POSTER

Experience in Bridge Management Systems in India

Expérience dans les systémes de gestion des ponts en Inde

Erfahrungen bei der Brückenunterhaltung in Indien

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1. THE SCENARIO OF BRIDGES IN INDIA

The effective utilisation of bridges over their full design life has occupied the attention of bridge planners and engineers throughout the world and more so in a developing country like India where resources are scarce. In India the bridges are owned by Governmental organisations, both for railway and road bridges. About 6400 road bridges were listed in a recent survey only on National Highways and of these about 50% were reported to need some form of repairs or rehabilitation. The other major road network is about 8 times as large as the NH network and is likely to have correspondingly more number of bridges which are in distress. It has also been reported that more than half the bridges have an age of above 40 years and bridge planning so far has been done with the assumption of an average life of about 50 years. Systematic maintenance of bridges has not been followed so far though the Railways have to an extent well organised bridge inspection and maintenance. This background gives an idea of the scope for bridge management in India.However, such problems are by no means peculiar to India. A recent report [1] mentions that in the U.S.A. about 45% of the bridges are in distress and talks of problems of paucity of resources, lack of proper inspection, etc. Hence India is also looking at the rest of the world for solutions adopted successfully elsewhere in the field of Bridge Management Systems (BMS).

2. BRIDGE MANAGEMENT PLANNING PROJECTIONS

In the last two or three years, a commendable awareness has grown among the agencies responsible for bridge management. Since all the bridges in India are owned by Governmental agencies the problem of BMS has to be addressed essentially by the State sector.A few papers have been published on the subject [2,3] and the apex body on road development in India, the Indian Roads Congress, has brought out guidelines on Bridge Management[4]. In the earlier days, maintenance and management of bridges were taken up only in an informal manner without any overall planning. This is sought to be remedied by the BMS envisaged in these documents . Basically this BMS covers inventory recording of the bridges and inspections & reporting, leading on to the build-up of a data base, maintenance, repairs & rehabilitation and planning for a replacement. The procedures and organisations for inspection, methodology for creating the data base and guidelines for effecting repairs, rehabilitation and replacement are discussed.

With regard to the above-mentioned broad sectors of activities, the various factors such as traffic, safety, economics, hydrological, engineering and organisational aspects are sought to be studied and structured integrally to form a Bridge Management System.Since a large number of bridges are involved, special teams and organisations have to be built up and personnel have to be properly trained.In the absence of such teams at present it has been suggested that Consultants be involved with the tasks of inventorying,inspection and preparation of schemes for repair and rehabilitation. This has been already implemented for some major bridges for which consultancy proposals have been invited for such activities.

The BMS specifically excludes planning, design and construction though it should start right from the conceptual stage.BMS can be successful only if adequate funds for maintenance and organisation for the same are earmarked in the planning stage, adequate steps are incorporated in the design stage to ensure longevity of the bridge, measures are built-in to facilitate maintenance and adequate care is taken during the construction stage for Quality Assurance.

3. CONCLUSIONS

The present lack of availability of an extensive data base for the large number of bridges, lack of awareness of such organised planning for maintenance and management, lack of adequate resources etc. are the various problems facing the bridge management agencies. Unless the recently evolved schemes of BMS are speedily implemented in a planned manner, the transportation sector in which bridges are vital links will face serious problems.

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Polish Bridge Management System: Marking, Planning, Budgeting

Système polonais de gestion de ponts: évaluation, planification, budget

Das Polnische Brückenverwaltungssystem: Bezeichnung, Plannung, Budget

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Polish Bridge Management System /BMS/ has been designed as a set of autonomous modules. In Fig.1. are presented modules and main functions of BMS.

