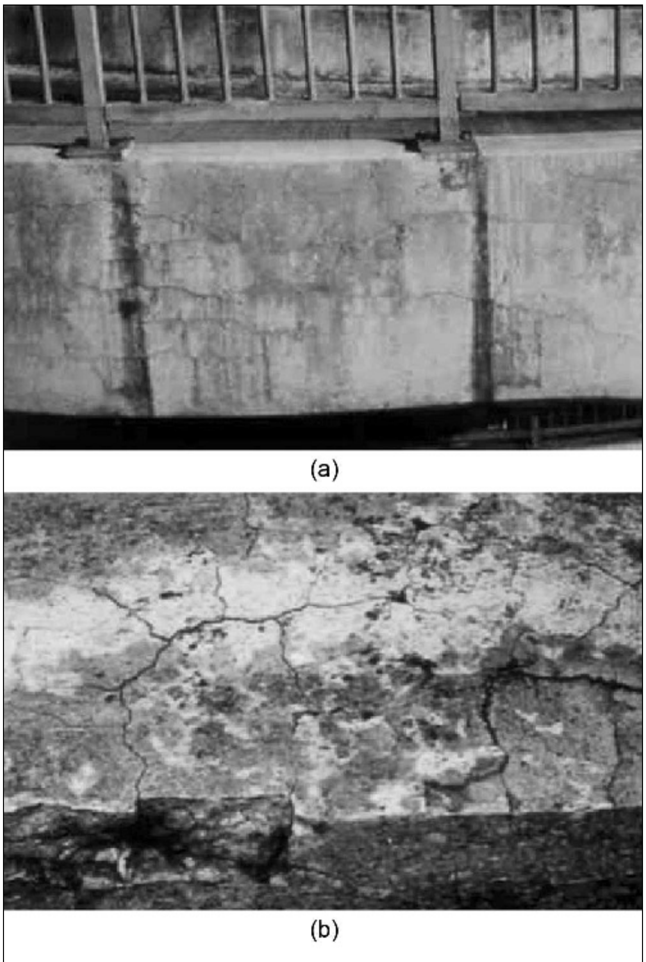


Figure 4. Evidence of ASR (reproduced courtesy of the Concrete Bridge Development Group.[11] Copyright reserved)

identified, ASR is addressed here because of its implications for bridges built after 1980. A considerable research effort went into identifying the circumstances in which ASR occurs, together with the suspect aggregates and in developing specifications. Those involved included the Departments of Environment and Transport, the Building Research Establishment (BRE), the Engineering Research Council, the Cement and Concrete Association, the Concrete Society, TRRL and the Institution of Structural Engineers (IStructE).

A Concrete Society working party on ASR set up in 1983, produced guidance notes and model specification clauses to minimise the risk of damage due to ASR: Concrete Society Report 30 *Alkali Silica Reaction—Minimising the Risk of Damage to Concrete*, 1987.[10] The C&CA, later the Cement Association, also set up a working party to produce guidance notes and produced its report, *The Diagnosis of Alkali Silica Reaction*, in 1987.

IStructE, through an ad hoc committee, produced interim technical guidance on the identification, engineering appraisal and management of structures affected by ASR.

All those involved in bridgeworks were asked to report on bridges considered to be suffering from ASR, including county council bridge offices and consulting engineering practices. Known research effort was coordinated by TRRL. Several universities and consulting engineers were involved in research projects and case studies.

Although considerable effort was mobilised to deal with ASR it was necessary for the DOT to issue direction for new concrete structures and for dealing with those that already existed. In 1988 the DOT issued three important documents. The 6th edition of its *Specification for Highway Work* contained provisions for the avoidance of ASR in new concrete structures, as did the associated Notes for Guidance.

For those authorities concerned with maintenance of the bridge stock, DOT technical advice note BA 23/86 was produced covering the investigation and repair of concrete structures affected by ASR. BA 35/90 superseded this in 1990 as more research came to hand.

It is to be hoped that bridges constructed on motorways in the UK and elsewhere after the issue of these documents will stand the test of time better than those, now clearly identifiable by the travelling public, where dark crazed lines and 'blown' concrete are evidence of the ASR phenomenon.

