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Design of Bridges for Optimum Construction and Maintenance Costs

Conception de ponts en vue d'une optimisation des coûts de construction et d'entretien

Brückenkonzepte für optimale Herstellungs und Instandhaltungskosten

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SUMMARY

The design for low maintenance of bridge structures begins at the conceptual design stage. A quality strategy shall be part of the design criteria serving as a basis for the selection of optimum structural concepts, configuration, and materials. Quality assurance systems are necessary in all phases during design, construction and service life. Systematic inspection and maintenance procedures, as well as monitoring systems will be required. Lately computerized bridge management systems have been developed to assist owners and bridge administrations in data processing and economical calculations for establishement of decision alternatives.

RÉSUMÉ

Le projet de la maintenance pour un entretien minimal des ponts commence au stade du concept de projet. Une stratégie qualitative doit permettre le choix des critères de projet et servir de base à la sélection de concepts structuraux, de la forme et des matériaux de construction. Des systèmes d'assurance de la qualité sont nécessaires à tous les stades du projet, de la construction et de l'exploitation. Des procédures d'inspection et d'entretien systématique ainsi que des systèmes de contrôle sont requis. Récemment, des systèmes de gestion informatisée ont été développés afin d'aider les maîtres d'ouvrage et administrations des ponts dans le traitement d'informations et le calcul des coûts, leur permettant ainsi de comparer plusieurs solutions.

ZUSAMMENFASSUNG

Der Entwurf für die minimale Unterhaltung von Brückenbauten beginnt bei dessen Konzept. Eine Qualitätsstrategie soll die Wahl der Entwurfskriterien erlauben und als Basis für eine Auswahl von Tragwerksystemen, der Form und den Baumaterialien dienen. Qualitätssicherungssysteme sind während dem Entwurf, Bau und Betrieb der Brücke notwendig. Systematische Kontroll- und Unterhaltungsverfahren wie auch Ueberwachungssysteme werden benötigt. In der letzten Zeit wurden computergestützte Brückenmanagementsysteme entwickelt, um Bauherren und Brückenverwaltungen in Datenverarbeitung und in Kostenberechnungen zu helfen, verschiedene Lösungen zu vergleichen.

1. INTRODUCTION

The optimum design for lowest overall cost during the intended service life begins already at the initial design stage. Decisions are made at this stage which, although not always realized, have a fundamental influence on the overall life cycle costs of the structure.

In the post-war years the main concern of the owners was to rebuild and further develop the total infrastructure and transport system. Little - if any - attention was spent on maintenance aspects and durability of the structures and how to repair, rehabilitate, strengthen, and possible expand them. These problems were left for the future generations to solve.

However, as the infrastructure systems in the industrialized world is now nearing completion and adequate capacity, and the total volume of existing infrastructure has increased drastically, in terms of replacement value, a growing burden of maintenance has been accumulated for the administrations and owners.

Budgets previously primarily allocated to new construction are now directed towards maintenance and rehabilitation projects for existing infrastructure elements. This has lead to an obvious need for greater awareness with regard to maintenance of any new or rehabilitated structure forming part of our substantial investments of society.

Numerous examples exist around the world where very high rehabilitation and repair costs have incurred by lack of proper consideration of maintenance aspects, in the design phase. Situation which in many cases could have been reduced considerably, and generally at no additional cost if maintenance had been a design parameter at the time of construction.

2. KEY ELEMENTS IN LOW MAINTENANCE

The key parameters for overall low and predictable maintenance cost are the following:

- Overall quality strategy
- Structural concepts and configuration
- Materials
- Quality assurance in design and construction phases
- Systematic inspection and maintenance procedures, and monitoring
- Management and budgetting systems for data management and generation of decision alternatives

Each of these parameters are contributary to the overall concept of maintenance and by proper consideration of these parameters can reliable maintenance prediction and planning be made.

3. QUALITY STRATEGY AND AWARENESS

In the initial planning stage the overall quality strategy must be determined with due consideration to the intended use of the structure.

Performance criteria must be determined, as well as design life, frequency of use, importance, built in reserves for future development in use etc.

Technical, economical, sociological, and other consequences of poor performance, break down and/or major maintenance operations must be considered when establishing quality standard.

If performance inferior to intended leads to very high additional user costs, complicated maintenance and repair under use, high risks, and if long service life is required, a high quality standard would be warranted.

