Monitoring to Prolong Service Life

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INTRODUCTION

Prolonging life of existing structures is an important aspect of the work of structural engineers. These structures cover a variety of types including bridges and buildings. In bridges the adverse environmental conditions, damage due to earthquakes or floods, human intervention such as the use of de-icing salts and increasingly heavy traffic loads require bridge inspection on a regular basis and detailed assessment of their safety for use when deemed necessary.

In terms of buildings, deterioration with time, damage due to earthquakes or tornadoes, change of use and/or even re-arrangement of the load bearing components due to architectural needs also require their inspection and assessment when necessary.

The assessment of many of these structures results in some restriction of use or otherwise relaxation of the safety margins. For bridges limitation of available funds and perhaps prioritisation of the strengthening or replacement programmes often means they need to remain in use for a number of years. In buildings similar restrictions can apply, however, in the case of historical structures, there is no choice but to come up with alternative solutions to provide longevity.

One of the methods that is becoming more popular amongst engineers is the use of monitoring techniques to establish the real behaviour of the structures and to determine the on going rate of deterioration in order to implement repair works at the right time.

This paper describes the use of monitoring techniques as an approach to prolong life of structures through describing the general strategy, available instruments and techniques. In addition, case studies are presented for projects on which monitoring is being used.

GENERAL STRATEGY

The flowchart in Figure 1 shows the basic strategy for deciding whether a monitoring system is required. Obviously, the reliable functionality of a structure has to be in doubt in the first place which could be as a result of a number of factors such as change of use, increased loading, deterioration and damage due to fire, blast, subsidence, earthquake etc. This would normally require a load capacity assessment of the structure, which starts by the collection of all the relevant information such as drawings, geotechnical investigations, previous inspections and records. This basic process has been used in the assessment of bridges in the United Kingdom using BD21(1) for the Highways Agency. A similar procedure is operated for buildings using "Appraisal of Existing Structures" for the assessment of buildings(2). The assessment would normally start from a simple and conservative approach based on the design parameters.

However, it could become more complex making use of the existing material properties, sophisticated analytical methods and supplementary load testing[3-4].

