Session B3

Maintenance of Structures
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Instandhaltung der Tragwerke

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Guidelines for a Handbook on the Service Life of Buildings

Directives pour un manuel de conservation des bâtiments

Richtlinien für ein Handbuch für die laufende Instandhaltung von Gebäuden

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SUMMARY

The goal of the research is the identification of the contents and aims of a handbook on the building life in service. The research puts forward a mode of building card, defines, in particular, concepts such as "maintenance pools" and consequent "inspective paths" on which the building inspection is based for the purpose of programmed maintenance. An indispensable tool for the proper management program of conservation, the building handbook is a document which undergoes continuous updates during the life span of the building.

RÉSUMÉ

Cette recherche a pour but la préparation d'un manuel pour la conservation des bâtiments en service. Elle propose un modèle de mise en fiche du bâtiment, règle spécialement les principes d'entretien et les parcours d'inspection. Pour une programmation correcte de la conservation, il est indispensable de posséder un manuel pour la conservation du bâtiment. Ce document sera sujet à des mises à jour continuelles au cours de la vie du bâtiment.

ZUSAMMENFASSUNG

Ziel unserer Studie ist die Bestimmung von Inhalten und Zielsetzungen eines Handbuches zur laufenden Instandhaltung von Gebäuden. Vorgeschlagen wird ein Modell zur karteikartenmässigen Erfassung des Gebäudes, insbesondere Konzepte wie die Gesamtheit aller Massnahmen zur Instandhaltung und die Kontrollgänge, die zur Inspektion des Gebäudes im Zusammenhang mit einer gezielten Planung der Instandhaltung notwendig sind. Unabdingbares Instrument einer korrekten Planung der Instandhaltung ist ein Nutzungshandbuch des Gebäudes, ein Dokument, das im Laufe der Lebenszeit des Gebäudes ständig aktualisiert wird. Dieses Handbuch setzt sich aus drei Teilen zusammen: der Gebäudekarte, dem Instandhaltungsbuch und dem Betriebsprogramm.

1. INTRODUCTION

"L'architetto non dee, tosto che e' finito qualunque edificio, abbandonarlo ma bisogna che gli stia intorno con diligente cura per conservarlo". "The architect, soon after any building is completed, must not forget it but must get around it with great care to preserve it (...)"; this is the opinion of the sienese physician T. Gallacini, 1564-1641, in his 'Treatise about architects mistakes". This exhortation is again very much actual in Italy at present time. In the last years, especially in the so called building boom period (1950 - 1960) buildings have been realized without any attention to basic requirements of project and construction qualities which were at odds with the profit rules; in this period construction made in a hurry and based on superficial planning allowed substantial savings on working force wages and on professional payments, but has yielded buildings which have deeply degraded within 15-20 years. Not only construction quality has been left out but also maintenance activity which has indeed allowed, during past centuries, the preservation of a huge and precious historical patrimony. Understanding the high value, both historical and economic, of the real estate has stirred up the awareness of careful planning and execution, also in view of management costs decrease.

The main reason which led the research group to elaborate a handbook for the building life in service stands in the persuation that each stage of the building process yields pieces of information (documents and data) which must be systematically collected in order to have, once the building is completed, a knowledge and maintenance guide tool of the predetermined planning quality; a tool which allows to collect continuously the functional and technological history of the building subsequently to its first use. Such a tool has been called the Building Informative System (B.I.S.) and is a complex of structured and systemized information concerning the building. Information can be aggregated in specific functional modules which are cards with different aims: historical and cultural goals (catalog of buildings and architectural masterpieces, etc.); fiscal goals (cadastral enrollment, real estate taxes, solid waste disposal taxes, etc.); public administrative goals (rescue plans, construction authorizations, adjustment to safety codes, etc.) and, particularly, maintenance goals (maintenance booklet, calculation of millesimal portions, organization of inspective and maintenance activity, etc.); moreover, such cards can be targeted for different uses (cadastral card, maintenance booklet card, catalogation of architectural patrimony card, etc.).

The management stage is made up of the building life in service and the administration phases (Fig. 1). The building life in service must be properly set in the planning phase and defined as precisely as possible at test time and when the building starts being used.

2. BUILDING LIFE IN SERVICE AND MAINTENANCE

The two words building life in service and maintenance are often considered synonimous in the technical language. On the contrary the "building life in service" configures a process [1] whose aim is to mantain predetermined reliability characteristics of the building, or one of its parts, to adequate, if necessary, building characteristics to new requirements and to optimize functioning costs; on the other hand, maintenance is the operational phase [2] of the building life in service, i.e. execution of programmed interventions.

The building life in service process entails subphases as follows:

a - *Building knowledge phase* [3], already undertaken in the planning and execution phases, allows to gather and elaborate, based upon the B.I.S., the Building Computerized Card finalized to the maintenance handbook.

b - *Maintenance strategy selection phase* is indispensable for the preparation of the maintenance program; in fact, possible maintenance strategies may be diverse: either a posteriori maintenance, a priori maintenance (programmed or at the limit state), or opportunity maintenance [4].

c1 - *Inspective control phase:* during operation, inspections are carried out in order to check, at given times, the fulfilment of the maintenance program, to survey situations of degradation or beginning damage, and/or to accomplish the opportunity maintenance. Specifically trained personnel should be available to carry out inspective activities for the technological system, as it already happens in mechanical and manifacturing industries and management of great public works (dams, railways, nuclear or electrical power plants).

c2 - *Control phase with calculation*, allows checks on the reliability of the technological system or some of its parts during operation, both with laboratory and in situ checks.

d - *Diagnostic phase*, has the goal to judge the state "of health" and of consistency (diagnosis) of the building or of some of its parts, referred to different technogical units and to specific technical elements. The diagnosis is the support for subsequent planning and estimates of expenditures for the intervention: possibly, it appraises the causes (etiology) [5]