## 9. PRESERVATION OF THE EXISTING BRIDGE STOCK[12,13]

This was not the end of failures that had an effect on practice, although the failure took place in the USA, two years before the collapse of the Ynys-y-Gwas Bridge. Early in the morning in June 1983, luckily very early, a truck and a dribble of cars were moving along part of a six-lane Connecticut turnpike carried by a bridge across a river. A man whose home is on the riverbank was looking out of his window. He said, 'I saw a truck and a car coming off the bridge and going into the water, then I heard people groaning. Without warning a 100 foot section of the bridge collapsed.'

Without warning is somewhat exaggerated, as later, people who lived near the turnpike said that for four or five years bits of concrete and steel had been falling off the bridge. Several had written to the state's Transportation Department and had complained of strange piercing noises when traffic used the bridge.

Although making little impact in the UK, this incident prompted a Federal study into the stock of highway bridges. The study concluded, very frankly, that 20% of American bridges were obsolete. Another 25% were unable to handle the weight of traffic allowed to use the roads they supported. In all, a quarter of a million American bridges were in critical need of repair. There was a need for some to be replaced or closed.

It should not be assumed that the state of American bridges pertains in the UK. British engineers have been cautious. Nevertheless the American problem again focused attention on the existing stock of bridges in the UK and their inspection, and need for assessment and maintenance or repair.

This became a continuation of the Bridgeguard story.[13] In November 1987 Mr Bottomley, minister for roads and traffic, announced a comprehensive programme for the rehabilitation of bridges on motorways and other trunk roads. The programme included the assessment and strengthening of older short-span bridges, many of them built before the introduction of national loading standards in 1922. The basis for the assessments was the new bridge assessment code BA 21/84, with its supplementary Advice Note BD 16/84. Some amendments to the code were necessary to allow for the government's stated intention to strengthen bridges so as to cope with lorries up to the EC limits of 40 t overall weight and 11·5 t axle weight. Discussions were held with the owners of bridges off the national road system to persuade them to carry out a similar programme for their bridges.

The new bridge assessment code, published in 1984, was prepared by a DOT working party with representatives of all major public bridge owners. The previous Code BD3/73 and its predecessor BE4 provided assessment loadings adequate for up to 30·5 t rigid vehicles and 32·5 t articulated vehicles. The application of these codes through Bridgeguard in the 1960s was intended only as a stopgap measure to justify some extra service life for older bridges, which were unable to carry safely the loading in the national bridge code BS153. Bridges that passed the assessment were still to be regarded as sub-standard with the proviso that the eventual replacement of these bridges should not be unduly delayed. This was a false hope because the recession in the economy that followed the rise in oil prices, ruled out early replacement. In fact many are still in use today. Although BD21/84 was aimed at the older structures the principles could also be applied to the assessment of more modern structures.

Following the publication of the assessment code DOT decided that it would be necessary to carry out a survey to estimate the costs of applying the code to the national bridge stock. The results were published in a report by DOT in March 1987 and identified about 50 000 bridges that were covered by the code. However, about a quarter of them would not meet the standards of the new code and would require strengthening or replacing.

The cost of strengthening the sub-standard bridges was estimated to be between £560 million and £830 million, which could be reduced by between £70 million and £150 million if permanent traffic restrictions were applied to those bridges where this was a more economic solution. The cost of assessment was estimated to be between £30 million and £40 million.[13]

Bridge assessment and the preservation of the bridge stock can provide many more challenges to the bridge engineer than the design of a completely new structure. It is not difficult to decide what the aims of a preservation policy should be, namely

(*a*) maintain acceptable standards of structural safety
(*b*) preserve transport amenity with minimum disruption
(*c*) provide wise husbandry of national assets and resources.

Nevertheless, review has shown that in some instances standards lapsed as more resources were drawn into the construction programme and some existing bridges have failed in part or had to be rapidly repaired.

The same criteria as set out earlier for considering the risk and economic consequences apply. 'Input resources' is a convenient collective term for the cost of strengthening and maintaining the existing stock including the costs of analysis and supervision. Once again the resources can be aimed at, first, reducing risk or, second, the economic consequences of entering a limit state, that is collapse, excessive deflection and displacement or local damage. Weighing a bridge by jacking at its bearings is an example of the first. The uncertainty in dead loading would be reduced, as would the insurance. The French have indeed weighed many of their bridges to aid assessment. Designing new structures so that failure will start to evidence itself by large deflections is an example of the second. The penalties of sudden failure are avoided and the insurance reduced. Risk and insurance issues are discussed at greater length elsewhere.[5,6]

A number of exercises have been carried out to improve the knowledge and reliability of the existing stock The pattern of highway bridges in 1980, about the time that the investigative work described above was undertaken, is shown in Table 1.