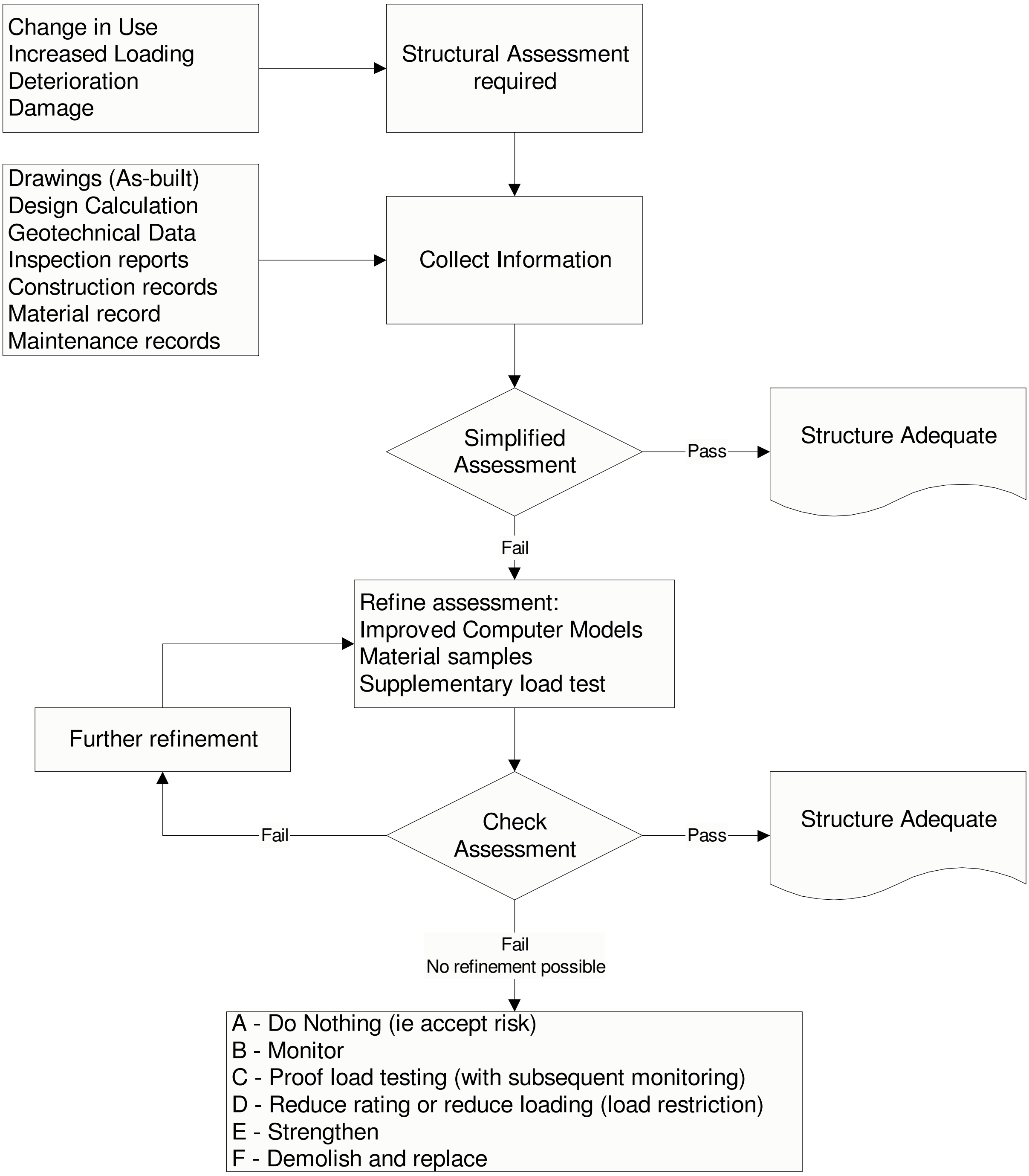

Figure 1. Flowchart showing strategy for assessment leading to monitoring

If all the attempts to pass the structure fail, the options available to the owner start from "Do Nothing" which is also often implemented while further investigations are carried out. However, this approach could have significant legal implications from Health and Safety point of view. The next strategy level is to monitor the structure. Provided monitoring is viable, it has a number of advantages over the rest of the options in Figure 1, which are as follows:

- Steps have been taken to improve the safety of the public or the users.
- Monitoring is providing a warning system.
- Rate of deterioration, if any, can be determined.
- Resources and funds can be released for more urgent projects (or developments).
- Future prioritisation for strengthening, etc. will be based on a performance based criteria.

MONITORING SYSTEM

The viability for the implementation of a monitoring system has to be established first. The following questions have to be answered.

- Does the deficiency to be monitored have a sudden failure mechanism? If yes, then the monitoring may not be the right solution or it has to be much more comprehensive.
- What components need to be monitored and to what accuracy? This affects the choice of instruments.
- What is the frequency of data sampling and is there any access limitation? Electronic devices and a data logger(s) may be needed.
- What is the design life for the system? The system has to be designed for the effects of weather and vandalism.
- How is the data to be accessed? A modem link and telephone may be required.

Other considerations, which may indirectly affect the choice of the instrumentation, are as follows:

- Time available for installation of instrumentation
- Requirements for traffic management
- Requirements to remove non-structural components to reach the main structural component to be monitored
- Purpose of the monitoring (ensure safety of users, improve engineering understanding, legal arbitration, determine cause and effect, or simply find out about trend of an event)
- Cost (sometimes this is the first thing to be considered but not always)

Monitoring Instruments

There are a number of different monitoring devices. The choice of which to be used is dependent on a number of factors, which have been referred to in the previous section. In Table 1, the details of a range of suitable monitoring instruments are given. This list is not exhaustive and manufacturers should be contacted as new devices with improved performance and resolution are being developed.

Data Acquisition

This is an important aspect of any monitoring system. In the circumstances where access is difficult or dangerous or very expensive or frequency of data sampling is very high, it is usually essential to have a datalogger and to use devices, which can be read electronically. The collected data can then be downloaded to a portable computer for subsequent data interrogation. It could be cost effective to use a telephone modem link to collect the data remotely. With the reliability of mobile phones, it has become possible to collect the data remotely from most inaccessible areas.

Table 1. Monitoring Instruments

Device	Measuring	Accuracy	Suitable for	Sampling
Tell-tale	Movement	0.1mm	Masonry etc	Manual
Calliper	Movement	0.05mm	General use	Manual
Vernier	Movement	0.01mm	General use	Manual
Dial gauge	Movement	0.02mm	General use	Manual
DEMEC	Movement /Strain	0.001mm /$10x10^{-6}$	Steel and concrete strains and small crack movements	Manual
LVDT	Movement	0.01mm	Steel, concrete and masonry	Electronic
VW Crack	Movement	0.001mm	Steel, concrete and masonry	Electronic
VW Strain	Strain	$5x10^{-6}$	Steel, concrete and masonry	Electronic
Tilt	Rotation	1 - 5 Seconds	Global rotation	Electronic
Inclinometers	Rotation	10 Seconds	Global rotation	Electronic
Accelerometer	Acceleration	1 to 5% range	Vibration	Electronic
ERS	Strain	$1x10^{-6}$	Steel strains	Electronic
Thermocouples	Temperature	0.1deg C	General purpose	Electronic
Thermistor	Temperature	0.1deg C	General purpose	Electronic
PR	Temperature	0.01deg C	General purpose	Electronic
Laser	Movement	0.1 to 1mm	Access limitation	Electronic
Precise levelling	Movement	0.1mm	General purpose	Manual
Photogrammetry	Movement	1 to 5mm	Large areas	Manual
Anemometers	Wind speed	0.3m/s	General purpose	Electronic
Load cells	Load	1% of max	Bearings and cables	Electronic
LPR	Current	10^{-9} Amp	Rebar corrosion in concrete	Electronic
Corrosion cells	Potential	10^{-3} Volt	Rebar corrosion in concrete	Electronic
Corrosion current	Current	10^{-9} Amp	Rebar corrosion in concrete	Electronic
Resistivity	Resistance	0.5kΩ.cm	Rebar corrosion in concrete	Electronic
ER Probe	Resistance	1% thickness	Loss of steel in concrete	Electronic