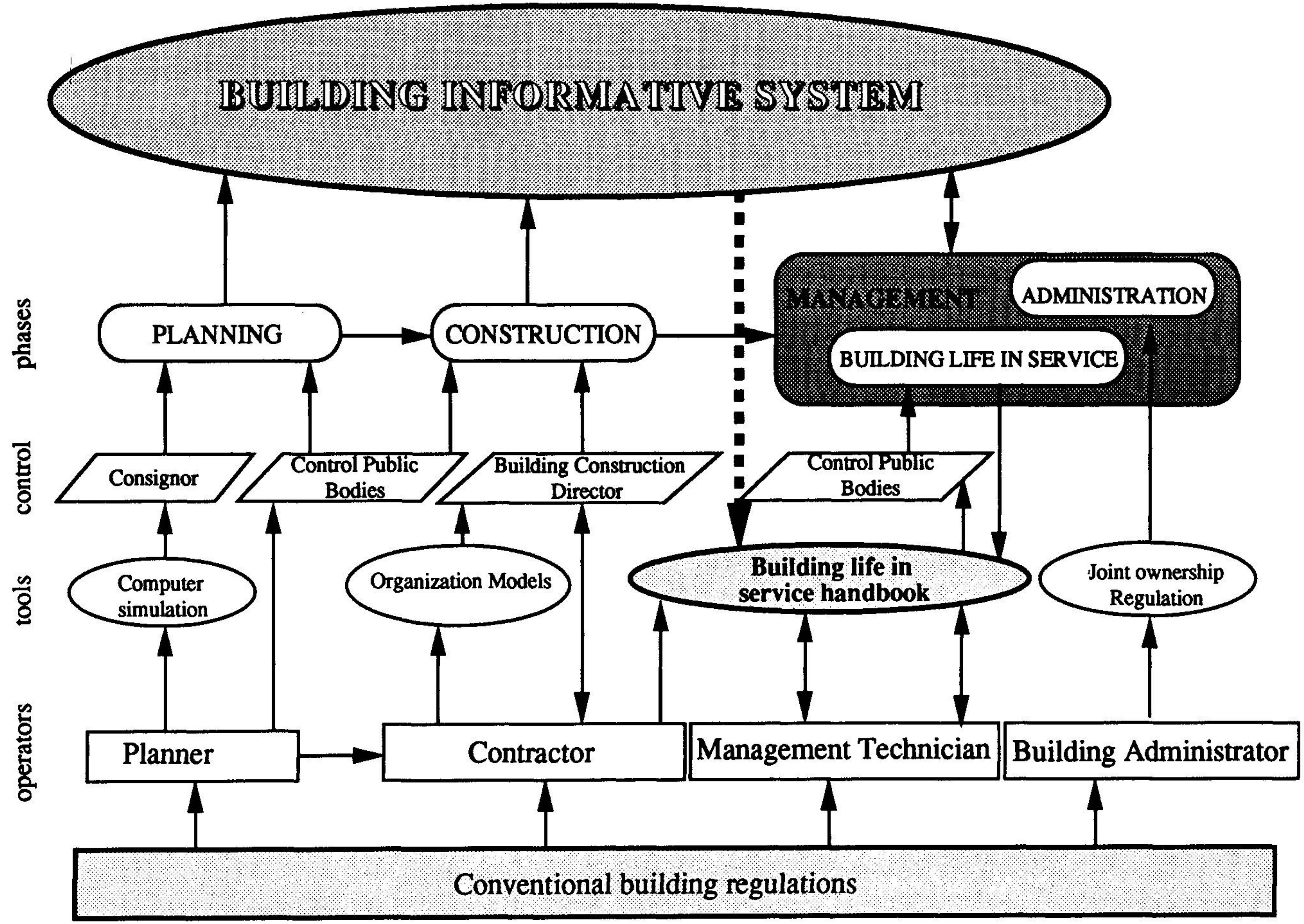

Fig. 1 The Management phase within the Building Process

that have provoked the degraded state (pathological state).
e - *Estimation of expenditures and work planning phase.* It is possible to prepare estimates of expenditures and a program of works to be done on the basis of the data obtained in the preceding phases on the consistency state, and of the diagnosis of the state of degradation.
f - *Maintenance phase,* is the building activity which has the goal to counteract aging and degradation phenomena, to repair unexpected and sudden damages, to adequate the building or some of its parts to new regulations or to different destination uses (in such case it is an improvement activity which is in between maintenance and rescue [6]).

3. THE BUILDING LIFE IN SERVICE HANDBOOK

Useful guidelines for handbook preparation are derived from the methodology based on the principle that only the exact building knowledge in its historical, technological and functional specificity (constructive technics, materials, systems, construction age, use destination, urbanistic bonds, etc.) allows to intervent in a timely and aimed manner and to adopt appropriate measurements for building life in service. Thus, an authentic anamnesis [7] of the building must be applied both as a methodological principle and an analysis tool.

3.1 The scanning of the building in maintenance pools

The building once completed requires a reading modality different from that used in the project and in the construction phase. The constituent elements are so deeply interrelated to constitute new entities which we propose to define "maintenance pools". For "maintenance pool" we intend an aggregation of elements and works which may have different functions but, insisting in the same space, interact one upon another; so that they determine the level of reliability of the aggregation. The limits of the maintenance pools are specific for each building and depend upon its physical configuration, on its use organization and on its ownership. An inspective path corresponds to each maintenance pool; various are the parameters which may guide to limit and define the pools (use omogeneity, belonging to the same technological units class); it has been deemed appropriate to consider as the leading aggregation criterion the straight sequence of what appears to the inspective personnel along the entire inspective path.
For example, once a global description of the building is given (Typology classification: 1 - Massing, Building type, Plan type; 2 - Structure: Foundation system, Floor systems, Wall systems, Roof system; 3 - Interior: Interior division and use, Mechanical and electrical systems), the analysis of the building, based on maintenance pools, must be done: each specific maintenance pool is examined in subsequent studios. Let us examine the maintenance pool "Facade". First, it must be localized with respect to the building as a whole and to the other constituent annexes (how many facades, blocks, wings), pointing out their orientation. Second, a global description of the principal characters is given: Walls (visually height: basement, raised basement, stories, attic, belt course), Finishes, Decorative elements, Additions (terraces, etc.), Doors, Windows. Third, each element or component is described analitically (e.g., Facade elements: joints, chimney and flues, gutters and downspelts, damp-proofing courses, lattices, flagholders, signs, sunshades, solar control device, vent outlets, lightining rods, lightining fixtures, branch circuits, communication).
The various tecnological plants require additional and specific inspection and must have peculiar control modalities.

3.2 The handbook contents

The building life in service handbook is an essential tool to plan the preservation. The handbook is a document which must be always kept up to date during the building life. It is prepared for each specific building by a management expert.
The handbook consists of three parts: the Building Card, the Maintenance Booklet, the Practice Program.
- The Building Card is the essential document which allows the complete identification of the building and records all the events important for the building life in service.
The Building Card must contain:
- the data deduced from the following documents: certificate of property, historical and new cadastral maps, approved project (when it exists), and any other document (technical and contractual) pertinent to technological and environmental systems, to location of technical systems inside the building and of their connections to public input and output canalizations, to a thorough building diagnosis including critical spots and full appreciation of the building consistency.