The statistics place bridges in three categories

(*a*) brick and masonry arches
(*b*) metal structures
(*c*) reinforced and prestressed concrete structures.

Virtually all arch bridges and 30% of metal structures were built prior to 1922, whereas virtually all concrete structures were built after 1922. It is the responsibility of the Highway Authorities to investigate the condition of existing bridges and make proposals for their repair and maintenance. They are also required to keep a register of the bridges in their care. These registers have been used for research purposes.

Table 2 lists the principal factors influencing expenditure on bridge maintenance and Table 3 lists the principal tasks in bridge maintenance; both tables, produced in 1988, are based on various studies undertaken by the TRL. Over the years since the American failures of existing bridges, increasing attention has been given in the UK to implementing a policy aimed at protecting the existing stock, as set out in these tables, which describe only superficially the extensive economic burden carried by the maintenance engineer. Much research has been instituted to ensure procedures are carried out and supervised with greater efficiency. Consulting engineers have been deployed to a greater extent and the manpower has become better trained.

## 10. CONCLUDING OBSERVATIONS

It is hoped that this paper has shown the effect that various failures have had on government technical policies governing the design and construction of new bridge works and the preservation of the existing stock of bridges in the UK. There cannot be a conclusion to this paper as new events will arise from time to time to trouble the future engineering fraternity with new problems that will require new administrative and technical solutions.

It would be unfair to concentrate, unduly, on the problems that have beset bridge design and construction without looking at the many successes. The enormous task undertaken over the last 50 years by the MOT engineers together with county highways and bridges departments, consulting engineering practices, road construction units and contractors in the supervision of the planning, design, construction and maintenance of the nation's motorway and trunk road bridges should be acknowledged. Approaching 4900 motorway bridges have been constructed, with many more on trunk roads.

Research and development undertaken by organisations such as TRRL, BRE, C&CA, BCSA, SCI, the Welding Institute, the

| | Brick and masonry arches | | Metal structures | | Concrete structures | |
|---|---|---|---|---|---|---|
| Owner | Number | % | Number | % | Number | % |
| British Rail | 4428 | 20·03 | 5022 | 46·42 | 1350 | 8·99 |
| British Waterways Board | 949 | 4·43 | 267 | 2·46 | 52 | 0·31 |
| Local authority and DOT Bridges in UK | 16 753 | 75·54 | 5528 | 51·12 | 14 976 | 97·30 |
| Total | 22 130 | 100·00 | 10817 | 100·00 | 16 878 | 100·00 |

Total of bridges in sample: 48 879
Estimated total in UK: 155 000

Table 1. Bridge stock in the UK, 1980[13]

| | | |
|---|---|---|
| Type, history and environment | 1. | Number and size of bridge for which the local authority is responsible |
| | 2. | Type and age of the bridge |
| | 3. | Quality of construction |
| | 4. | Traffic carried, environment and ground conditions |
| | 5. | History of past maintenance |
| | 6. | Techniques and materials used for maintenance |
| Technical matters | 7. | Access to structure: provision of fixed or moving inspection/maintenance equipment |
| | 8. | Type of inspection (i.e. principal or general) on which the maintenance requirements are based |
| | 9. | Whether work is done by agency or contractor |
| | 10. | Reduced maintenance where bridge is to become redundant |
| Organisation and planning | 11. | Control of traffic during work |
| | 12. | Budgetary limitations—is work determined by need or by staff or finance unavailability |
| | 13. | Overheads or agency charges |
| Financial and accounting practices | 14. | Allocation of costs as between maintenance and new works and as between road and bridge maintenance |
| | 15. | Whether other types of highway structures are included under bridge maintenance costs |
| | 16. | Uneven flow of work and contract delays |

Table 2. Principal factors influencing expenditure on bridge maintenance[13]

universities and many other bodies in conjunction with designers and constructors have provided a stream of developments in the whole of the bridge field. The work within the BSI together with all those involved in the preparation of codes of practice and standards relating to the design and construction of bridges is acknowledged. The work of the Standing Committee on Structural Safety in reviewing questions of structural safety and making recommendations for action, including the failures discussed in this paper, is also acknowledged.

The story is mostly one of success and great credit should be accorded to all those professionals and administrators who participated in the road programme. The practice of certification has now spread to all aspects of highway engineering in the interests of safety and avoiding undue risk.