On the other hand temporar structures with short intended service life and limited use requires lower quality standard. However, lower overall quality standard should not be confused with lower safety standard. This fact has been recognized relatively late, and most newer codes of practice requires same structual safety (partial coefficients) for short life structures as for permanent structures.

If a key bridge is taken out of service on a major high capacity highway due to rehabilitation works, and traffic due to this must be diverted and rerouted via major detours causing unacceptable congestions and consequently very high additional user costs dublication of the facility may be necessary, e.g. 2 parallel and independent structures which can be taken out of service one at a time for rehabilitation, strenghtening or rebuilding without affecting the other.

It is generally accepted that high initial quality leads to high initial cost and generally minimizes maintenance costs. Likewise it is believed that low initial cost invariably leads to high maintenance costs.

This is, however, not always the case as shall be demonstrated in the following.

The real challenge to the designer is to obtain the best of the two worlds - low initial and maintenance costs by selection of proper structural concept and configuration, use of best suited materials, and innovative ideas based on experience and feed-back from past performance of similar structures.

Correspondingly high initial cost does <u>not</u> necessarily lead to low maintenance costs! - if the high initial cost is caused by inexpedient selection of structure type and materials for the use intended.

4. STRUCTURAL CONCEPT AND CONFIGURATION

The selection of the structure concept and configuration will have a significant influence on the later maintenance requirements of the structure.

Structures like bridges are a complex combination of materials and mechanical components exposed to very severe environment, and it is generally considered unacceptable to temporarily interrupt their use for servicing.

It is thus required that service and replacement of worn out components is minimized, and where unavoidable, that such replacement can take place with minimum influence on the use of the facility.

Bridge components may be categorized in primary main components like the roadway deck, girders, columns, and foundations, whos life will determine the actual life span of the structure.

These components have in common that they are very difficult, if not impossible, to replace during service life. Main cables of large suspension bridges also belong to this category.

Other components are rather short lived, and provisions for replacement one or several times during the service life must be considered. Such items are components subjected to wear and tear, corrosion, or fatigue, as well as other forms of deterioration. Like bearings, expansion joints, road pavements, surfacing, painting, sealing, and cable stays and hangers on cable supported bridges.

Innovation of bridge technology for low maintenance must, therefore, be directed towards:

- reducing the number of short life components to a minimum,
- protect the components from premature deterioration and wear
- provide for easy access for regular inspection and servicing
- prepare for scheduled replacements

By the use of unconventional methods it is possible to minimize both initial cost and maintenance requirements.

For the Farø bridges in Denmark, use of a low cost dehumidification system in the bridge box girder has saved about 8-10% of the initial superstructure cost by eleminating the cause of steel corrosion - humidity - instead of specifying painting of the interior of the girder.

The use of such a system which is made of standard components also reduced net present value of maintenance costs over the service life.