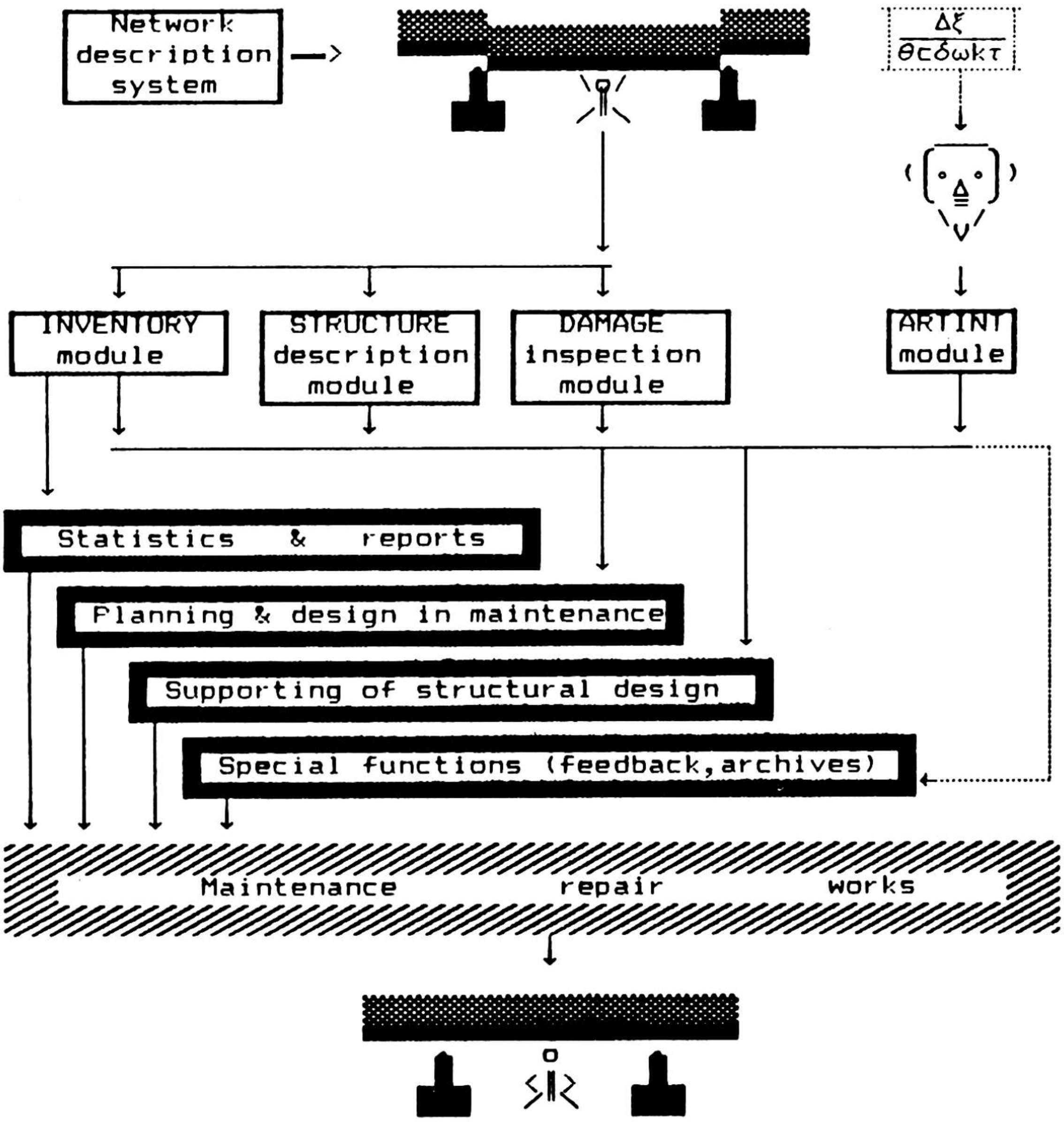

Fig.1 General diagram of Polish B M S

MARKING. Technical state of bridge structure is described by Bridge Serviceability Index /BSI/. BSI is calculated as a fuzzy value of the impairement level of structure. Logical operation of BSI calculation takes into account type of bridge structure, types of damaged elements, sorts of damages, location and intensity of damages. In target of bridge position on repair list settlement Total Bridge Serviceability Index /TBSI/ is calculated. Besides the value contained in BSI, bridge life service, traffic, accidents and important nontechnical data are included in TBSI calculation formula. Fig. 2. presents idea of fuzzy treatment of the BSI and TBSI.

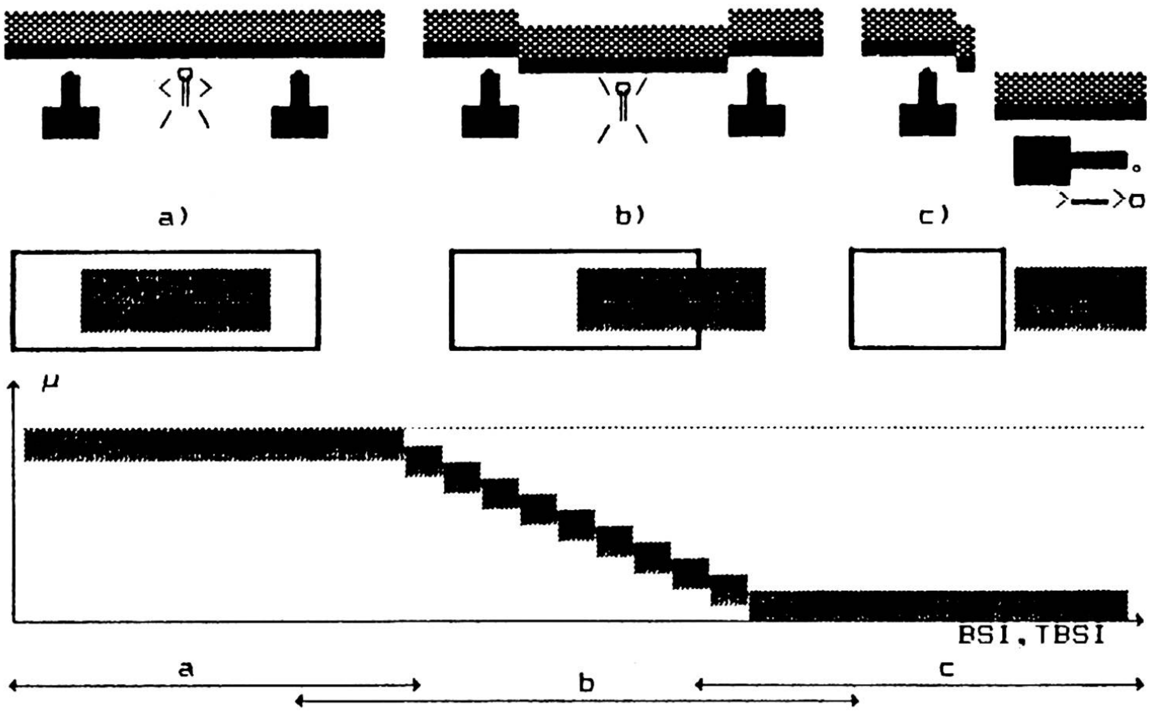

Fig.2 Idea of fuzzy treatment of the B S I & T B S I

PLANNING and BUDGETING. Position on repair list given by TBSI and various strategies of maintenance in fuzzy expression are main logical conditions of planning and budgeting process. Idea is contained in Fig.3.

