Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 38 (1982)

Artikel: Highway bridge inspection: principles and practices in Europe

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DOI: https://doi.org/10.5169/seals-29514

Highway Bridge Inspection: Principles and Practices in Europe

L'inspection des ponts routiers en Europe: principes et pratique

Grundregeln und Praktiken bei der Strassenbrückeninspektion in Europa

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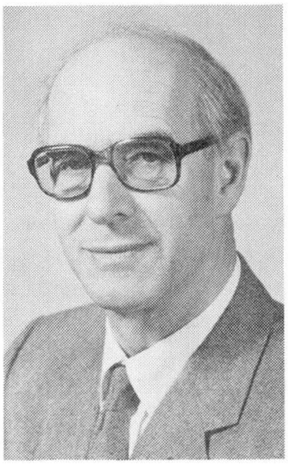

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SUMMARY
The state of the art of Bridge Inspection in Europe is reviewed and certain general principles and practices identified. The purpose and classification of systematic inspection and the formats of inspection reports are discussed. Instrumental aids to inspection are assessed and the prospects for automated monitoring examined.

RESUME
Le rapport passe en revue les récents développements dans le domaine de l'inspection des ponts en Europe et met en évidence certains principes techniques généraux. Le but et le classement des types d'inspection systématique et la présentation des rapports d'inspection sont discutés. Les instruments pour l'inspection sont évalués et les perspectives d'automatisation examinées.

ZUSAMMENFASSUNG
Die Arbeit untersucht den Stand der Technik bei der Brückeninspektion in Europa und zeigt bestimmte allgemeine Grundregeln und Praktiken auf. Zweck und Klassifizierung einer systematischen Inspektion sowie die Art der Inspektionsberichte werden diskutiert. Instrumentelle Hilfsmittel für die Inspektion werden bewertet und die Aussichten für eine automatisierte Kontrolle untersucht.

1. INTRODUCTION

Inspection is an essential ingredient in the assessment, maintenance, repair and replacement of bridges and, in a broader context, it provides the feedback of information on performance in service to design and management. The primary justification for inspection is the promotion of the safe passage of highway users, coupled with the protection of capital invested in bridges, with the minimising of operational cost and interference with traffic flow [1]. In addition there are many secondary reasons for inspection which arise from legal, social and political considerations, such as fear of legal liability, of unfavourable publicity, of political embarrasment, and loss of revenue and of professional and national reputations or prestige.

The emphasis on safety is in harmony with the evolving design philosophy of limit states [2]. These are limiting conditions beyond which a structure or element is assumed to become unfit for its purpose. They may be broadly classified either as ultimate or collapse limit states or as serviceability limit states. Catastrophic collapses of bridges in service causing personal injuries are, fortunately, rare, but even so the public is unwilling to accept any risk of collapse even though technical and economic considerations show that this cannot be achieved. In such circumstances, inspection provides a check on unforseen and unfavourable developments and gives the public a measure of assurance and confidence that is unlikely to be provided by a rational assessment of risk.

The serviceability limit states having a direct bearing on inspection are cracking, deflection, displacement, deformation, vibration and loss of material. Limits for such states are more difficult to define and quantify than those for collapse because they have to be related to the circumstances in which they occur and they may only need to be set in terms of the secondary effects they produce. For example, flexural cracking of a reinforced concrete beam may be of little structural consequence until it produces corrosion of reinforcement. Furthermore, each bridge has a certain uniqueness even though there is some standardisation of design and of components. It is likely that feedback of information from inspection will assist with sharpening the definitions of serviceability, and with identifying their practical effects.

On a more parochial level, further purposes of inspection can be identified as:
- Detection of actual and potential sources of trouble at an early stage; the "stitch in time" philosophy.
- Systematic recording of the state of the structure.
- Checking the effects of changes in construction materials and techniques, in permitted loads and in the environment.
- Providing information to make remedial action more cost effective.

2. TYPES OF INSPECTION

Whereas the inspections carried out during construction of a bridge are solely concerned with its quality and the quality of its elements, the in-service inspections are also concerned with changes in quality over a period of time. They are, therefore, some measure of reliability, if the latter is defined as the probability that the system will operate without failure for a given time under given conditions. A distinction is drawn between periodic inspection and breakdown inspection; the former is carried out on a regular basis, the latter being done when there are signs of failure. Over the past decade there has been increasing emphasis on periodic inspection, justified more by social and safety reasons than by economic ones. It has gradually become more structured and systematic, to improve its effectiveness. Expediency and restraints on resources will, however, ensure that many inspections are only done in association with a degree of breakdown and urgency.