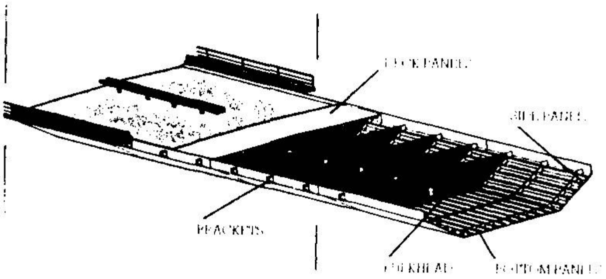


Fig. 4.1 Farø Bridges. Box Girder

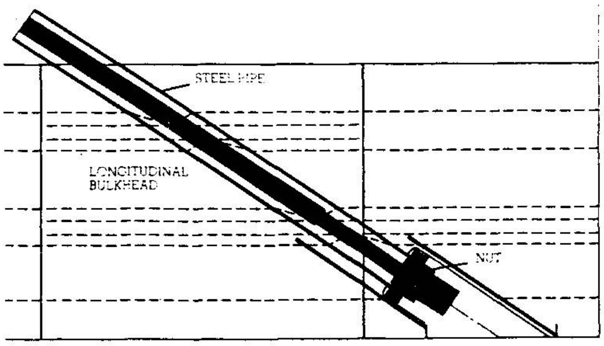


Fig. 4.2 Farø Bridges.
Stay Anchorage in Girder

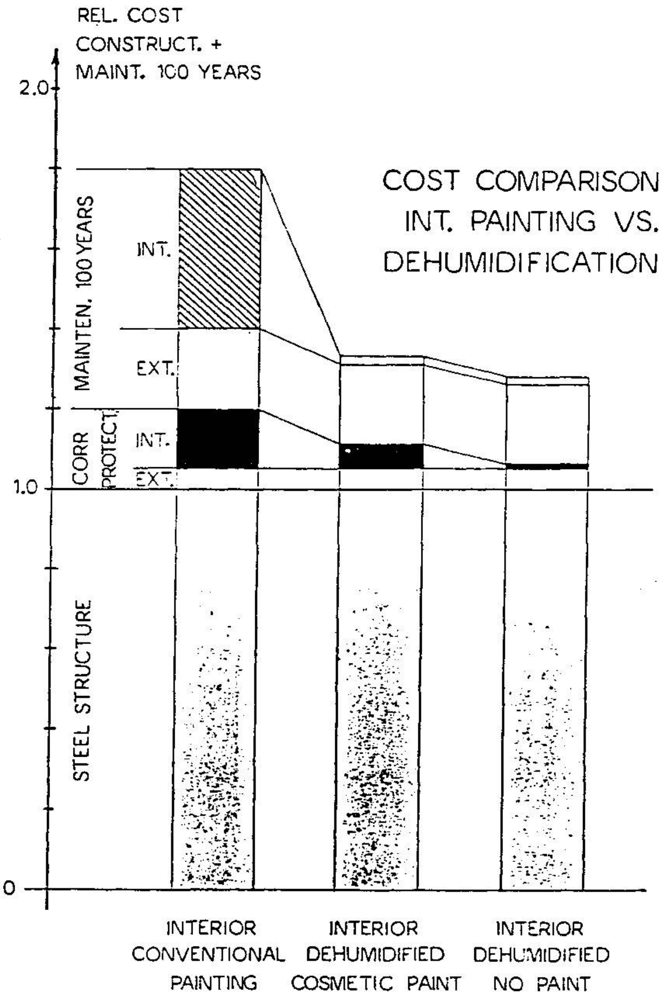


Fig. 4.3 Steel Box Girder.
Cost Comparison

Due to placement of all stiffeners in the interior dehumidified air space, only 20% of the total, 400,000 m^2, steel surface is exposed to the exterior environment, and due to smooth surface easy to inspect and maintenance.

The interior congested by stiffeners, corners and inaccessible areas, and voids as well as machined parts like cable stay anchorages, electrical equipments etc. is safely and permanently protected by the dry environment. The initial cost amounts to DKK 5.00/m^2 and net present value of 100 year maintenance DKK 20.00/m^2 using an interest of 4% p.a.

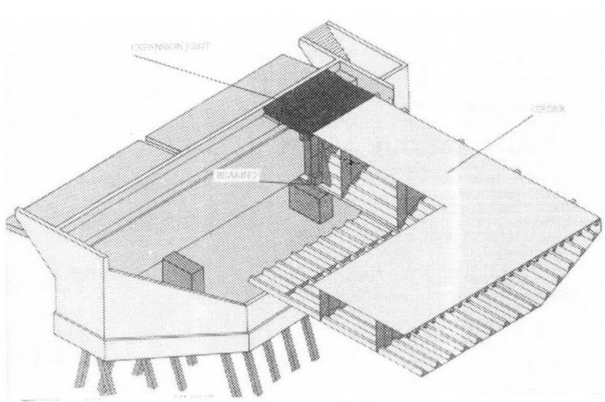
Easy acces to components requiring inspection and maintenance shall be provided. Expansion joints and bearings must be accessible during operation. It is a well known fact, that if access is difficult, the necessary inspection and maintenance will not be executed as planned.

New ideas can further cut down on maintenance.

For the Farø bridges the number of maintenance intensive expansion joints have been cut to a minimum. The bridge girders have been made continuous from coast to coast, in fact 2 bridges each continuous for 1600 m and 1700 m, respectively. Expansion joints capable of up to 1 m respiration have been installed only at the abutments.

Easy access has been provided by stairs and cellar space and platforms allowing amble space for inspection, maintenance - work and replacement in full upright position of expansion joint parts and abutment bearings.