However, there are some lessons to be learned so that errors are not repeated. No engineering project should be undertaken or new law passed without deep consideration of the resources in manpower, equipment and knowledge availability. Policies need to be determined at the start between the resources needed and those available. Innovation should not be employed without research to discover whether there are dangers in its use unrecognised by its promoters. Checks should be thorough and searching, and should not be sacrificed to meet demand. Training should be at a level to meet the technical and practical requirements of any new programme.

It is of interest to note that the Victorian engineers made models and tested parts to investigate the practicalities of construction. Nevertheless failures occurred and brought about change in future methodology. It is not possible to escape failure but the risks can be reduced as described, especially if a cohort of well-trained engineers can be produced, who are adaptable to any new programme of works that may be visited upon them.

More detail of the events described and the people involved can be found in the several volumes published by the Motorway Archive Trust, describing the motorway achievement, but especially in one yet to be published in that series—*Motorway Bridge Superstructures and the people involved—A Historical Record* by F. A. Sims,[1] which together with volume 2[4] of the archive set have formed the principal sources for this paper.

| Frequency of mention | | Maintenance task |
|---|---|---|
| Most frequently mentioned | 1. | Painting and repair of steel bridges |
| | 2. | Repair of damaged concrete (cracking, spalling and rust damage) |
| | 3. | Repair of stone and brick structures (e.g. pointing, pressure grouting, replacing stones and bricks, insertion of ties and rebuilding spandrel walls and parapets) |
| | 4. | Maintenance of movement joints |
| | 5. | Waterproofing and sealing |
| Frequently mentioned | 6. | River works—protection against scour |
| | 7. | Drainage |
| | 8. | Replacement of parapets with improved types |
| | 9. | Maintenance and renewal of bearings |
| Less frequently mentioned | 10. | Strengthening of weak structures |
| | 11. | Clearing and removal of vegetation |
| Occasionally mentioned | 12. | Problems with prestressed concrete |
| | 13. | Deck surfacing |
| | 14. | Timber structures or decks |
| | 15. | Vandalism—graffiti removal |
| | 16. | Installation and maintenance of inspection equipment |
| | 17. | Protective coating to concrete |

Table 3. Principal tasks of bridge maintenance[13] (Note: since 1988 the frequency of mention of some maintenance tasks may have changed, e.g. problems of drainage and removal of vegetation are more frequently mentioned)

## REFERENCES


1. Sims F. A. *The Motorway Achievement, Motorway Bridges, Their Superstructures and the People Involved.* The Motorway Archive Trust, 2000.
2. Holland A. D. Bridges, modern structures, design, development and standardisation. *Municipal Engineer*, March 1965.
3. Department of the Environment. *Inquiry into the Basis of the Design and Method of Erection of Steel Box-Girder Bridges—Interim Design Appraisal Rules.* Department of the Environment, London, 1971.
4. Bridle R. J. and Porter J. (eds). *The Motorway Achievement, Frontiers of Knowledge and Practice*, Vol. 2. Thomas Telford, London, 2002.
5. Bridle R. J. Structural safety and the Department of the Environment. *Proceedings of the 3rd International Safety Conference, Institution of Civil Engineers, London*, March 1976.
6. Bridle R. J. Accounting for human error. *The 12th Conference of the Australian Road Research Board*, August 1984.
7. *The Final Report of the Committee on Falsework*. HMSO, London, 1975.
8. Woodward R. J. *Conditions within Ducts in Post-tensioned Prestressed Concrete Bridges*. Transport and Road Research Laboratory, Crowthorne, 1981, Report LR 980.
9. *Durable Post-tensioned Concrete Bridges, Technical Report 47*. Joint Concrete Society/Concrete Bridge Development Group, Concrete Society, September 1996.
10. *Alkali Silica Reaction Minimising the Risk of Damage to Concrete, Report 30*. Concrete Society, 1987.
11. Darby J. (ed.). *Guide to Testing and Monitoring the Durability of Concrete Structures, Technical Guide 2*. Concrete Bridge Development Group, Concrete Society, 2002.
12. Holland D. A. and Dawe P. Bridge rehabilitation, Department of Transport, fifteen-year strategy. *Proceedings of the 1st International Bridge Management Conference, University of Surrey*, March 1990.
13. Dawe P. Inspection, assessment and strengthening of highway bridges, background. *Proceedings of Meeting of the Institution of Civil Engineers*, May 1988.