Bridge inspection practice, in Europe, as reviewed by the OECD Road Research Group in 1975 [1], can be broadly classified, in terms of its intensity, frequency and scale, in the following categories:

- Superficial Inspection. This is carried out by maintenance personnel as and when they are in the vicinity of the structure. Only major defects or damage will usually be detected.
- Principal Inspection. This is carried out by trained personnel at regular intervals at two levels of intensity and frequency. The general inspection will be made at intervals of one to two years and the major inspection, requiring close and thorough examination, will be made at intervals of three to six years. Written, diagramatic and photographic records will be kept of the more important observations.
- Special Inspection. This will be carried out in unusual circumstances, for example, when there are signs of serious damage or when the bridge has to be reassessed for changes in loading or environment.

The principal inspection falls into the category of periodic inspection whereas special inspection is of the breakdown type.

This empirical classification reflects the complex interaction of a large number of factors, such as life expectation of bridges and their elements, their rate of deterioration, the consequences of unserviceablity and failure and the resources available for inspection and maintenance. These are difficult to quantify, but they need to be considered in the examination of present practices and the identification of trends for the future.

2.1 Rates of Deterioration

It is accepted in design that different elements will deteriorate at different rates. Those which are renewable or replaceable without loss of safety can have relatively short lives, for example surfacings, joints and guard rails. Their replacement does, however, carry the economic penalty of interference with traffic. With respect to setting the frequency of inspection, it is the shortest period for replacement which is of primary interest and, for the elements referred to, this can be as short as 5 years. The condition of many of them can be very adequately assessed by a superficial inspection and any secondary consequences of their deterioration, for example, the effects of water penetration through waterproofing and joints, examined in more detail during a general or major principal inspection. This implies that at least two principal inspections would be required to recognise trends in performance before early failure, which, in turn, determines a period of around not more than about 2 years between general principal inspections. For major elements of a bridge whose failure might precipitate or constitute collapse, the life expectation is very much longer, normally between 60 and 120 years. In the British design rules [3], for example, there is an expectation of a life of 120 years with a probability of failure in fatigue of about 2.5%. Taking all forms of degradation into account the European mean life expectation is around 60 years and actual life may be as low as 20 years. As the major principal inspection addresses itself to all structural details, a frequency for it of at least 2 per 20 years seems desirable. In manufacturing industry there is a reasonably well established procedure for relating reliability of a system to the failure rates of its elements [4]. For reasons discussed in the Introduction it is not possible to translate this directly to bridge reliability or serviceability. However, some general ideas might usefully be borrowed and perhaps used as a framework for future collection and analysis of data. It will not be possible to collect meaningful data on failure rates, because the numbers of identical elements subjected to the same in-service conditions will be very small and incidence of complete failure rare. However, if a measure of deterioration is substituted for failure then similar patterns of performance are discernible. For example, the length or width of cracks, or both, might be used as a quantitative measure of deterioration and its rate of change with time would be expected to show the "bath tub" form of Fig 1 experienced with failure of manufactured articles.