On the pier tops is provided via electrically powered monorail through the box girder from the abutments to each pier via easy access manhole with hinged and counterweight balanced lid. Workers can work in an upright position for lubrication and other maintenance of the sliding bearings. Long life is ensured by protecting the movable parts by dust seals and bellows.



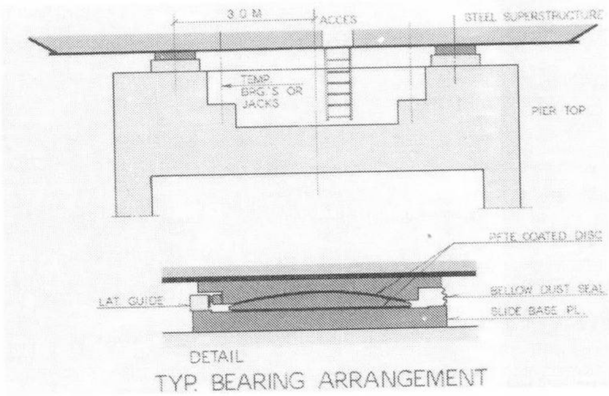


Fig. 4.4 Farø Bridges. Abutments

Fig. 4.5 Farø Bridges. Pier Top

The accummulated travel of bearing part, (temperature expansion etc.) as recorded for calibration of optimum inspection intervals and provisions are made for easy replacement of bearings under service by local strengthening of the box girder and extra plinth on the pier top designed for jacking. Bearing replacement can take place without interruption of traffic.

Another maintenance saving feature is the use of hydraulic cylinders for restricted and controlled support and movement of the bridge girder at the main towers. The system is extremely robust and maintenance free as compared to a system of vertical and horizontal sliding bearings and mechanical linkage which would otherwise have been required.

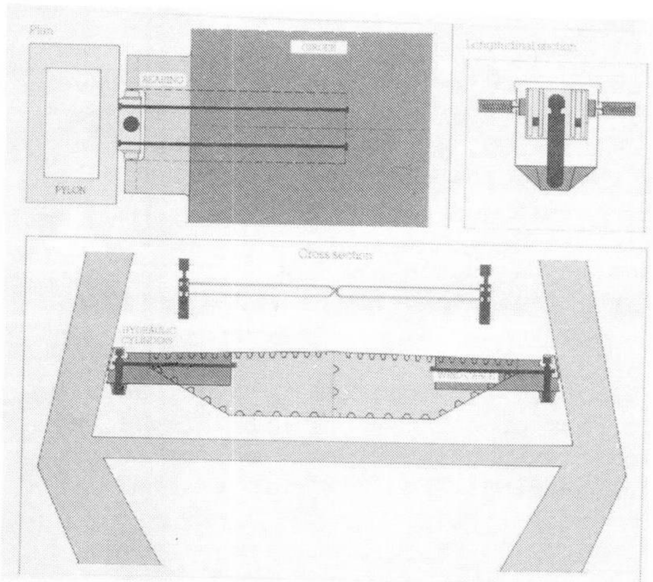


Fig. 4.6 Farø Bridges. Bearing between Pylon and Girder

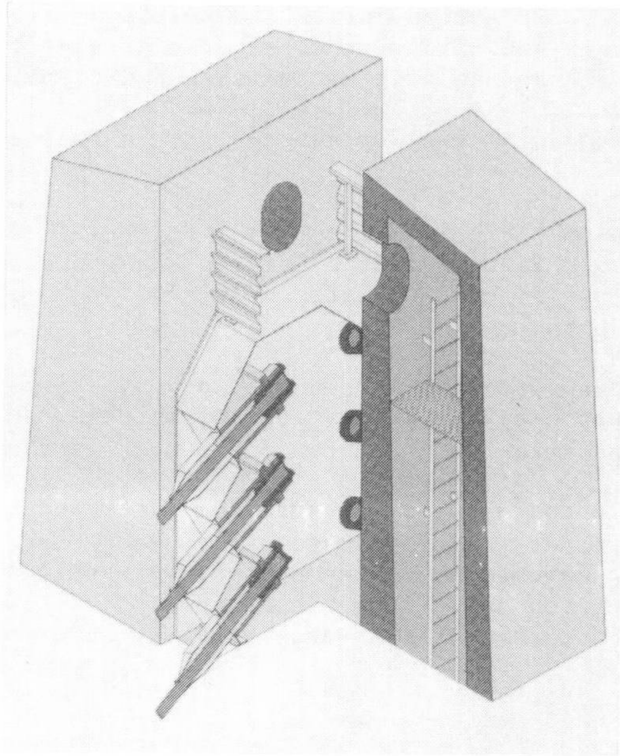


Fig. 4.7 Farø Bridges. Stay Anchorage in Pylon Top

The cables for the stayed portion of the bridge are anchored in the top of the pylons into a robust bearing walled steal box structure posttensioned to the concrete tower legs by bars. Due to the rather difficult access on the outside, the box has received a thorough protection by zincspraying and 4 layer paint system which should ensure a very long life before new treatment will be required.