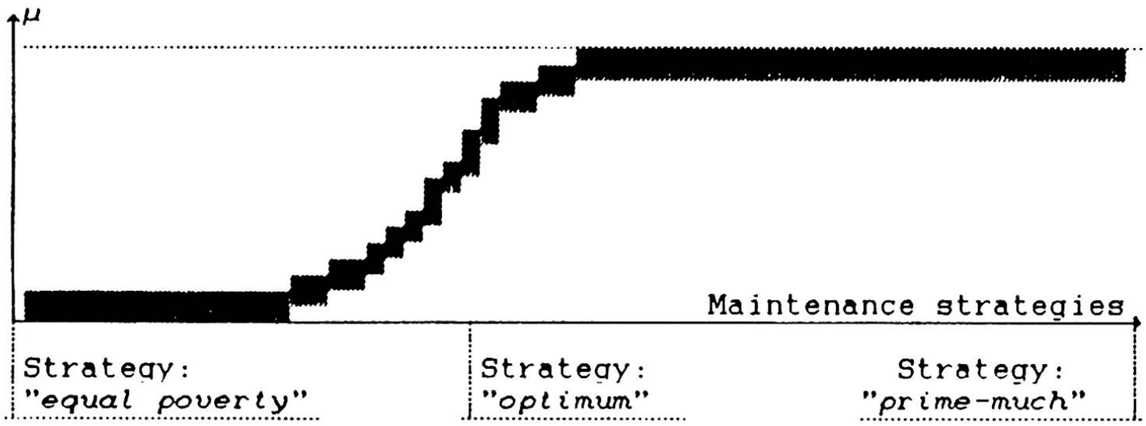

Fig.3 Fuzzy expression of maintenance strategies

Modelling of Bridge Structure Performance in a Bridge Management System

Modèlisation de la performance de structures dans un système de gestion de ponts

Modellierung des Verhaltens von Brücken in einem Datenverwatungssystem

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1. BRIDGE MANAGEMENT SYSTEM IN FINLAND

Finland's National Roads Administration is currently developing a bridge management system for its 12,000 bridges. The system will identify the preferred set of bridge actions throughout the network of bridges, and over time recommend what actions should be taken and to what scale and cost.

The network level optimization algorithm works with populations of bridge components that are similar in their construction and use. Altogether 25 bridge items are modelled for optimization processes. The condition of bridge components is expressed in terms of discrete condition states. Changes in condition are expressed as stochastic transition probabilities from one condition state to another. The mathematimatical process used defining the year-by-year changes in condition is the Markov chain method.

2. MARKOV CHAIN METHOD

The probabilities of transition from one state to another are presented in a so called transition probability matrix (or simply transition matrix). The probabilities are for changes in condition in the space of 1 year. Changes after N years can be predicted by multiplying the original state vector (present distribution of condition states) by the transition matrix N times. The transition probabilities are assumed to be unchanged during these years.

Generally the original state vector is known or at least easily determinable. The greatest difficulty with the Markov chain method is the determination of the transition probabilities.

The scheme for producing transition probability matrices in the Finnish management system is shown in Figure 1.

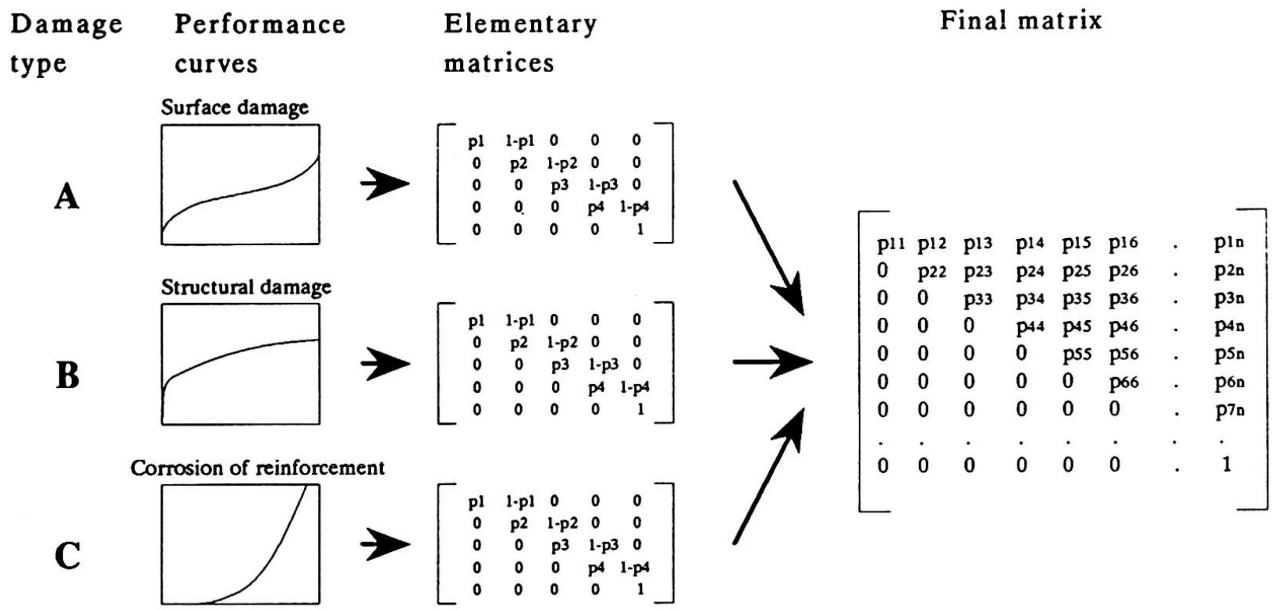

Fig 1. Basic principle behind transition probability matrices for bridge items.