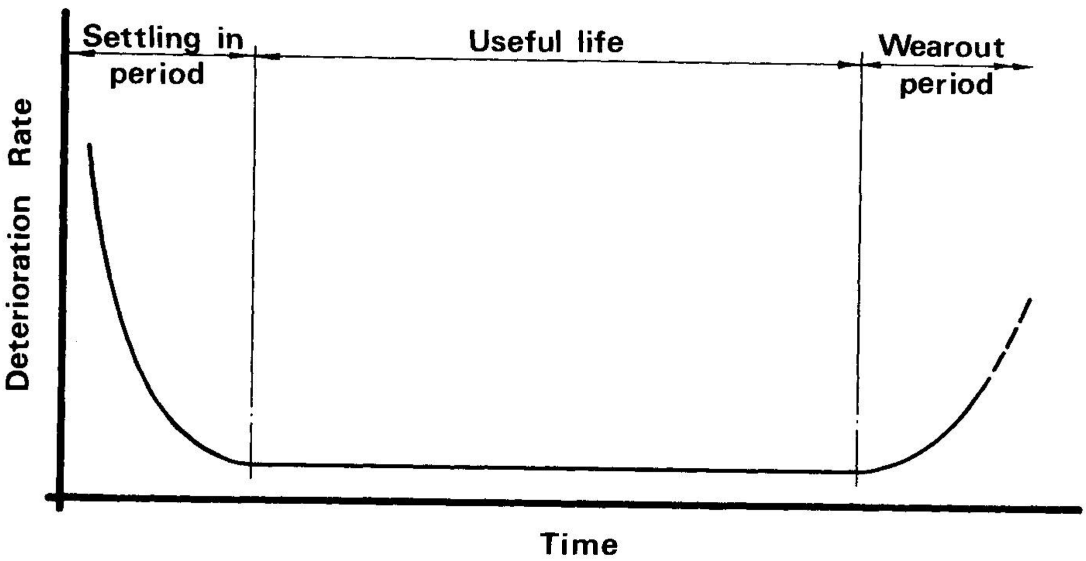

Fig. 1. Change of rate of Deterioration

Defects will become apparent in the early life of an element due to imperfections inherent in the material or introduced in the construction processes. Many of these may be rectified by the constructor during the contract maintenance period immediately following the opening of the bridge to traffic. Gradually such defects will become less frequent until the deterioration rate levels off to a low value during the period marked in Fig 1 as "useful life". A constant deterioration rate will be synonymous with random occurrence of defects. Eventually there will be a significant increase in deterioration rate as the element enters the wear out period of its life, when decisions will have to be taken about repair, rehabilitation or replacement.

The concept of a constant rate of failure, k, provides the following simple relationship between the reliability, R, after a given time, t, in service:

$$R = e^{-kt} \qquad - (1)$$

in which the failure rate will be defined as the number of failures, n, in the accumulated hours in service of all comparable elements, Nt, subjected to comparable conditions, so that

$$k = n/Nt \qquad - (2)$$

If this concept is applied to the bridge as a whole and, if it is assumed that all bridges fail at a 100 year life, the equivalent failure rate would be about 10^{-6} hr^{-1}. The Bridge Administration of Rheinland - Pfalz, Germany applied the reliability concept to the performance of a sample of bridges in service, defining k as a function of failure mode and maintenance intensity [5].

The mean time before failure, ϕ, defined as the sum of the number of hours in service per failure, for a constant failure rate, might be regarded as a pointer to desirable inspection frequency. ϕ will be the reciprocal of the failure rate, ie 1/k. Defined in this way, it strictly only describes the useful life period of Fig 1, whereas mean life of an element includes a significant part of the wear out period as well and is sometimes taken as a measure of how long it takes for wear out to begin. If time is measured in intervals of ϕ, the reliability function for a constant failure rate takes the form:

$$R = e^{-t/\phi} \qquad (3)$$

This is shown in Fig 2.

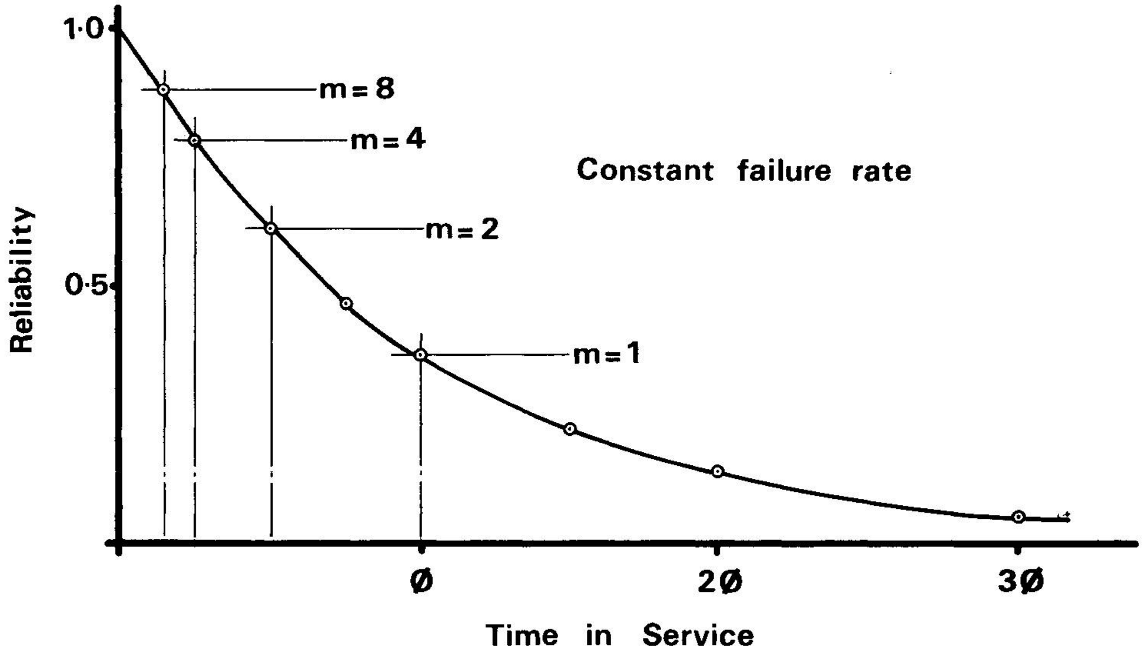

Fig. 2. Reliability and Failure Time

The probability of an element surviving to ϕ is 0.37. The period between inspections might be selected as some fraction of ϕ, (ϕ/m), which gives an acceptable reliability, using the expression:

$$m = -1/\log_e R \qquad (3)$$

If a probability of failure for a random failure mode is thus to be kept below 10%, at least ten inspections would need to be carried out during the mean time before failure. With only two inspections the corresponding probability of failure would be 39%.