Easy access is provided by elevator in the tower legs to the complicated interior with cable anchorages, stiffeners, shims etc. This space is efficently and inexpensively protected against corrosion by dehumidefication.

The stay cables are spaced closely to allow replacement one at a time under service. The traffic only being limited locally by a local single lane shut down for working area during replacement. Cable stresses in neighbouring stays will only increase marginally due to the close spacing and girder stiffness.

The replacement of roadway pavement is foreseen in the the girder shall remain stable on its bearings during removal of all pavement on one side of the bridge even under strong wind conditions. Traffic may then temporarily be directed to one side of the bridge during repaving without impairing safety.

5. MATERIAL SELECTION

In addition to the normal structural strength criteria the most important criteria in the selection process is durability for the intended use, environmental exposure, and desired lifetime.

Environmental deteriorating forces are severe for transportation infrastructure being unprotected and exposed to aggressive atmosphere, sea water, de-icing salts, high winds, and pounding traffic. Therefore, durability is most often the governing criteria.

Many attempts have been made in recent years to improve durability of concrete. These attempts have been encouraged by increasing concrete deteoriation problems experienced in many countries after the hectic building and construction activity in the late sixties and early seventies.

The most significant improvements have been directed towards:

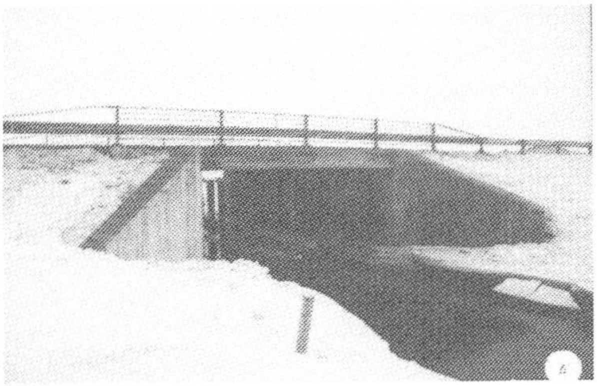
- use of non-reactive concrete aggregates to avoid alcalic reactions,
- avoid initial cracking of the concrete by controlled temperature gradients during the cement hydration process,
- production of dense low permeable concrete by minimizing w/c ratio using additives like superplastifiers,
- addition of silica fume and/or fly ash, partly in substitution for cement, in order to improve homogenity (reduce bleeding), density permeability and minimize hydration heat generation and thereby temperature gradient induced initial cracking,

Further, intensive research is being carried out for extra high strength concretes using normal weight or even lightweight aggregates primarily for use for deepwater platforms in the North Sea and for longspan bridges.

Traditionally, Danish bridges are equipped with waterproofing bituminous membranes applied in hot liquid asphalt for 100% adhesion and a multilayer asphaltic pavement on top. Such systems are expensive, and the excellent 100% quality is difficult to achieve under normal practical circumstances, leading to often premature leakage and accellerating deterioration.

The encouragement to avoid such protective systems or develop new technologies is, therefore, high.

For two experimental bridges built by the Danish Road Directorate, the pavement and waterproofing has been omitted all-together, and silica fume and fly ash concrete developed in research projects in close collaboration between client, designer, contractor, readymade concrete supplier, as well as testing laboratories. Concrete mixes with various silica and fly ash contents, as well as other parametric variation have been tested by accellerated methods in laboratory. The bridges have now been in service for some years and behaviour is promising.