A Delphi questionnaire was considered the best techniques for producing performance curves. It was sent to the best specialists available including bridge inspectors, other bridge officers and research scientists.

The respondents were asked to draw the performance curves for all damage types pertaining to all bridge items, assuming that the structures are never repaired. They were also asked for information concerning the dependences between damage types.

Several methods are available for the process of transforming performance curve data into transition probabilities. The method used in the Finnish application is in principle the same as that given by Jiang et al. [1]. A specially tailored computer program uses "iteration" for finding the final solution for transition probabilities.

The elementary matrices created as described above are combined to the final matrices respective to each bridge item. The number of final states (which determines the size of the final matrix) is the product of the numbers of states in the elementary matrices.

The transition probabilities of the final matrix are estimated as the product of the corresponding elementary transition probabilities, taking into account, however, the possible dependences between damage types.

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Resource Allocation for Rehabilitation Projects in Ontario

Allocation des moyens dans la rénovation de ponts en Ontario

Mittelzuweisung für Brückenerneuerungsprojekte in Ontario

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1. COST EFFECTIVE METHODS

The Ministry of Transportation, Ontario, is responsible for the management of approximately 3000 bridges on the provincial highway system. It spends about $35 million a year, averaged over the last five years, on the maintenance and rehabilitation of these structures. The financial analysis methods used by the Ministry at the project and network levels to allocate funds in a cost effective manner to meet these needs are described here.

1.1. Present Value Analysis: Present value analysis is used by the Ministry to choose the most cost effective method over the life of the structure from various viable rehabilitation and replacement options at the project level.

The present value of future costs of various treatments for each alternative over the life of the project is determined. The alternative with the least life cycle present cost is the preferred alternative. This allows for the comparison of alternative schemes on an equitable basis.

The parameters required for the analysis are the life cycle agency costs for each alternative, residual life values, and discount rate. Sensitivity analysis are carried out by varying the discount rate. The effects of changes in agency cost estimates are checked by assigning different probabilities of occurrence to agency costs. It is shown that the effects of inflation can be ignored. The analysis is carried out on a spread sheet program written for Lotus 1-2-3, version 2.01.

1.2. Incremental Benefit/Cost Ratio Analysis: Incremental benefit/cost ratio analysis, IB/IC, has been tried by the Ministry to allocate funds between bridges at the network level and found to work satisfactorly.

The incremental benefit/cost ratio is the ratio of additional benefit realized in moving from one improvement alternative to another, divided by the corresponding increase in cost.

The results of present value analysis carried out at the project level for each bridge on the current year's program are used as input into the incremental benefit/cost ratio analysis. Rehabilitation and replacement alternatives for each bridge are listed in order of increasing costs and the IB/IC ratios calculated. Alternatives for which the IB/IC ratios fall below one are discarded. Usually, as the level of cost increases IB/IC ratio decreases, however, if the IB/IC ratio should increase with an increase in cost an adjustment is made to that particular option. The options are sorted in descending order of IB/IC ratios. For the usual case of limited budgets the order of preference is the order from the highest to the lowest incremental benefit/cost ratios.

The parameters required for the analysis are the agency costs and benefits. If user costs and benefits are available they can be included. The analysis is carried out on a spread sheet program written for Lotus 1-2-3, version 2.01.

2. APPLICATION:

2.1 Project Level: The present value analysis at the project level is used routinely by the Ministry for all the projects on the rehabilitation or replacement programs.

2.2 Current Year Network Level: The incremental benefit/cost ratio analysis method at the network level for the current year was successfully tested on bridges in one of the five Regions of the Ministry. The system will be implemented in all the Regions in the near future.

Northern Region has 134 bridges that are to be rehabilitated within the next 5 years. Of these 18 were scheduled for the 1990 program. The condition surveys for these bridges were reviewed and various rehabilitation options were considered including the replacement option as this is required to determine the agency benefits. Cost of each option was estimated and the incremental benefit-cost ratio analysis carried out.

Some of the bridges had only the replacement option as the feasible option. Projects for which a decision has already been made on a particular option may be excluded from the analysis, or fictitious incremental benefit cost ratios may be input for those projects, so that they are on a higher priority level. The second approach was used in the above analysis.

Incremental benefit/cost ratio analysis gives a list of priorities based on the condition of the bridges and the costs to improve those conditions. This priority list may need to be adjusted to include other factors that go into making the final selection of bridges that should be on the current program.

2.3 Multi-year Network Level: Incremental benefit/cost ratio can similarly be used to prioritize bridges that will be rehabilitated over a number of years. The cost estimates for some of the bridges will be approximate as detailed condition data would not normally be available beyond a two year period. The analysis would be refined on an annual basis.

3. CONCLUDING REMARKS: The allocation of funds to bridge rehabilitation and replacement options at the project and network levels can be based on rational financial analysis principles. A few jurisdictions, including the Ministry of Transportation, Ontario, are starting to use these principles in the management of their bridges, others are expected to follow as these principles are better understood by the engineering fraternity.