Such a diagnosis requires specific technical knowledge (historical-architectural, statical and constructive, chemical, etc.). By comparison to what happens in the medical field, the diagnostic [8] activity articulates in a series of logical-analytical subphases, i.e., informative (the observation of an objective sign or of the complex of several signs, carried out in the control phase) and synthetic, the judgement.

- the building executive project, or in its absence, the dimensional survey that includes the preparation of adequate technical papers (plans and sections), detailing the components lifespan and their capability to be inspected.
- The Maintenance Booklet articulates in three parts: a) the maintenance pools; b) the inspection program; c) the maintenance program.

The first part lists and describes the maintenance pools; the second part describes inspective paths, the inspection calendar, agents and tools for adequate control, i.e., observations, chemical and physical laboratory tests, in situ tests with portable instruments and non-destructive tests, etc. The third part is the maintenance program derived from the maintenance strategy chosen in relation to both the quality levels to mantain and attain, and the financial resources available in the short and long run. In the maintenance program are listed the interventions, their periodicity and executive modalities, and operators qualified to carry them out.

- The Practice Program specifically indicates the use modalities of the building in order to decrease degradation caused by improper use (ventilation of premises, rules to favour or limit insolation, etc.).

Such a program should be useful for the final user and the building administrator, in order to avoid requests which are either unexpected and/or contrary to established planning criteria (Fig. 2).

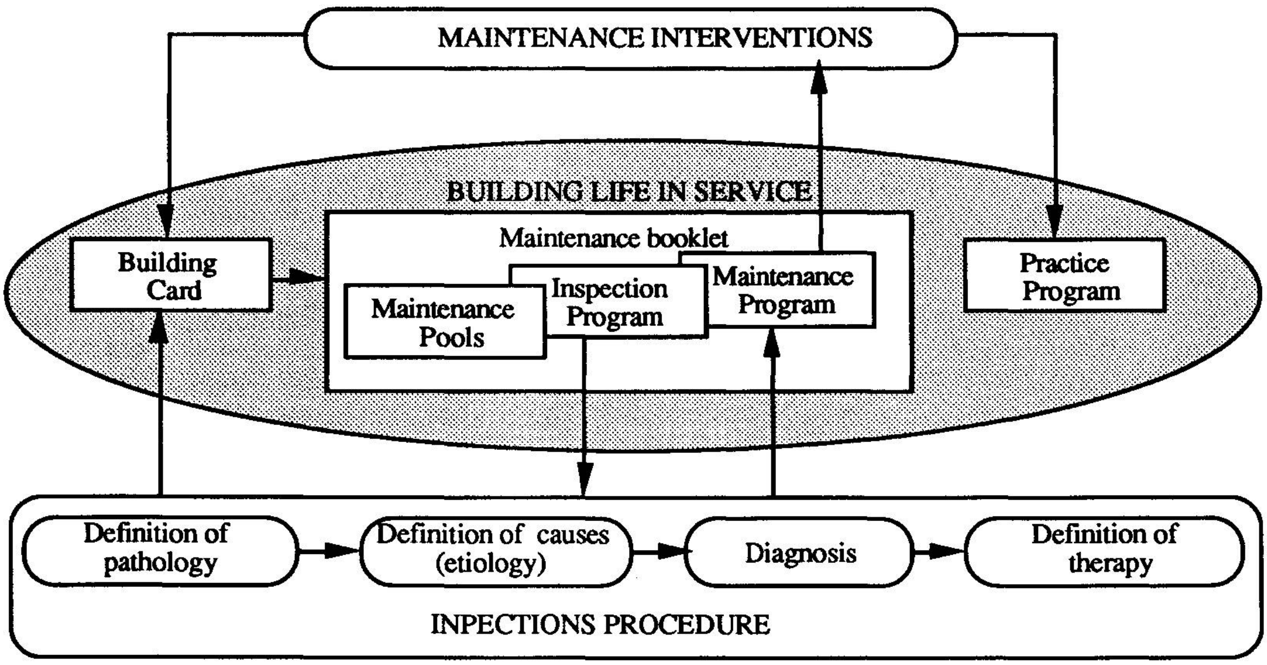

Fig. 2 Relationships between constituent parts of buildings life in service handbook, inspections procedures and execution of maintenance interventions

4. CONCLUSIONS

In the present communication, we have explained the reasons which led to the elaboration of the maintenance handbook, and have outlined methodological guidelines for its preparation.

Moreover, we have underlined the importance of the link between the knowledge phase and the management phase, indispensable link for the preparation and constant update of the building life in service handbook.

Quite often the building process remains incomplete with respect to the management phase because its social and economical importance has not been understood yet, and also because it is not mandatory the preparation of tools necessary for proper unfolding of the management phase.
In Italy, maintenance is shaping up, as time goes on, as the leading activity in the building field. Thus, there are immediate needs for new organization models of building contractors, for new specializations and professional expertise, now centered in the building administrator, for new contract models, and for new technological proposals.

NOTES

1 For process we intend a structural whole of entity linked up each with another by relative conditions.
2 For phase we intend each of caracteristical and different moments of a continous development.
3 The definition of knowledge process is given in: E. Dal Zio, V. Dal Piaz, R. Paparella, E. Rinaldi and F. Vergine, S.M.I.R.N.E. Il sistema metodologico intelligente al recupero nell'edilizia, University of Padua, 1994
4 Branch of knowledge dealing with causes of a disease or abnormal condition
5 Definitions relative to mentioned concepts are given in:
6 Rescue refers to the global process, whereas maintenance, restoration, recovery and restructuration refer to different types of the rescue.
7 Anamnesis: reminiscence. In medicine, a preliminary case history of medical patient, referable both to the investigation of the specific pathological condition and to general and foundamental stages of the patient's life, i.e., physiology, remote and recent pathology.
8 Diagnosis: the act of identifying a disease from its signs and symptoms; an investigation or analysis of the cause or nature of a condition, situation or problem.

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Evaluation of Bridge Condition for Improved Maintenance Policy

Évaluation de l'état des ponts pour une meilleure politique de gestion

Beurteilung der Brückenzustände für eine bessere Unterhaltspolitik

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SUMMARY

This article describes the quoting system and the method used by the French Ministry of Transportation for evaluating the condition of the bridges situated on the French national road network. The objective is to give an "IQOA" indicator representative of the overall state of the network. The first evaluation of all bridges longer than 2 meters was made in 1994. The paper presents the main results.

RÉSUMÉ

Cet article décrit le système de cotation et la méthode utilisée par le ministère de l'Équipement, des Transports et du Tourisme pour évaluer l'état des ponts situés sur le réseau routier national non concédé français; l'objectif est de fournir un indicateur "IQOA" représentatif de l'état global du patrimoine; la première évaluation a été faite en 1994 sur la totalité des ponts de plus de 2 mètres de portée; les principaux résultats sont fournis.