The foregoing simplifying assumption of a constant rate of failure illustrates a general principle. In practice, the failure rate is likely to be variable and will be further complicated by the interaction between the failure of elements comprising a complete structural system such as a bridge. It is observed in fatigue behaviour that as the service time increases, the crack size increases and the residual strength decays, thus increasing the failure rate [6]. Furthermore, for the longer service lives in aggressive environments, fatigue failure rate will be influenced by degradation of the material due to other mechanisms, such as corrosion. As a general rule, it may be stated that inspections are going to be beneficial by truncating the tail of the statistical distribution of flaw size at the larger flaw end. The extent of the improvement in structural reliability and safety will depend on the quality of the inspection.

For redundant systems made up of many elements with a constant failure rate, the overall system failure rate will increase with time. If it is subjected to periodic inspection and consequent corrective maintenance, the failure rate may be taken as returning to zero after essential maintenance is done. An average failure rate may then be taken over several periods of inspection and this average approximates to a constant value. System reliability, measured in terms of mean times to failure, when plotted against the time between periodic inspections will then take the same form as Fig 2. Periodic inspection and maintenance will not improve the reliability of a system without redundancy, but it will improve the probability that an element or system that has failed will be restored to operational effectiveness within a given time.

2.2 Consequences of Failure and Unserviceability

The form and frequency of inspection will be influenced by the likely consequences of failure or unserviceability. A degree of unserviceability is more likely to be tolerated than is a high risk of collapse. If the latter is suspected, then usually the first reaction is to increase the frequency and intensity of inspection. In some cases this may provide the necessary assurance to preclude the need for further action.

It is the safety or reliability of the bridge as a complete structural system that is the ultimate concern of the owner and this is usually determined from the reliability of its components. Many system-component relationships exist, but probably the two main ones are the series and parallel relationships. In a series system, failure of any of the components results in failure of the system. An example would be the failure of the support or deck of a simply supported structure. The overall reliability of the series system will be the product of the reliabilities of its components. In the parallel system, the system does not fail when only one component fails. There is, therefore, a degree of redundancy which determines that a certain number of components must fail before the system fails. In such a system it is the product of the unreliabilities of the components which gives the system unreliability; unreliability being defined as unity minus reliability. An example of a parallel or redundant system is given by a multi-beam deck with a connecting composite slab. From the safety aspect, the system will only be redundant to the extent that certain beams might fail without reducing the global factor of safety below unity. Most bridges will be combinations of series and redundant systems and most of the redundancy will be active, that is, the components are in continuous service. When one component fails the conditions imposed on some other components become more onerous, thereby accelerating their failure rate. By identifying and repairing the failed component quickly in a redundant system a large increase in reliability can be achieved, since the system is only vulnerable during the time the component is damaged and under repair.

Some failures are partial, in that the bridge does not collapse, but it may be put out of service. An example would be the failure of the one bearing in a single bearing support. Such failures are usually readily apparent during any of the types of inspections listed previously. It is more problematical to determine trends towards partial or complete failure, but if sequential inspections and assessments give rise to suspicion, then they may initiate a process of derating or load restriction.

The severity of the consequences of a defect is one of the means that can be used in classifying defects. This has been done for steel and concrete structures by the Ministry of Transport in France [7] [8] [9], using the following categories:

B - Defects without important consequences apart from appearance.
C - Defects which indicate the risk of abnormal developments.
D - Defects which indicate developing deterioration.
E - Defects which show a change in structural behaviour and which may affect durability.
F - Defects which indicate the approach to a limit state, necessitating restrictions on use and rendering the structure unserviceable.