Inspection Planning and Maintenance of Structures Subject to Fatique

Organisation de l'inspection et de l'entretien de structures sensibles à la fatique

Plannung von Inspektion und Unterhaltung ermüdungsgefährderter Tragwerken

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An increasing number of fatigue sensitive structures, including bridges, aircraft and offshore platforms are being used beyond their design lifetimes. There is growing concern about the safety of such structures, especially because the fatigue life can vary a lot from the design life. However, it is important to note that structures are usually redundant and failure of a single section does not constitute structure collapse; collapse usually occurs after a sequence of section failures. Furthermore, in the case of fatigue there is some time elapsed between the individual section failures, i.e. fatigue is a progressive phenomenon. Therefore it is possible to use inspection schemes to monitor fatigue damage. If the damage is excessive (i.e. the safety of the structure drops below an acceptable level), then appropriate repair can be carried out. In other words, effective inspection strategy can allow us to use existing structures beyond their design life and yet maintain an adequate level of safety.

In this paper, two important aspects of such inspection strategy are discussed; selection of sections to be inspected and use of inspection results in assessing the safety of a structure.

A section should only be inspected if there is a relatively large likelihood of detecting damage (if there is a relatively low chance of detecting damage, it is not worth inspecting the section). The likelihood of detecting damage will be large only if 1) there is a relatively high probability of damage occurring in the section and 2) the damage can be detected (this is a function of the location of damage and of the detection method used). These two factors can be combined to give a net probability of detecting damage at a section (as described in Dalane, et.al., 1991).

Furthermore, a section is only worth inspecting if it is important to the integrity of the structure (i.e. it is not worth inspecting a section whose failure does not significantly reduce the safety of the structure). This effect can be measured by the increase in system failure probability due to the failure of the section.

Based on the above concepts, we propose a measure of importance for inspection :

Importance of section i = P [Detect damage at section i]
* {P[system failure with section i failed] - P [system failure with intact structure]}

where P[ ] is the probability of occurrence of event [ ]. Note, the system failure probabilities are calculated for the time period after inspection.

In terms of using inspection results to assess the safety of a structure, we suggest using Bayes theorem, e.g.,

P[Collapse in sequence i,j,k given an inspection outcome]
= P [Collapse in sequence i,j,k and inspection outcome]/P[Inspection outcome]

Application to an offshore structure

This tripod steel jacket platform is located in the North Sea in a water depth of 70 m with an airgap of 22 m (Fig.1). The two main sources of risk are extreme waves and fatigue. Therefore systems reliability analyses were carried out to identify important sequences of failures, both in fatigue and under an extreme wave, that lead to collapse. (Note, important sequences are those that are most likely to occur). These sequences and their probabilities of occurrence are shown in the failure tree of Fig. 2. (Karamchandani, et.al., 1991). In this failure tree, each branch corresponds to failure of a section in fatigue or an element under an extreme wave. Each node corresponds to a damaged state of the structure and the number in the node is the probability of reaching the corresponding damage state i.e., it is the probability of occurrence of the sequence of section failures represented by the branches leading to the node. Note, all the initial failures are in fatigue.

Using the important measure defined above, section 680B was found to be the most important member for inspection. Note, this is easy to understand. It is most likely to be damaged and it is also important for the integrity of the structure - in fact it occurs in almost all the important sequences - (Fig. 2). Therefore, inspection of this section in the 10th year of service is considered. Four hypothetical outcomes of the inspection are studied; no damage is found, a 14 mm crack is found, a through-thickness crack is found, and the section is found to be failed. These observations are used to update the probability of occurrence of two critical sequences (the most important sequence of two fatigue failures, i.e., 680B in fatigue followed by 611B in fatigue and the most important sequence of combined failures, i.e., 680B in fatigue followed by 620 under an extreme wave). The results are presented in Fig. 3 in terms of the hazard rate. (The hazard rate is an annual measure of risk. The hazard rate of the sequence at time t years is the probability that the sequence will occur in time [t,t+1] given that it has not occurred in time [0,t].

Consider the sequence of two failures in fatigue (680B followed by 611B) in Fig. 3a. The dashed line A is the original hazard rate (i.e, without inspection). If no crack is found, the hazard rate is lower than the original rate. This is to be expected because the inspection tells us that the structure is "safe" at the 10th year. If a through-thickness crack or a failed section is found, then the hazard rate is larger than the original rate. This is also to be expected because the inspection tells us that the structure is weaker than expected at the 10th year. The most interesting result is when a crack of 14 mm depth is found (note, wall thickness is 28 mm). Initially, the hazard rate is lower than the original rate, but soon it becomes much higher. The reason for this is the following. This information tells us that there is still some time to failure and therefore the hazard rate for the immediate future is very low. However, this information also tells that the fatigue damage is occurring faster than expected and therefore if we look at a more distant instant of time, there is a greater chance that the sequence will occur, i.e., the hazard rate is greater.

The results for the sequence of combined failures, i.e., 680B in fatigue followed by 620 under an extreme wave, are similar. The main difference is in the case where a failed section is found - the updated hazard rate is constant. This is because the remaining event in the sequence is failure of 620 under an extreme wave and this has a constant annual probability of occurrence.