ZUSAMMENFASSUNG

Dieser Artikel beschreibt das Notiersystem und die vom Infrastruktur- und Verkehrsministerium verwendete Methode, um die heutige Lage der Brücken auf dem französischen nicht konzessionierten Straßennetz zu bewerten; das Ziel ist es, einen Indikator "IQOA" zu geben, der für die Gesamtlage des Brückenbestands repräsentativ ist; die erste Bewertung von allen mehr als 2 Meter langen Brücken fand 1994 statt; die hauptsächlichen Ergebnisse werden vorgestellt.

1. THE FRENCH ROAD NETWORK. MAINTENANCE POLICY IN THE NATIONAL NETWORK.

The French road network has about 900,000 km of roads, of which 36,000 km belong to the State; 6,000 km are operated by toll motorway companies, and 30,000 km are managed directly by the Road Directorate of the Ministry of Equipment, Transportation and Tourism.

On the national non-conceded road network managed directly by the Road Directorate, we could register a patrimony of 18,500 more than 2 m long bridges, 1,000 km of retaining walls, 45 km of tunnels and 96 km of noise barriers. The only bridges represent a value estimated at 70 milliards of French francs, or about 10 % of the value of the whole corresponding road patrimony.

Since 1992, the Road Directorate is engaged in a voluntary policy of preserving the condition of its patrimony, whether it may be composed of pavements or of bridges, and to this end they put two indicators into place, namely:

- IQRN (Image Qualité du Réseau National) for pavements,
- IQOA (Image Qualité des Ouvrages d'Art) for bridges.

This last indicator is now extended to tunnels and will later on be so for retaining walls.

The objective of this is:

- to have an evaluation of the condition of the network and its evolution in time by means of physical and financial indicators,
- to draw economic lessons from this evaluation in order to fix the yearly budgets for maintenance,
- to define the policies for the contract maintenance by managing services.

At present, the Road Directorate devotes about 300 million French francs every year as external costs for the maintenance and repairing of its patrimony in bridges, or about 0,45 % of its value.

2. ORGANIZATION OF THE SUPERVISION AND MAINTENANCE OF THE BRIDGES IN THE NATIONAL NETWORK

The construction and management of the national road network are placed under the authority of the Road Directorate giving a great decision delegation to the County Directorate (DDE), which are one hundred in number, in the framework of the budgetary credits allocated to them.

The continuous supervision of the bridges is under the responsibility of Land Sub-Divisions, which are a dozen per DDE on average ; the supervision is made according to an instruction of 1979 fixing the periodicity and level of inspections as a function of the importance of the structure and the risks it generates.

These Sub-Divisions have at their disposal technical support made up of a Departmental Cell for Engineering Structures (CDOA) placed in the office of the County Directorate and in charge of evaluating the severity of defects, giving a diagnosis, making repair projects and proposing intervention priorities to the County Director.

For detailed inspections requiring specialized means of access or measurement, or for making analyses or studies on complex bridges, the County Direction can call upon specialized centres (Centres d'études techniques de l'Equipment), 8 in number in France, but in any case the County Directorate remains responsible for the quality of the supervision and the good state of the bridges.

The specific methods and materials necessary for their tasks are prepared and distributed by the Service d'Etudes Techniques des Routes et Autoroutes (SETRA) and the Laboratoire Central des Ponts et Chaussées (LCPC).

3. INVENTORY

The diagram Figure 1 illustrate the composition of the patrimony of bridges and culverts of a length superior to 2 meters analysed by type of bridge.

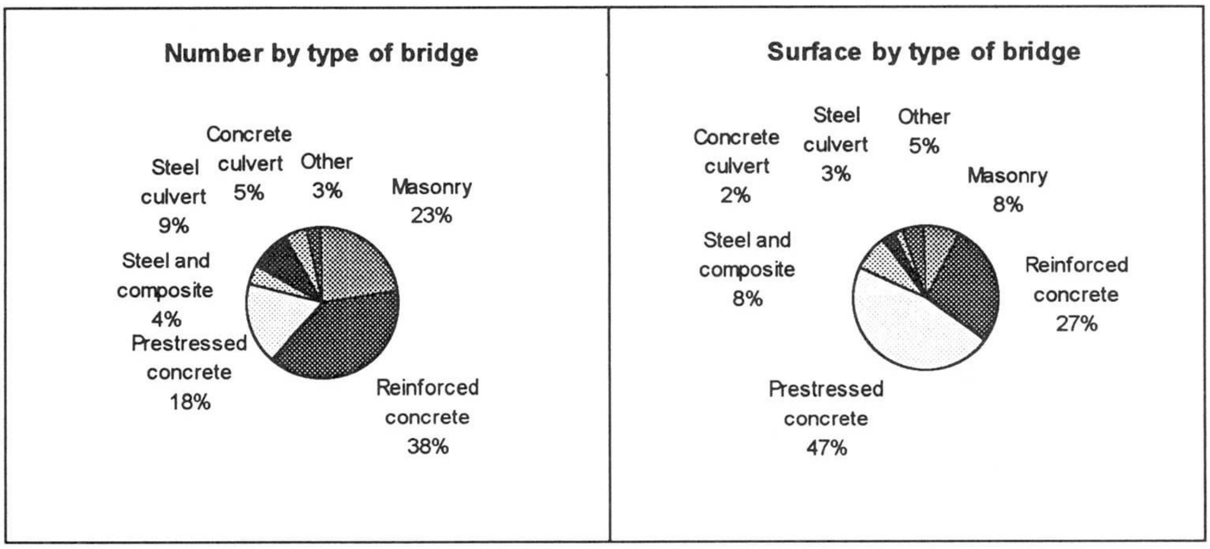

Figure 1 : Inventory of bridges and culverts greater than 2 meters

4. EVALUATION OF THE PATRIMONY CONDITION

The evaluation made in the framework of the IQOA operation dealt with the whole patrimony of bridges and culverts, or 18,500 structures ; it was made using the detailed inspection reports when these existed and were sufficiently recent ; for the rest of the patrimony, the evaluation was made on the basis of a rapid visual appraisal made during a period of half a day per bridge and without specific means of access.