DEMEC = DEmountable MEChanical strain gauge
LVDT = Linear Variable Displacement Transformer
VW = Vibrating Wire (Crack or Strain) gauges
ERS = Electric Resistant Strain gauges
LPR = Linear Polarisation Resistance
ER Probe = Electrical Resistance Probe
PR = Platinum Resistance

For further information on corrosion monitoring refer to BRE Digest 434, Corrosion of reinforcement in concrete: electrochemical monitoring. November 1998.

Data Management and Presentation

The data from manual monitoring systems or those collected by a datalogger have to be processed systematically to identify spurious readings and ignore those that are erroneous. However, no data should ever be thrown away. The normal method of presentation of data is by the use of a spreadsheet software, where key readings could be presented in a tabular format while the bulk of the data is converted into graphs. The facilities available in today's spreadsheet software packages have made them an integral part of almost all monitoring systems. The spreadsheet can be programmed to produce simple reports of the results of the monitoring, carry out statistical analysis and give warning if certain limits are reached.

Purposely developed software packages are also available which can be used to collect and handle data. In addition, these software packages can be used to interrogate the results and produce reports. Such a system was used on the Dee Estuary Bridge(5), north of Wales, where a multitude of instruments were installed in a pilot scheme to implement remote bridge management in the UK.

Trigger Levels

The main objective of any monitoring is to decide whether there is a need for an intervention when set of readings exceed certain predetermined levels. These are normally referred to as "trigger levels" and their determination is a matter of engineering judgement, previous records, performance of similar structures in similar circumstances and occasionally political and social considerations. For major structures, the trigger levels should be determined by a panel of experts.

CASE STUDIES

Several different case studies are detailed below which give the reasons for adopting certain types of instrumentation, their arrangement, method of data acquisition and the type of results that can be obtained.

Langstone Harbour Bridge

The Hayling Island Bridge was built in 1955 to replace an old timber bridge, which connected the island to the mainland at Langstone. The present bridge is prestressed concrete and consists of 29 simply supported spans of 9.75m and additionally four spans of 2.14m located at roughly the fifth points. The decks are supported at each end by five reinforced concrete piles and a reinforced concrete capping beam cast in situ. The 9.75m spans consist of 16 rectangular prestressed concrete beams 457mm deep, placed side by side, jointed with a dry packed mortar and transversely stressed with twelve 5mm diameter Freyssinet wires. Each beam was post-tensioned with two 28.6mm diameter Lee-McCall bars laid to a parabolic profile. A full description of the construction procedure was published by Melrose and Eyre in 1957(6).

The first span from the mainland side of the bridge was load tested by the Cement and Concrete Association in 1957(7). In addition, two precast beams were load tested to destruction, one at an age of 3 months and one at an age of 2 years. These tests indicated prestress losses of 3% and 22% respectively.

In 1989 further work was carried out by Gifford and Partners. In situ concrete stresses were measured by taking 3 instrumented stress-relief cores(8-9) and 3 instrumented slot-cuts(10) in spans 1,4 and 14 from the north end of the bridge. These spans were chosen after obtaining a finger print of the performance of all the spans under a 45 tonne axle similar to HB which traversed the bridge over night to reduce disruption to traffic. Each span was instrumented with 12 vibrating wire gauges on the soffit at midspan. Strains were measured in the longitudinal and transverse directions of the deck and across the longitudinal joints between the beams.

The estimated prestress loss in the longitudinal direction ranged between 5% to 33% which was comparable to those of 1957(6). The loss in transverse prestressing was about 44% with a remaining compressive stress of 1.7N/mm^2 across the longitudinal joints between the beams.