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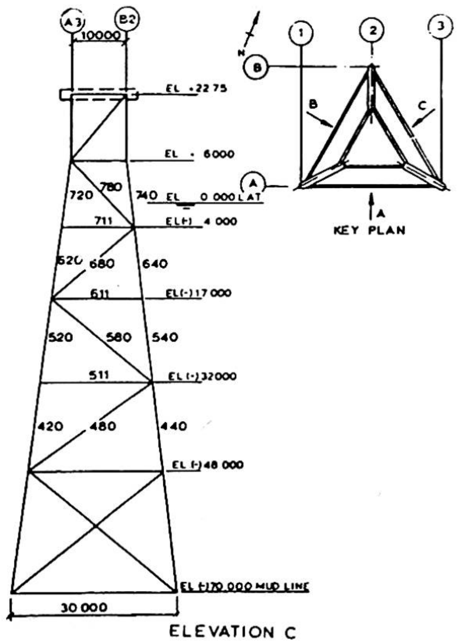
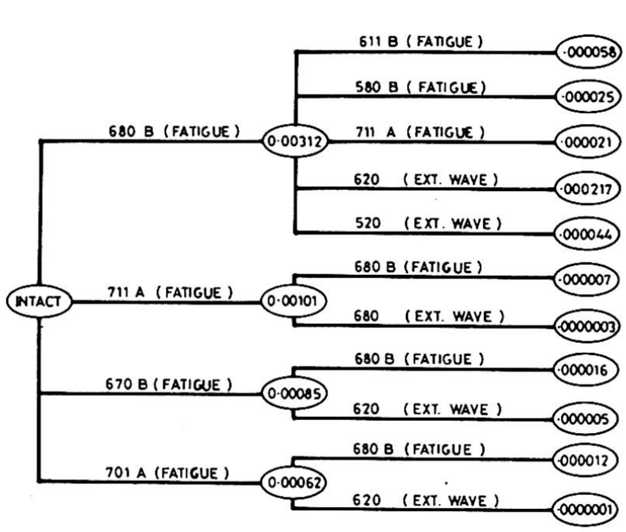


Fig. 1 Tripod Platform



Note: The symbols A and B indicate the two ends of a member (e.g.570B is the section at end "B" of member 570)

Fig. 2 Important sequences of failures

a) Sequence : 680 B in fatigue followed by 611 B in fatigue b) Sequence : 680 B in fatigue followed by 620 under an extreme wave. Notation : A-no inspection (design stage) B-no crack is found C-14mm crack is found D-Throug thickness crack is found E-Section is found to have failed.

Fig. 3. Updated hazard rate of most important sequences with inspection after 10 years in service (Dalane, 1991)

Systems Approach in the Inspection of Suspension Bridges

Approche globale de l'inspection des ponts suspendus

Gesamtplanung bei der Inspektion von Hängebrücken

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1.0 INTRODUCTION

In the early part of this century, a number of suspension bridges were built in the metropolitan areas of the USA. These heavily traveled bridges are aging rapidly due to fatigue, corrosion and wear. While it is not practical to replace these bridges, especially in a megalopolis, these bridges can be salvaged by maintenance and rehabilitation through regular inspection that will keep them functioning for the demanding traffic needs of the next millennium. Hence methodical inspection and reporting has assumed paramount importance.

2.0 INSPECTION AS A PROCESS

A scientific and systematic approach for bridge inspection is outlined in figure 1. It is critical to recognize inspection as a process and not as an isolated event that takes place on a periodic basis. By doing so, the need based attitude, which normally has short term applications only, can be transformed to a wider spectrum that encompasses several short and long term applications. For example, the quantitative condition rating of elements allows tracking of their conditions over a period of time so as to monitor the overall condition of the bridge; inventory of bridge

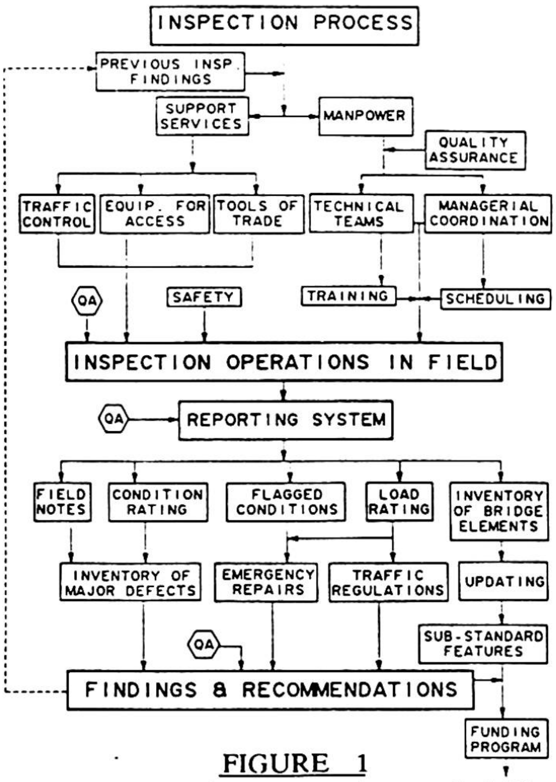

FIGURE 1

elements complements the rehabilitation expenditure planning, etc.

A case study of the recently completed biennial inspection of the Manhattan Bridge, New York, USA is presented below wherein the above principles were implemented.

3.0 CASE STUDY

Manhattan Bridge is a 90 year old bi-level suspension bridge carrying 7 lanes of vehicular traffic and 4 tracks of New York City transit trains. The AADT (1988) was over 75,500 along with 960 trains a day. This bridge, being one of the major crossings serving the City of New York, requires uncompromising traffic restrictions on the allotment of time for inspection and rehabilitation.