This evaluation was made in such a way that we could distinguish the condition of equipment (pavements, footways, cornices, retaining devices, drainage devices, expansion joints under pavements and footways, operating equipment, etc.), the condition of the protection elements (waterproofing layers, the anticorrosion coating of metal surfaces, stone facing, rocks, etc.), as well as the condition of structure elements (bridge decks, supports, bearing devices, foundations). This distinction allowed us to define three great classes of characterizing the state of the bridges:

- class 1 groups the bridges in apparently good condition ;
- class 2 concerns the bridges showing defects of equipment or protection elements, or minor structural defects ;
- class 3 unites bridges with damaged structures.

A sub-classification was made to take the urgency of intervention into account. So in the bridges of class 2, we distinguish the bridges of class 2E requiring urgent special maintenance in order to prevent the development of disorder in the structure (for instance of a faulty waterproofing layer), and the bridges of class 2S requiring an urgent intervention in order to warrant the security of the road users (for instance a damaged balustrade). Among the bridges of class 3, we distinguish those in class 3U requiring urgent repair works because of an immediate or short-time insufficience of bearing capacity. The decision flow chart presented resumes this method of classification.(Figure 2)

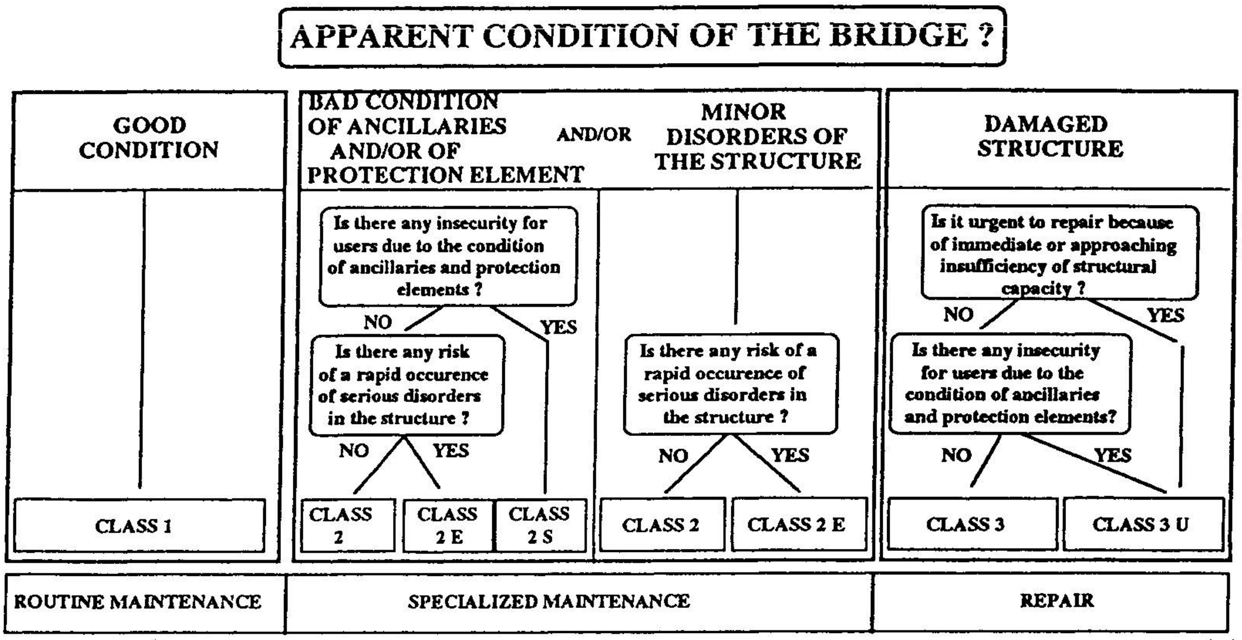

Figure 2 : Flow chart for classification of bridges

In order to make use of the operation of evaluating the condition of the bridges in situ, all the bridges were divided into two categories:

- the first category concerning the common bridges which have been inspected by the Equipment Sub-Divisions, which have thus made up the exhaustive list of defects found on each bridge ; this first rating was then validated by the CDOA centre.
- the second category groups the rest of the bridges whose rating was made directly by the CDOA, by means of the results of a recent detailed inspection, or on the basis of a rapid visual appraisal.

In order to help all the actors in the classification and ensure the homogeneity of the rating on the whole territory, the Réseau Technique de l'Equipement, made up of the SETRA, the LCPC and the CETE's elaborated the two following types of documents:

- **the inspection reports** intended to the agents of the Sub-Divisions and made in such a way that people without a specialized knowledge of bridges should be able to class the different defects stated ; these documents are richly illustrated (see Figure 3) and include the complete illustrated list of all the defects that it is possible to find in a given type of bridge

- **catalogues of the main disorders** explaining the defects and their possible causes and proposing a class for each type of defect ; these 23 documents form an aid to the classification for the CDOA's use.

The documents were distributed when launching the IQOA campaign, with the putting into place of a specific training, intended on the one hand to the CDOA directors and on the other hand to the agents of the Sub-Divisions in charge of inspecting the bridges.

The class assigned to a piece of equipment, an element of protection or a part of the inspected bridge is obtained by choosing the highest of the quotations mentioned for each defect connected with it. On the basis of a summary sheet resuming for each structure the class assigned to the equipment, the deck and the supports, the CDOA assigns the bridge to the most unfavourable class.

All the information contained in the summary sheets, namely the main characteristics of the structure and the results of the evaluation, are then united into a data file ; after the control of the homogeneity of the ratings by the CETE's, the processing of this file is then achieved at the national level.

An evaluation of the rating accuracy and more particularly the correctness of placing bridges into classes 3 and 3U will be done during this year, if necessary after more detailed inspections.

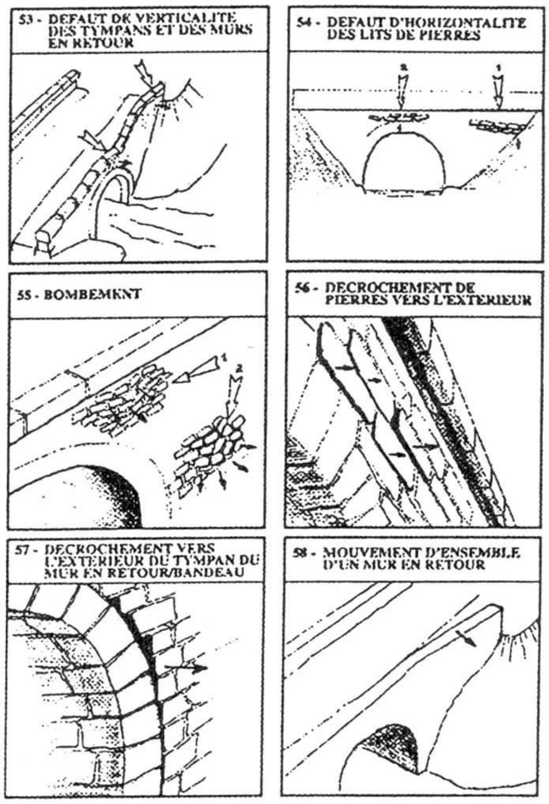

Figure 3 :Example of visit report of disorders (for masonry bridge)

5. THE MAIN RESULTS OF THE EVALUATION

The following graph charts give the main results of the first campain of evaluation : the distribution by class (in number and in surface) and the analysis according to the type of bridge.