2.3 Resources for Inspection

The frequency and intensity of inspections will obviously depend on available resources in terms of manpower, its skills and the available equipment. In Europe there has been a long-established practice of recruiting inspectors from the more able group of craftsmen and tradesmen employed in the building and civil engineering industries. Only in this way could the number of people required with the necessary basic skills be obtained. Over the past decade there has been a requirement for added knowledge of basic theory and this is being met by in-house and extra-mural courses. Only in France has formal training in bridge inspection being undertaken on a national scale, but several countries have intensified their training method at regional level. Since inspection is closely allied to maintenance, the practice in a few countries is that bridge inspectors carry out minor maintenance not requiring equipment larger than hand tools. Greater involvement in repair work has usually been discouraged to preserve objectivity of inspection. With the growing relative importance of maintenance and inspection in highway operation and management, there is an expansion of knowledge in this subject area, which is giving it greater technical respectability. At the same time, bridge inspectors are acquiring a better status and self-confidence.

Technical equipment in support of the visual observations made during principal inspections has generally been confined to simple hand tools, gauges, markers, binoculars, mirrors, magnifying glasses, movement and crack width gauges. This is not so much due to restrictions on the purchase of more elegant and complex apparatus, as to the realisation that greater elegance, complexity and refinement does not improve the results of inspection to a degree which justifies the cost and effort involved. This is exemplified by the principle, "Inspect only as much and as accurately as is necessary", contained in the report of a Project Group set up by the German Federal Highway Institute [10]. For special inspections, more advanced diagnostic testing is necessary and justifiable, even to the extent of deploying techniques which are in the stage of research and development. The boundary between research and practice is fluid, so that some procedures that were research projects 10 and even 5 years ago are now close to application during principal inspections. Examples are the measurement of half cell potentials and resistivity in reinforced concrete for determining the risk of corrosion activity.

The means of access are an important aspect of inspection and are a resource which can strongly influence its quality and methodology. The neglect of maintenance considerations in the design of bridges over the past two or three decades is gradually being remedied, but it is going to be reflected for some time in the difficulty of getting access to the more vulnerable parts of bridges. Traditionally long steel bridges over estuaries and deep valleys have been recognised as being in need of regular inspection and maintenance and have been equipped with maintenance gantries. Some gantries have had operational deficiencies, and have presented a significant maintenance problem themselves. The hope that concrete bridges would be maintenance free has not been fulfilled and this has encouraged development of a range of access measures. The mobile hydraulic platform operating from the bridge deck is probably the most versatile and has been widely used in Germany, Italy and France. Average utilisation of such equipment is not high, however, ranging from 400 to 1100 hours per annum for each machine in 1975 [1]. Relatively heavy equipment may be needed to meet operational and safety requirements and it will occupy two lanes of a bridge deck. The overall weight of current machines is between 50 and 150 times the load carrying capacity of their platform, depending on reach. A further obstacle to their use is the increasing height of parapets and noise barriers demanding different forms of articulation and larger operating ranges. In Germany a third generation of this type of mobile bridge inspecting equipment is going into operation to overcome some of these problems. The railways have been dealing with them for many years and have given careful consideration to the design of special access machines to operate in both the upward and downward mode in the presence of overhead electrified lines [11].

In Britain the demand for such machines for highway work has not been great. This is probably because of a combination of several factors such as the absence of hilly terrain on major routes, the availability and adaptability of the simpler lifting hydraulic platforms for inspecting street furniture and some doubts about the cost effectiveness of the more versatile machines. However, the increasing cost of using scaffolding in some of the more difficult situations may cause some reconsideration of this aspect. Walkways are being looked upon with increasing favour, not only for the longer spans where they have been traditionally installed, but also for medium spans in inaccessible locations. When used as the supporting framework for demountable platforms made of standard prefabricated planks, they can provide a flexible system of access for both inspection and maintenance.

3. TYPES AND SEVERITY OF DEFECTS

There are a variety of ways of describing and classifying defects and the condition of the structure, all of them directed at making bridge inspections more comprehensive and uniform. One way is to group defects in terms of the main elements of the structure [1]. A considerable development on this is the illustrated catalogue format adopted in France [7] [8], in which the defects are broadly classified in terms of the type of structure and are then described in detail, with photographs and comments, and given an index of severity on the scale described in section 2.2 of this paper. A combination of a scale of severity of defects with a scale of their extent has been proposed by a Bridge Inspection Panel of the UK Department of Transport [12]. By a subjective integration of the rating of severity of defects on individual components, an assessment of the general condition of the structure is derived. It can be argued that using any scale or index calls for judgements on the likely consequences of defects that are beyond the capabilities of the inspector. Nevertheless any qualitative scale is likely to involve judgement to some degree. They do provide a framework for a rational approach and it is hoped that most of their shortcomings will be overcome by practical experience.