Spans 4 and 14 have each been monitored with 9 VW strain gauges since 1989. The strains in the longitudinal and transverse directions are measured at three points in each span. Also at these locations, the transverse strain across the longitudinal joints between the beams is monitored. The main intention of monitoring is to pick up any changes in the transverse concrete stresses, which could be lost as a result of loss of prestress in this direction. The transverse prestressing, due to this form of construction, is vulnerable to corrosion. It has been found that strains in the bridge have not changed significantly since the start of the monitoring.

A3/A31 Guildford Flyover

The A3/A31 Flyover comprises a two span single cell pre-cast segmental externally post-tensioned concrete box deck supported on a reinforced concrete pier. The main span is 50m over the A3 and the side span is 20m. The structure was built in the mid 1970's and since then has had series of problems. Corrosion of some of the tendons resulting in some cases in their severance necessitated a structural assessment, including in situ stress determination and an upward load testing to estimate the remaining level of prestress. This was carried out by first conducting a significant amount of initial analysis to identify the critical areas and levels of prestress loss required to cause the initial cracking of the concrete.

Initially the bridge was instrumented and monitored for a period to identify the diurnal temperature fluctuation effects on strains. The instrumentation was extended to 16 vibrating wire gauges to cover the concrete segments and the corresponding joints between the segments at midspan and over the central pier. Midspan deflection was also measured with the use of LVDT's. Upward load was applied in increments up to 100tonne at mid main span. The maximum upperbound of prestress loss was determined in the absence of any crack detection in the joints. In addition, the relative stiffness modulus of the segment joints to that of the precast sections was determined to be 59%.

The bridge has been strengthened in the mid 1990's as the condition of the external prestressing was considered not to be predictable. However, the monitoring and the load testing conducted allowed time to complete the design of the strengthening without the need to close the bridge. More details of the bridge and its historical problems which have lead to its strengthening are included in a paper by Brooman and Robson(11).

A Motorway Bridge in England

A major motorway bridge in England, which carries a carriageway of a motorway over another motorway, has been monitored over the past 7 years. It is a four span in situ concrete bridge with two suspended spans over the motorway below. The monitoring has been as a result of cracks at the throat of the concrete Mesnager hinges supporting the suspended spans, which were detected during the inspection undertaken for the assessment of the bridge. The initial investigation measured dead load stresses in the reinforcements across the hinge. Then the crack widths and the strains in the reinforcements were monitored. This monitoring utilised 8 LVDT's and 6 VW strain gauges and the system was connected to a datalogger, which was manually downloaded approximately every six months.

Recent inspections have indicated that crack widths in certain parts of the hinges have increased. These were carried out using go/no-go purpose made stainless steel (filler gauge) rods to measure crack widths. During the inspection material sampling was taken from the throat of concrete hinges and precise levelling was also carried out. As the system in place was only limited to the centre-line of the bridge, a monitoring system was devised by the author to extend the exiting system by another 26 LCDT's, 2 thermocouples, a datalogger and a modem mobile phone link. The present arrangement is required in order to provide an easily accessible and frequent monitoring system. The condition of the bridge is constantly under review and the monitoring is to be further expanded by the undertaking of an endoscope examination of the hinges (both non-destructively and by drilling holes) and using the X-ray technique to look at the condition of the reinforcement.

Given the stage the investigation has reached presently it is not possible to report any results. However, it is possible to state that the daily movements of the bridge at the hinges and the behaviour of the reinforcement and concrete around the cracked throats have become a subject that may require a programme of research to determine the likely effects from corrosion, fatigue and the magnitude of the applied live and permanent loads.

The above monitoring regime ensures that the safety of the structure is not in any doubt, by monitoring any changes in the condition of the bridge.

A Historical Building in London

A major grade one listed masonry building in London is being monitored presently using crack mapping, precise levelling, manual crack width measurements, 12 VW crack and 6 tilt gauges. The system was set up by the author as cracks have been widening since a recent modification to the structure. The monitoring was recommended to identify the need for any underpinning. In addition, due to the size of the project the renovation of this building is carried out in phases. Therefore it is important to keep a record of the events for any possible future discussion and investigation as to the cause of the movements and the corresponding consequences. The VW crack and tilt gauges are being monitored via a telephone modem link to a datalogger. It is hoped to be able to release some results in due course.

CONCLUSIONS

Monitoring is a tool that can be used by engineers to:

- Base their decision for the safety of the structure on facts rather than assumptions.
- Determine the priorities based on the severity of performance criteria.
- Distribute the efforts, resources and funds in a more effective way.
- Limit the expenditure when it is not really necessary.

In addition, the information derived from the monitoring of the structures have provided engineers with:

- Improved understanding of structural performance.
- Refinement in analytical methods to estimate the theoretical performance and effects of strengthening options.
- Verification of new designs and their structural behaviours to improve design methods.
- Collection of information to apportion cause and effect in disputes.

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