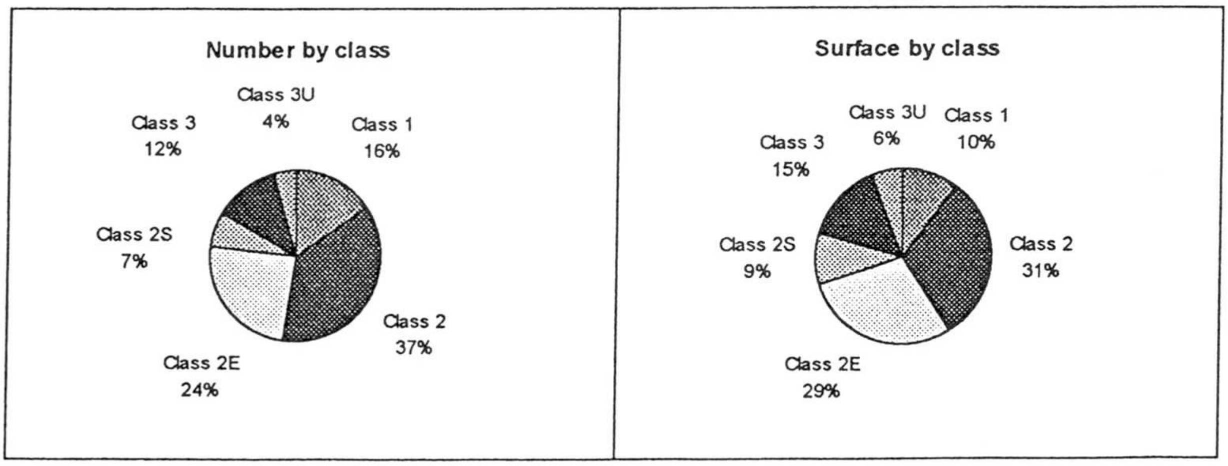

Figure 4 : Overall distribution by class of bridges and culverts

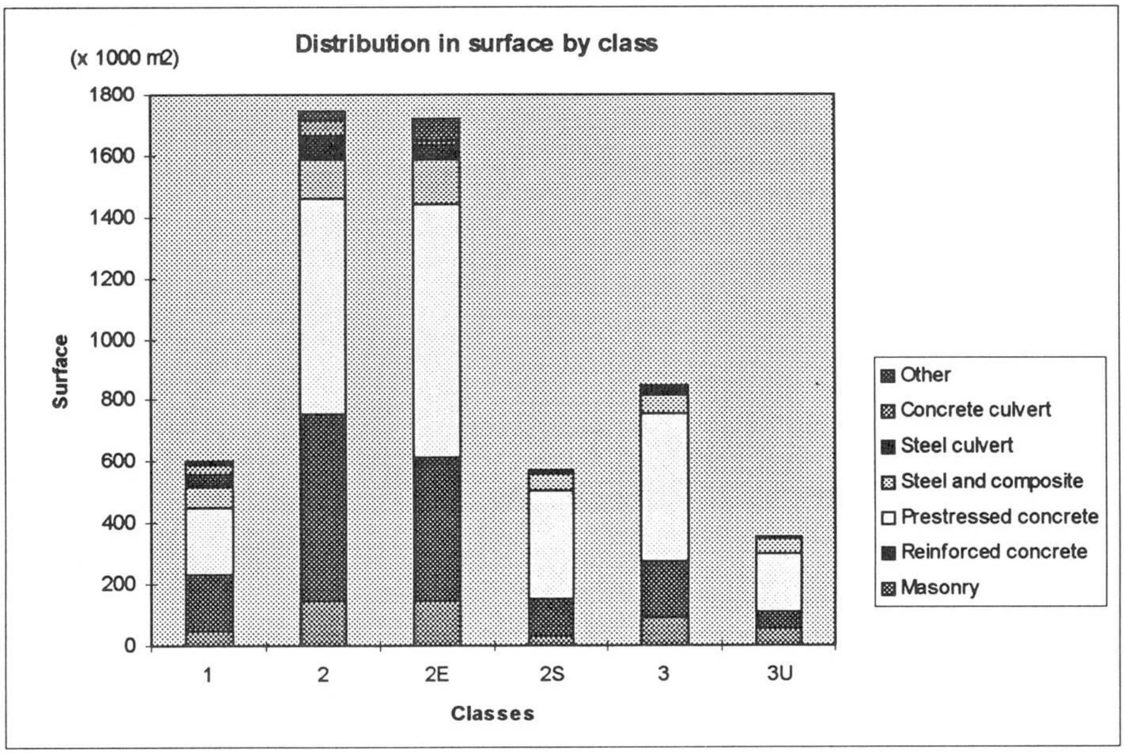

Figure 5 : Distribution by class according to the type of bridge

6. ESTIMATION OF THE REPAIR COSTS

The following step foreseen in 1995 consists of estimating the costs for repairing the patrimony independently of any budgetary constraint ; the method is based on the principle of segmentation of the population as a function of the criteria having a strong influence on the costs (criteria such as class, age, type of bridge, ...) ; after the lot-drawing of a sample of bridges, we are going to make a precise estimation of the repair costs of the chosen bridges and extrapolate them to the whole population. Other information such as the estimation of the costs of the bridges stated in the three-year plan of heavy repairs, will be used in the framework of this operation.

7. CONCLUSION

The evaluation of the bridges in the national road network was launched in April 1994. At the end of the year 1994, about 80 % of the bridges have been inspected and classified ; we must note that the DDE agents were rapidly engaged in this operation, which has the first merit of giving them a package of tools for inspecting the bridges, which was missing before ; the return of information on the patrimony of each DDE will allow us to improve the taking into account of its preservation in the ongoing maintenance programming.

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Development of a Bridge Maintenance Consulting System

Développement d'un système de maintenance des ponts

Entwicklung eines Beratungssystems für Brückeninstandhaltung

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SUMMARY
A diagnostic system used for the quantitative diagnosis of bridges has been developed. Diagnostic evaluation methods for fatigue, diagnosis, bearing capacity and remaining life are presented.