Smith [13] and Blockley [14] have examined the history of the more spectacular bridge collapses over the past century and have attempted a broad classification in terms of causes. It is of interest to note that in the sample of 143 cases examined by Smith, 113 occurred after two years in service and the causes may be broadly classified thus:

Flood and foundation movement (57% scour)	59%
Defective material or workmanship	14%
Overload or accident	11%
Earthquake	10%
Fatigue	4%
Corrosion	1%
Wind	1%

Blockley examined structural reliability theory in dealing with parameter uncertainty and its inadequacies in dealing with system uncertainty. He also discussed the effects of human errors and listed these as either deliberate or non-deliberate acts. Against this background he produced the following main categories of causes of failure which are design and construction orientated:

- Overloading and/or understrength
- Random hazards
- Oversight of basic mode of behaviour
- Errors in construction and communication
- Adverse financial, political or social climate
- Misuse or abuse

These categories are of interest, but they do not necessarily reflect the pattern that emerges from inspection of bridges before they fail and do not give a clear indication of how effective inspection might be in anticipating and preventing failure. Unfortunately, there are no statistics on this, so that the following discussion is largely speculative. In order to embrace serviceability, as well as collapse, failure is taken to mean unfitness of a structure or element for its purpose. Failure modes may be classified as either catastrophic failures or degradation failures.

- Catastrophic failures are both sudden and complete. A sudden failure is one which could not be anticipated by prior inspection and a complete failure results in the total cessation of function.
- Degradation failures are both gradual and partial and result in deviations from acceptable limits without complete cessation of function. They can be anticipated by prior examination.

It is difficult to restructure the above percentage classification of the data on complete failures collected by Smith, but assuming the failures due to flood and scour were sudden, catastrophic type failures account for about 80% and degradation type failures for only about 20%. This is not surprising in view of the fact that all the failures listed attracted considerable publicity in view of their catastrophic nature and, in many cases, were the subject of public enquiry. Many of them would not have been detected by prior inspection, even with modern equipment.

Periodic inspection can only anticipate failures of the degradation type, and it does so by revealing changes in defects. If design and construction are to become more maintenance orientated then in addition to making structures more accessible, there should be recognition of the limitations of inspection by having larger partial safety factors and higher quality for materials in locations where a catastrophic type of failure can occur or where the probability of detecting a partial failure is low before it becomes complete.

4. INSTRUMENTAL AIDS

In the present state of the art, periodic bridge inspection is done primarily by direct observation assisted occasionally by touching and listening. For the immediate future there seems to be no practical alternative to the combination of the trained eye and the experienced and perceptive mind, so that the role of instrumental aids will be a supporting and confirmatory one. The simple optical equipment referred to previously can enhance the power of visual observation and there is probably scope for the application of closed circuit television, with its image enhancement capability, to the detection of defects at a distance, above as well as below water. Monitoring on colour television of the image obtained by an endoscope or borescope in a confined location is a considerable improvement on the view through the normal eye piece with the added advantage of obtaining a video recording. However, it is possible to increase the sensitivity of detection methods to the point where the indication of flaws is either false or confusing. The author has attempted to examine fine crack patterns in a concrete surface with the use of a fluorescent dye. The dye was in the form of a powder of 10μm particle size suspended in a volatile liquid. After application to the surface the particles concentrate along the line of any cracks, wider than 10μm, and become visible in ultraviolet light. This technique provided some assistance in tracing the extremities of visible cracks, but it tended to cause confusion where crack patterns were ill-defined or where the concrete surface was rough. Most of the cracks revealed were characteristic of a normal concrete surface and had no structural significance.

Visual inspection has obvious limitations in terms of detecting internal and hidden flaws, in assessment of quality, in making remote observation, and in speed of response. Research is in progress to overcome some of these limitations and it is having some success, but at present it falls well short of providing the ideal diagnostic service the inspector and engineer would like to have.

Since inspection is primarily concerned with safety its ultimate goal is the determination of structural condition and strength. Strength, whether intrinsic or residual, is not directly measurable without causing unacceptable damage, so that all non-destructive methods rely on an indirect evaluation of strength by measuring some other quality, whose correlation with strength is determinable. Sometimes this correlation is tenuous and involves intermediate stages. For example, in the ultrasonic testing of concrete the transit time of 50kHz pulses through the concrete are measured to give the pulse velocity. This is directly related to the elastic modulus, density and Poisson's ratio, all of which have an indirect association with concrete strength. The exact nature of this association depends on the composition and quality of the concrete. To achieve an assessment of strength which is with ±25% of the actual value usually requires calibration of pulse velocity using cubes or cylinders of identical composition which can be strength tested. If the concrete contains reinforcement there are added complications because of the higher velocity of sound in steel.