The 1990 biennial inspection was performed over a period of 4 months. The authors were in the team of 11 Registered Professional Engineers and 10 Structural Engineers. The inspection was conducted for the New York State and New York City Departments of Transportation.

As the train tracks are located on the outer portions of the bridge, the eccentric train loads penalize the stiffening trusses and floor systems with torsional effects. During the inspection more than 1200 defects were recorded and 615 of them were flagged demanding immediate attention. Prompt corrective actions were taken by the New York City Department of Transportation in terms of performing emergency repairs, reviewing the load rating and temporarily closing of one lower roadway lane and two tracks of NYC transit, pending repairs. Some of the major defects are highlighted in the bridge cross-section in Figure 2

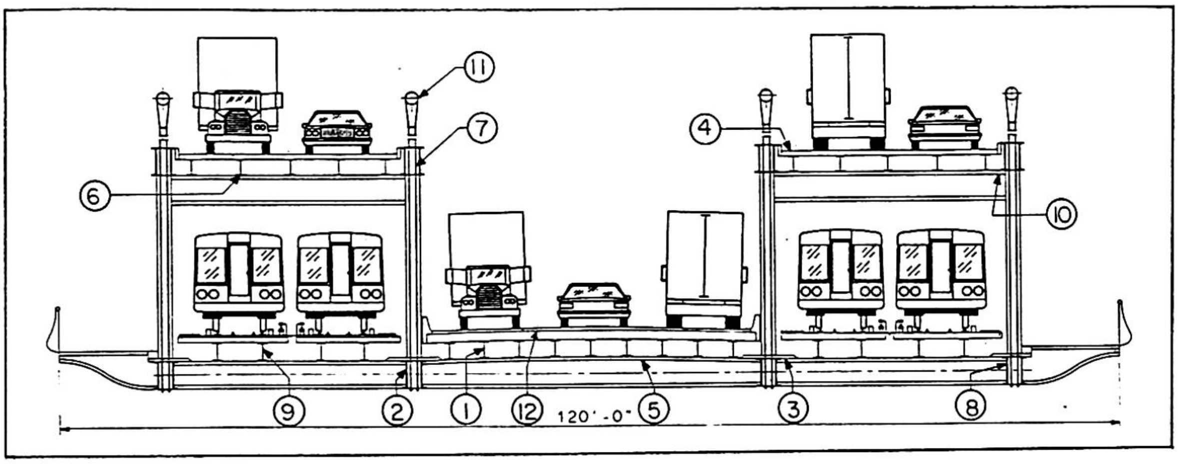

FIGURE 2: CROSS SECTION OF MANHATTAN BRIDGE, NEW YORK - *Major Defects Reported*

1. *Cracks in stringers*
2. *Corrosion*
3. *Cracked continuity angle*
4. *Deck defects*
5. *Corrosion of top flange*
6. *Uplifted Stringer brg.*
7. *Suspender wear/ Striking top chord*
8. *Cracked chord splice*
9. *Track Stringer Brg.- Displaced/cracked*
10. *Cracked floorbeam end*
11. *Corroded Cable Wrapping at lower saddle*
12. *Leaky deck joints*

4.0 INSPECTION INFORMATION SYSTEM (IIS)

A system of collecting, preparing and representing a comprehensive database from the data collected in the field became a powerful tool for decision making on issues like traffic limiting, planning for rehabilitation, etc. This database included past and present condition ratings of various elements, classified listings of hazardous conditions demanding immediate action, respective actions taken, etc. New York State Department of Transportation has developed a system of quantitative rating of elements based on the residual capacity and functionality of the element instead of using terms like "Sound", "Fair", "Satisfactory", etc. On a scale of 7 (new condition) to 1 (hazardous condition), a rating of 3 denotes "serious deterioration and not functioning as originally designed." Usage of this system led to drastic reduction in the subjectivity of the rating between inspectors.

For the Manhattan Bridge, a database of defects and flagged defect conditions was prepared. It also included the condition ratings of over 30,000 elements of the bridge. Defects observed during the previous inspection were also reviewed and checked whether repaired or not. With all the above information when organized and mapped, the contour of even rated elements revealed a pattern of deficiencies on the bridge. Individually, this information could not have revealed the complete picture. For example, the flagged condition would identify a serious defect, but would not present any information about adjoining members, without which the overall condition of the bridge could not be visualized. In one particular instance, the owners of the Manhattan Bridge decided to close one lane of vehicular traffic after observing a concentration of low ratings on the floor system of the lower roadway. It was this systematic and logical approach that eased the process of decision making.

5.0 CONCLUSION

The potential of IIS is multifarious. It can act not only as a management tool to attend to immediate needs, but also can improve forecasting and the process of selective rehabilitation to match the available funding. IIS will become more and more valuable, particularly in metro areas, as the existing older bridges will gain more prominence due to the impracticality of replacing them.

Modal Analyses of Concrete Bridges at "Stora Höga", Sweden

Analyse modale de ponts en béton, en Suède

Modalanalyse bei Betonbrücken in Schweden

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1. INTRODUCTION

Two high-way bridges were loaded to shear-failure, [1]. Simultaneously, modal parameters were measured and analysed, [2]. To accomplish the measurements, the bridges were excited vertically with impacts, and the responses were measured with accelerometers. Frequency response functions were computed and averaged as well as coherence functions to check the quality of measurements.