RÉSUMÉ
Un système de diagnostic a été développé pour récolter des données sur les ponts. Le document expose les méthodes d'évaluation de l'état de fatigue, la capacité restante et la durée de vie restante.

ZUSAMMENFASSUNG
Beschrieben wird ein neuentwickeltes Diagnosesystem für Brücken. Aufgeführt sind Beurteilungsverfahren zur Diagnose von Ermüdungserscheinungen, Tragfähigkeit und verbleibender Lebensdauer.

1. INTRODUCTION

Japanese railroads have improved in train speeds, and increased traffic volume, and stricter conditions are imposed on their use. On the other hand, since structures deteriorate, reasonable measures of lengthening their lives have become necessary. For that purpose, a quantitative analysis of actual conditions such as damage, and the bearing capacity or durability of existing bridges and measures such as appropriate repairs and reinforcement are required.We developed the BMC (bridge maintenance consulting) system. This system is designed to systematize the quantitative soundness diagnostic technology which have been used by some specialists and help maintenance engineers perform quantitative soundness diagnosis easily.
The kind of evaluation and diagnosis which the BMC system can handle is described in the following.

2. SOUNDNESS OF STEEL BRIDGES AND ITEMS FOR EVALUATION

The soundness of a steel bridge is judged from its bearing capacity or durability and usability as a measure of the extent of being put to use not merely from the degree of deterioration.
(1) Damage: degree of deterioration of structures
(2) Bearing capacity or durability: what load can a structure endure? What durability does it have?
(3) Usability: convenience of use and reasonability and adaptation to the performance requirement of users.
The foregoing is described in the following.

3. EVALUATING DAMAGE

The BMC system is used for measurement and analysis and the evaluation of bearing capacity and remaining life based on these data.Items for diagnosis and evaluation regarding fatigue damage of steel railroad bridges are as follows.
(1) Will fatigue damage occur? (fatigue limit)
(2) When will fatigue damage occur (predicting the age when fatigue damage occurs)
(3) Knowing the range of measures for similar structures (defining a range)
(4) Deciding when measures should be taken (emergency of measures)
(5) Investigating the cause of fatigue damage
(6) Selecting and confirming measures and method

Fig. 1 shows the flow chart of standard evaluation of fatigue damage.

First, an evaluation is made of a fatigue limit only from detected working stress values. An assessment is made here to see if fatigue will

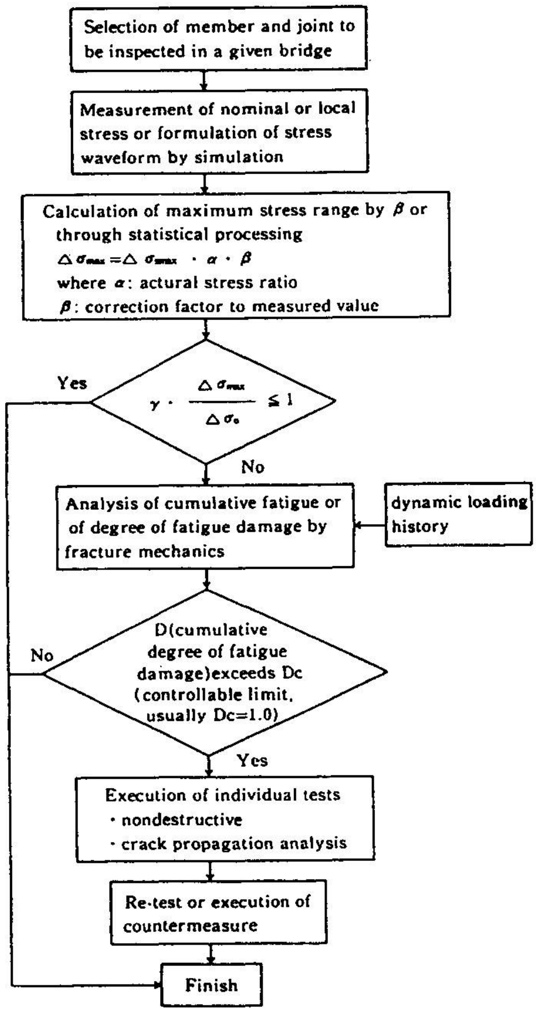

Fig.1 Flow of fatigue damage evaluation

pose a problem at this point in the future. If it is decided that it will be problematic, go to the next step. In the next step, an evaluation is made of cumulative fatigue including the influence of repetition. Load history and stress history are introduced to calculate the degree of cumulative fatigue damage (D) and remaining life. Table 1 shows one guideline for evaluating soundness against the degree of cumulative fatigue damage and remaining life. The degree of cumulative fatigue damage here shows the extent of accumulated fatigue damage. $D \geq 1.0$ shows that a member is considered to have reached its fatigue limit. That is, D=1.0 shows that a fatigue crack occurred in a member, and has become long enough to make the member lose its performance or function. However, to be conservative in evaluation, D=1.0 can be an indicator of the occurrence of a crack.

Cumulative fatigue damage(D)		Classifications of evaluation	Reflection on inspection
$D \geqq 1.0$		A1	Implementing detail inspection
$1.0 > D \geqq 0.8$		A2	
$0.8 > D \geqq 0.5$		B	Important items of inspection
$0.5 > D \geqq 0.2$	$D \geqq \frac{\text{Age}}{\text{Assumed design life}}$		
	$D < \frac{\text{Age}}{\text{Assumed design life}}$	C	Parts of watch in inspection
$D < 0.2$		S	Routine inspection

Table 1 Classification of soundness evaluation based on cumulative fatigue damage

4. EVALUATING BEARING CAPACITY

4.1 Calculating Bearing Capacity

In the case of steel railroad bridges, the bearing capacity of an existing structure is evaluated as a stress ratio or bearing capacity. The evaluation formula is Formula (1).
Stress ratio (SR) = $\sigma_m/\sigma \times 100\%$ .... (1)
σ_m: maintenance limit stress intensity
σ: maximum stress intensity acting on a member when a train is coming in at an allowable maximum speed.
$= \sigma_d + \sigma_l + \sigma_i + \sigma_c$
The allowable maximum stress intensity acting on a member is the one when service load acts on the current section performance.
The maintenance limit stress intensity (σ_m) is the allowable stress intensity used in evaluating the strength of an existing structure. The maintenance limit stress intensity is explained below.