Various methods of assessing concrete strength in existing structures are described in a recent British Standard [15] and a wider review of testing techniques for all the main materials in bridges was given in the OECD Report [1]. The latter also drew attention to particular problems where instrumental aid might be of assistance to inspection, indeed might be the only possible means of carrying out an inspection. One of the problems referred to was the state of fully bonded prestressing steel tendons in post-tensioned concrete. Some of the methods tried to solve this will be briefly described to illustrate some of the difficulties involved.

No direct non-destructive method of examining the condition of tendons embedded in a structural member has been developed hitherto. Radiography comes nearest in principle to achieving this, but under the conditions encountered in bridges it can provide little information on the degree of corrosion of the tendon or its loss of section. This is because the change in optical density on the radiograph is either too small or too limited in area to be detected. This is hardly surprising when it is realised that the radiation of X or gamma rays have to penetrate a thickness of concrete of 0.5m and more, with an exponential reduction in their intensity with thickness, and with a marked penumbral effect due to size of the radioactive source.

It is known from past experience that little or no corrosion of tendons occurs when the ducts in which they are placed are fully grouted with cementitious grout. The condition of the cable might, therefore, be inferred from the continuity and density of the grout. If no voids are present, then the tendon is assumed to be well protected whereas the presence of voids is taken as a potential corrosion risk. The lack of continuity of grout is more readily detectable on a radiograph than corrosion of steel, but in practice there are limitations. Because voids are more likely to occur in the upper part of a duct and because the surface between the grout and a void is approximately horizontal, the X rays or gamma rays should be directed horizontally to detect void boundaries. However, the image projected on to the radiograph will be masked by tendons and by metallic duct formers in the same plane. Nevertheless, it is possible to detect voids in ducts in narrow concrete webs and beams with no more than one duct in any horizontal plane.

To obtain detailed information on the state of the tendon and the grouting, it is necessary to resort to more destructive means [16]. 25mm holes have been drilled into a number of ducts on selected bridges in the UK, using as-built drawings to locate them. The ducts were carefully opened to avoid damage to the tendon and then inspected using a borescope. Where a void was present the state of the tendon could be examined. If possible samples of grout were removed for analysis. From 3 to 5 holes were drilled into each duct. Air was evacuated through each hole in turn and the pressure (degree of vacuum) measured at remaining holes. This gave an indication of continuity along the duct. The volume of any voids present was measured by connecting the evacuated holes to a water gauge consisting of a perspex tube dipped in water. The rate at which air could leak out of ducts was determined from the input flow rate of nitrogen gas applied to the holes at a pressure of $17N/mm^2$ above atmospheric pressure. Where high flow rates were measured, the points of leakage could be determined by the generation of bubbles in a soap solution applied externally to the structural member.

Voids were discussed in 55% of the ducts examined in 10 bridges. They were usually larger in older bridges and in diaphragms cast in-situ between beams. Voids tended to be concentrated at high points in the duct profile and were found most frequently where they were deflected upwards over supports in continuous structures. They may also be present near anchorages. In six of the bridges, voids were of sufficient size so as to reveal the tendons, but even so they were covered with a thin film of cement paste and there was no evidence of serious corrosion. The degree of protection would be inferior to that given in a fully grouted duct and will be at greater risk from carbonation and ingress of chloride ions. Thus the maintenance of protection may depend on how well the ducts are sealed.

Another method of assessing the integrity of the tendon and the anchorage is to determine the level of residual prestress at strategic locations in the concrete. Although more complex than observations on the condition of the tendon, it does relate directly to the most important structural effect and provides a direct indication of the loss of prestress. A method for measuring residual strength by partial stress release is being developed in France [17]. It involves cutting a thin slot in the surface of the concrete by circular saw and then inserting a thin flat jack into it. The pressure on the jack is increased to restore the strain across the slot to the level in the concrete before it was cut. The pressure at nil strain is then the initial stress. Tests done hitherto show a maximum difference of 10% between the measured stress and an applied stress. Difficulties may arise if the concrete at the surface has markedly different properties to that in the interior of the member, either due to the method of construction or the curing, weathering and ageing in service. They may be partly overcome by cutting slots to different depths. If reinforcement is present and it is cut some corrections have to be made for local redistribution of stress. The level of stress measured is the resultant value, from which stresses due to live, dead and environmental loads would have to be deducted to obtain a meaningful value of residual prestress. If, therefore, the residual value is relatively low there is the risk of large errors.