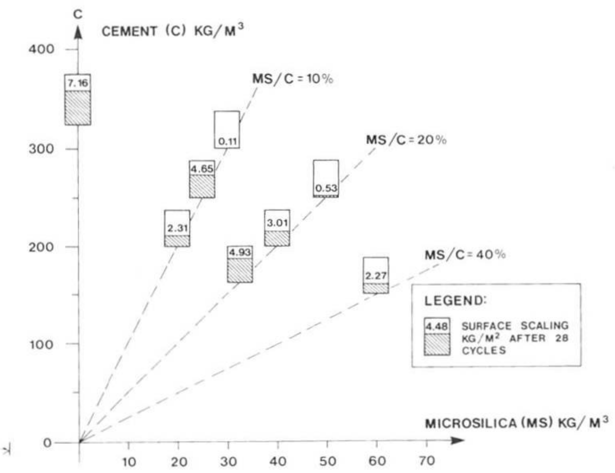


Fig. 5.1 Ry Å. Experimental Bridge.

Fig. 5.2 Freeze-thaw tests. Concrete with different amounts of microsilica and no air entrainment

Other possibilities under investigation are the substitution of the bituminous membrane techniques by latex or polymer modified overlays. Such method could be of particular interest for rehabilitation of existing bridges as an alternative to replacement of the traditional pavements.

6. QUALITY ASSURANCE IN DESIGN AND CONSTRUCTION PHASES

Once a durability and maintenance strategy has been selected for a given structure it is important to ensure that this strategy is implemented in all phases from conceptual design through construction and operation.

This should be assumed by a quality assurance system in accordance with modern QA-principles by means of which the inspection and maintenance objectives are defined along with other criteria. A policy of access, durability of individual primary and secondary project elements, replaceability and adaptibility shall be defined as a basis for conceptual design and ensuing phases of the work. The QA system specifies procedures and staff requirements to be followed and requirements to checking and documentation.

For the construction phase a transfer of the project to the contractor takes place via tender documents and the contract. It is fundamental for the continuity in the quality assurance that the quality strategy and objectives is likewise transferred to the contractor through tender documents and for major complicated jobs also by quality conferences with the contractor responsibles at all levels. The contractor, thus motivated, should be required to demonstrate and document his own quality assurance programme to ensure the job is done right in the first place, and that proper documentation is produced.

Such QA programmes has consistently been used for the Farø bridges in Denmark, resulting in generally very high quality of design and construction at competitive cost.

7. INSPECTION AND MAINTENANCE

The aim of the system of inspection and maintenance procedures is to maintain the level of service by a minimum of cost. An example of systematical inspection programme is given below for the Farø bridges:

To control the inspections and maintenance works a system of manuals is used:

- o Inspection plan including organization diagram
- o Inspection, instructions
- o Maintenance, instructions
- o Report, instructions

The inspection plan includes routine inspections by local personnel and principal inspection by trained inspectors. Based on the reports from these inspectors, decisions are made whether maintenance works or further special inspections by selected inspectors are necessary.

The frequency of routine inspections varies from daily (road surface) to every six month, while principal inspections take place every 3-6 year.

The reports on inspections and maintenance works give information by which both remaining life and future costs for different parts of the construction can be estimated.

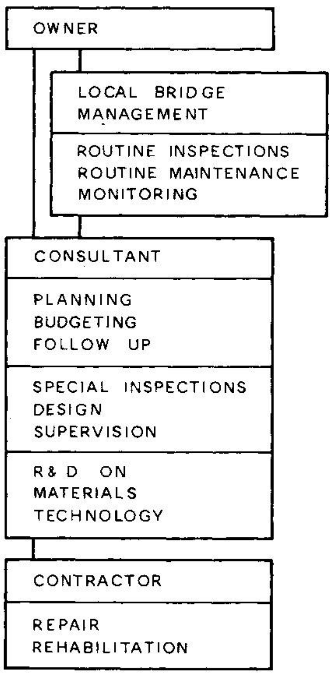


Fig. 7.1 Diagram of typical maintenance organization

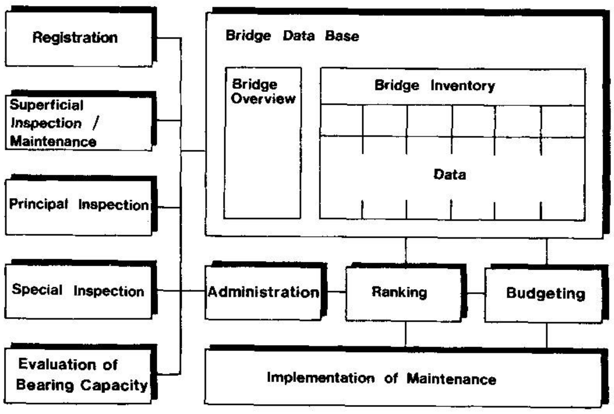


Fig. 8.1 Diagram Bridge Management System

8. BRIDGE MANAGEMENT SYSTEM

The growing quantity of maintenance implies a large number of inspection reports and construction data. To get a comprehensive view or to analyse the consequences of alternative maintenance proposals, an efficient data handling system is needed.