The purpose of the project was to gain experience of modal analysis of concrete bridges with impact excitations, establish requirements for the equipement, analyse the changes of modal parameters and relate them to changes in spatial parameters.

As a result of the project, an efficient measurement -technique was adopted, by which severe changes in stiffness and boundary conditions may be detected. Reference measurement of the undamaged structure has to be made. High accuracy in measurement results is necessary, since discrepancies in modal parameters compared to the virginal state are generally small. A refinement of the method is to establish a "Finite Element" (FE) -model to be correlated to the measured modal model. The purpose is to up-date the spatial parameters in the FE-model to obtain the same modal parameters as in the measured modal model. The FE-model may then be used in future comparisons for checking the condition of the structure.

2. DESCRIPTION OF BRIDGES AND MEASUREMENTS

2.1 Prestressed concrete bridge

The prestressed bridge was a frame with two straight girders monolithically cast together with a curved bridge-deck. The span was 32 m and the width ~ 10 m. Before the shear-failure test was performed, successive damages in form of bending cracks were introduced by overloding the center cross-section. This was made with hydraulic jacks, acting on steel bars, fixed to the ground. After each loadstep, measuarements of modal parameters and damages were made.

The impacts were accomplished by a falling weight, mass ~ 60 kg, supplied with a visco-elastic damper. The weight was dropped from ~ 0.80 m on a load-cell. The recorded forces were ~17 kN, with a contact -time ~ 20 ms. The force-spectra show that half of the applied energy excited the bridge in vibrations below 40 Hz. The "Time Reccord Length" was 8 seconds, giving a measured frequency resolution of 0.125 Hz. The responses were measured at 27 points along 3 lines on the bridge-deck. The excitations were made at the same point in all measurement-series.

2.2 Ordinarily reinforced concrete bridge

This bridge was a plate-frame structure for local traffic. The span was 21 m and the width ~5 m. To get shear-failure in this bridge, additional reinforcement in form of steel-plates were glued to the lower surface of the concrete-plate. Two measurement-series of modal parameters were made before and two after application of the steel-plates. Later the bridge was loaded to shear-failure by vertical forces applied close to one of the supports, and therafter a final modal measurement was made.

Impacts were introduced with a special equipement, consisting of a falling weight ~40 kg, an impact load-cell, and a visco-elastic damper to avoid bounces. In the first measurement a 5.5 kg sledgehammer was used. The impacts were made at 60 points along 5 lines on the bridge deck. The responses were measured at two different points, to allow for comparisons between frequency response functions.

3. RESULTS

Valuable experience is gained from different measurement-techniques. Impact excitations may be used and the results are accurate enough to detect minor defects, if the measurements are performed carefully. The most efficient way to measure is to use a stationary excitation point and several accelerometers properly fixed to the bridge surface. It is not necessary to measure in so many points in a regular sceme.

The result of the analyses shows small but significant changes in resonant frequencies for increasing damage or increasing stiffness. In case of the prestressed concrete bridge, the center cross-section was successively cracked, influencing the bending modes to a higher degree than the torsional modes. In Fig.1 a typical bending mode is shown and the relative difference in resonant frequencies compared to the reference state as a function of a damage index. The modal shapes may be used to localise damages in the structure by computer-comparisons in a systematic way. Damping ratios are more sensitive to the measurement- and analysis-technique and the obtained results are difficult to evaluate properly.

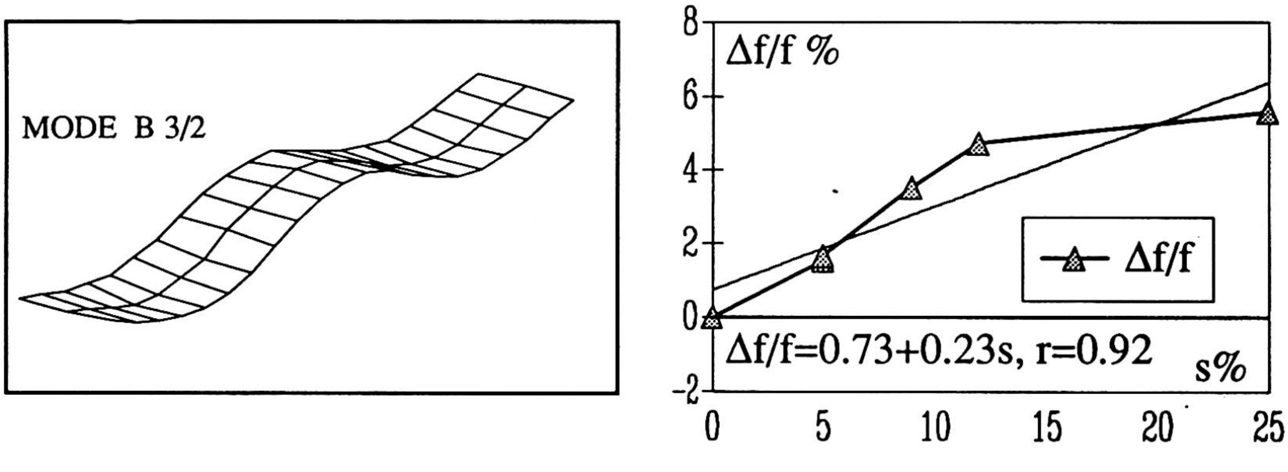

Fig. 1 A bending mode for the prestressed concrete bridge and the relative difference in resonant frequency as a function of a damage index s, with regression-line and correlation coefficient r.

4. REFERENCES

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