5. MONITORING OF BRIDGES

Techniques and equipment for monitoring the overall condition of a bridge present possibilities of making a rapid assessment of condition and changes in condition, and of detecting faults which might not be found by visual inspection. However, no method has yet been perfected which provides a practical and universal means of monitoring. The following are some techniques which have been suggested or are under development:

5.1 Changes in Geometry

A project group of the German Federal Highway Institute has reported on the monitoring of bridges [10] and proposals are made for the measurement of geometric changes as a means of detecting faults in the structure. Various methods of measuring are proposed including conventional geodetic techniques, hydrostatic levelling, electronic range measurements, laser measurements, photogrammetry and electrical and mechanical measurements. The procedure requires that a reference state for the bridge be established initially and limit values prescribed for various inspection measurements to be made. Selected main checks are first made and only if these show results outside the limit values are the full set of detailed supplementary measurements made. The methods of measurement proposed appear to be most applicable to medium and long span bridges where the geometric changes are likely to be large enough to be measured with sufficient accuracy. Most of the current problems with short span concrete and composite structures are such that, even where there is substantial development of a flaw or loss of material, the resulting geometric changes are small and difficult to distinguish from thermal effects.

5.2 Changes in Response to Vibration

The objective is to relate defects in the structure to changes in dynamic characteristics. The development of a technique using traffic and wind-induced vibration has been described by McKenzie and Macdonald [13]. It consists of temporarily attaching accelerometers to the structure and making simultaneous recordings of the vibrations. The modes of vibration and damping may then be determined by computer analysis and this provides a signature of the structure which will change only if the properties of the structure and its supports are changed.

In the SHRIMP method developed by Savage and Hewlett [19], a variable frequency sinusoidal force is applied to a point in the structure and responses at other points are measured. These responses depend mainly on fixity and stiffness of connections to other parts of the structure. Both the above vibration methods measure loss of stiffness, not loss of strength. A loss of stiffness implies a loss of strength, but a serious loss of strength could occur, as with a crack in a steel member, before producing a measurable loss of stiffness.

5.3 Acoustic Emission

This technique can detect and locate cracks by the sound produced during their development. Continuous recording is therefore needed and this makes it suitable only for vitally important parts of the structure such as the main cables in a suspension bridge. It has also been used in an endeavour to detect cracks during loading tests on a damaged reinforced concrete structure and during repairs to a post-tensioned concrete anchorage. In both the latter cases the results were disappointing and no clear pattern of crack development or of a relationship between emission and scale of cracking could be identified.

5.4 Support Reactions

Diruy [20] and Chatelain [21] have described the development of an instrumented bridge bearing for measuring the redistribution of reactions under prestressed concrete bridges. Measurements made over a period of 5 years showed the effects of creep and shrinkage but superimposed upon this are variations due to thermal changes. It is not known whether the results would give a definite indication of loss of stress in the structure due to corrosion of tendons. The specially designed bearings have to be installed during the construction of the bridge. Other commercially produced instrumented bearings are available but the development of load-measuring techniques without special bearings would simplify the use of this method of monitoring. The monitoring of support reactions would provide a valuable indicator of changing conditions in continuous structures.

5.5 Corrosion Monitoring

The risk of corrosion of reinforcement and prestressing tendons may be assessed by installing electrical resistance probes [22] during construction of the bridge. The probes consist of exposed and protected thin metal electrode and, as the former corrodes, the electrical resistance of the probe changes. To obtain representative results, probes should be placed at a number of points within the structure and it may be necessary to ground the probes to the tendons.

The techniques described in sections 5.4 and 5.5 above require the installation of instruments in a structure and this can sometimes only be done during construction. It follows that, if condition monitoring is to make a significant contribution to bridge inspection, the techniques and equipment have to be carefully considered during design.

6. ECONOMICS OF INSPECTION

Attempts were made to compile costs of bridge inspection and maintenance in the reports of the OECD [1][9]. Firm data was difficult to obtain because most highway organisations did not identify them as separate items. Various estimates showed that in 1974 the annual cost of inspection ranged from $13 to $130 per bridge. The low cost figures probably referred to superficial inspections of small structures. Ratios may be more meaningful. For example, the ratio of annual inspection cost to current construction cost, both expressed in terms of unit area of bridge deck, varied from 2×10^{-4} to 7×10^{-4}. The annual maintenance cost expressed as a ratio of current construction cost ranges from 0.3×10^{-2} to 1.5×10^{-2}. Combining the two gives a ratio of inspection cost to maintenance cost in the range of 1.5% to 20%. In many European countries maintenance cost of bridges has multiplied 3 or 4 times in the past 5 years reflecting not only a growing rate of deterioration, but also, hopefully, the increased effectiveness of inspection.

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