It is the objective of bridge management to maintain the functioning of every single structure and ensure an optimum life of its different elements. This objective must be fulfilled in due consideration of technical, economical, aesthetic and political lines.

A management system could be divided into three modules:

- Registration

  Bridge data are stored in a data base whose structure ensures updating and avoids double registrations. The users can choose fixed ouput forms such as bridge overviews or create individual output forms containing selected data.

- Inspection

  The system ensures that regular inspections are started at the right time and made to standards as detailed in the manuals. The necessary data - the "working basis" - are printed out to the inspection engineers, who will report their findings including condition marks and remaining life for the bridges and the elements.

  Bridges are divided into elements and sub-elements depending on the conditions of the bridges - elements are introduced when damages occur and deleted after repair.

  The amount of inspection data is by this dynamic element structure kept to a minimum.

- Ranking and Budgeting

  A ranking point is calculated for each bridge on the basis of the condition marks for the elements. All bridges are subsequently arranged according to their condition.

  Repair schemes are made for the bridges which are placed higher in the priority list. The preferred repair scheme for a bridge is based on a net present value comparison.

  The overall budget needs are calculated and adjusted to budget limitations, when the maintenance strategies for the individual bridges are finally adjusted.

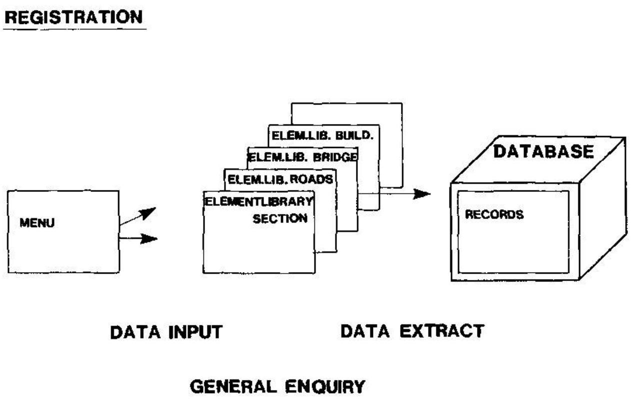


Fig. 8.2

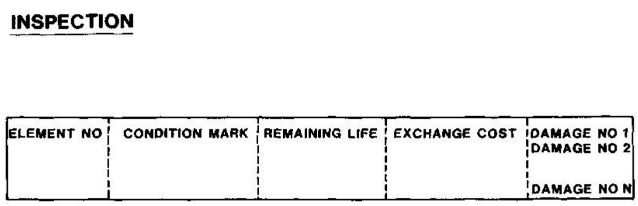


Fig. 8.3

To make sufficient maintenance plan and corresponding cost estimates, an assessment of remaining life of the construction or parts thereof is necessary.

Reliable methods for the assessment of remaining life of bridge elements are difficult to establish and a definitive settlement of the lifetime is only possible at the time when the bridge elements are replaced or condemned. Therefore, the system takes full advantage of this acknowledgement and thus comprises two components:

- Marking System for the registration of the present condition combined with an estimate of the remaining life and the cause of deterioration.

  The closer one gets to the end of the lifetime, the shorter inspection intervals and the more correct is the estimate.

- Log System for the registration of the actual development. The accepted conditional marks and the inspection date for each bridge element are kept in the system. This log forms the background for statistic analysis together with information on materials, surroundings and loads. Lifetime estimates are thus supported by these logs.

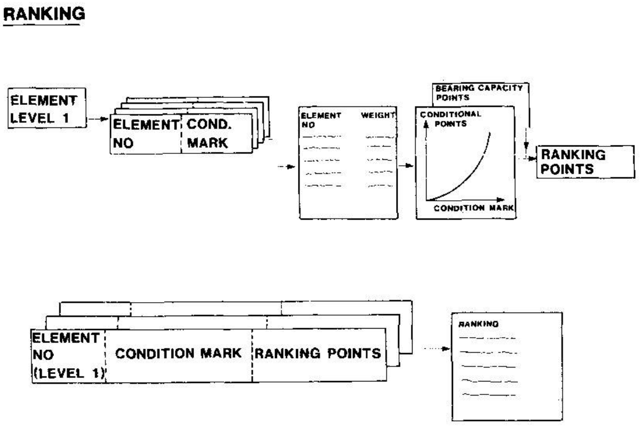


Fig. 8.4

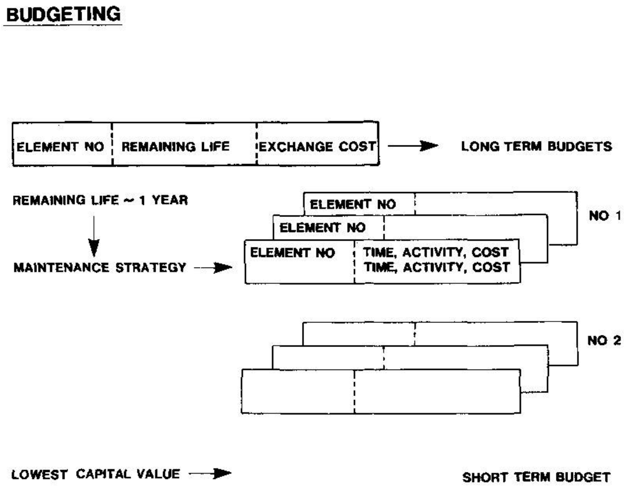


Fig. 8.5

The priority and budgeting system is based on inspection results - visual, such as damage registration, condition marks, remaining life and estimated repair costs - and special, such as detailed repair schemes.

The regular bridge inspection provides data detailed to an extend which corresponds to the actual condition of the bridges: A bridge may be registered by one element with 1) conditional mark of say 1, 2) remaining life of say 50 yeas and 3) estimated costs for replacement of the element (- bridge) after 50 years of say 7 mill. DKK.

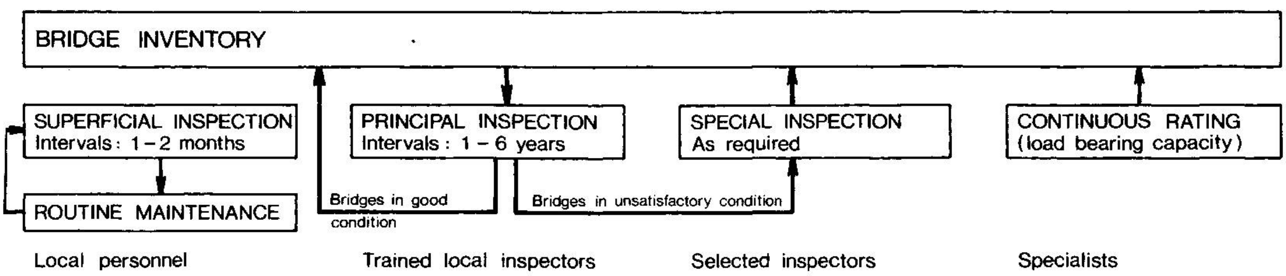


Fig. 8.6

If from experience the inspector is aware that some of the bridge elements have a remaining life of less than the above mentioned 50 years, he introduces these elements (expansion joints, membranes etc.) and corresponding 1) conditional mark, 2) remaining life, and 3) estimated costs.

During the following inspections, the number of elements are increased and conditional marks, remaining life and estimated costs are adjusted. The closer to remaining life of 0, the more correct predictions.

Elements of the bridges have been assigned a factor reflection its contribution to the overall function of the bridge. Bridge condition points are then calculated based on the condition mark of each element and its factor.

A ranking of all bridges is performed on the basis of the condition points and the remaining life.

Bridges having top priority are highlighted and detailed investigations are called for. These investigations may lead to adjustments of the condition marks, remaining life and costs or alternatively to repair schemes.

The system analyses the repair schemes and calls attention to the scheme with lowest net present value.

Budgets are available at any time with relation to latest inspection records. Short term budgets are usually based on the detailed repair scheme provided by the special inspection and long term budgets are normally based on estimated remaining life and replacement costs.