4.2 Maintenance Limit Stress Intensity

The value set here is the allowable stress intensity set in designs, for which the factor of safety was reviewed. That is, in existing bridges, working load can be identified, so the factor of safety can be reviewed. Specifically, the maintenance limit stress intensity is obtained by increasing the allowable stress intensity under temporary load in new designs by 25% and adding the influence of fatigue to some extent. Formula (2) is used to calculate maintenance limit stress intensity.
$\sigma_m = \sigma_{fo} \cdot \gamma_1 \cdot \gamma_2/\sigma_m$............(2)

Here, γ_1 and γ_2 are factors considering the influence of fatigue.
The actual stress ratio (α_n) is the ratio of measured stress to design working stress and is set on the basis of the result of the measurement of many actual bridges.
The actual stress ratio here is 0.65 for members with a span of 10 m and under and 0.75 for members with a span of 10 m and over.

4.3 Classifications of Evaluation for Bearing Capacity

The calculated bearing capacity is evaluated as a stress ratio and classified by a measure of soundness as shown in Table 2. These values can change depending on the level of maintenance set by each business organization. Shown here are actual result-based values.

Soundness evaluation classification	Stress ratio (SR %)
AA	SR ≦ 100
A1 or A2	100<SR≦120
B	120<SR≦150
C or S	SR > 150

Table 2 Measure of Classifications of Soundness for Bearing Capacity Ratios

4.4 Flow of Bearing Capacity Calculation Using BMC System

Input data necessary for evaluation are shown below.
(1) Data necessary for evaluation and the flow of diagnosis
Main input data necessary for execution are as follows.
(A) Technical data of bridges
(B) Technical data relating to load (track deviation, cant, centrifugal force, positions to watch)
(C) Cross-section (original cross section and reinforced cross section), the amount of corrosion
(D) Data necessary for calculation of maintenance limit stress intensity and shock load (train speed, engine type)
(E) Structural data of floor framing
(2) Load input
The kind of load that is used for evaluation includes dead load, shock load and centrifugal load in addition to train load. As for train load, the axial load and wheel base of each train is stored in the data base for use in calculation. Other loads are inputted at time of calculation.
(3) Calculating working cross-section force
The cross-sectional force of each member is calculated, using a structural analysis module, on the basis of the form of the structure. The kind of structure that can be treated includes the following.
- Simple girders (main girders of deck bridge plate girders)
- Floor framing of through bridge plate girder and truss bridges
- Main trusses, oblique girders, curved girders, and lattice girders of truss bridges

(4) Inputting cross-sectional forms of members
The cross-sectional forms of members to watch are inputted. They are cross-sectional deficiencies due to corrosion, etc. and cross-sectional characteristics of reinforcement made during use. These data can be stored in the data base of the system.
(5) Selecting maintenance limit stress intensity

The maintenance limit stress intensity can be set from the quality of members and operation conditions.

5. EVALUATING DURABILITY (remaining life)

5.1 Definition of Remaining Life

It would mainly be corrosion and fatigue that determines the physical life as durability of a steel bridge in use [3].
Corrosion is evaluated from time to time by the foregoing bearing capacity evaluation. However, fatigue is defined as a condition that may appear in the form of a crack with unparalleled progressiveness not seen in other damage as a result of the accumulation of deterioration in concealed sites (critical damage). Fatigue damage is considered as one of indicators to determine durability and the time until the function of a member will be damaged by fatigue is considered remaining life [4].
The BMC system can perform remaining life evaluation in the two cases as given below.

5.2 Flow of Remaining Life Evaluation in BMC System

The theoretical flow of remaining life evaluation is shown in Fig. 2.

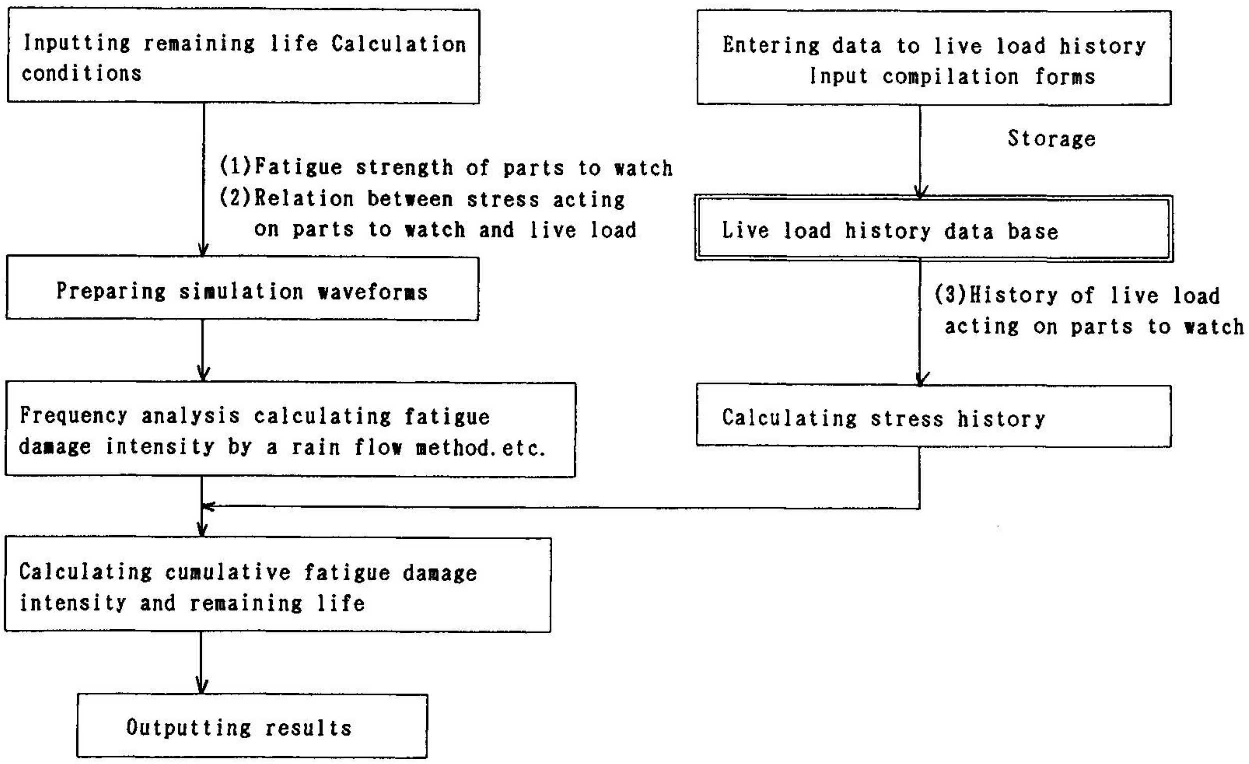

Fig.2 Flow chart of remaining life evaluation and calculation

5.3 Input Data

(1) Fatigue strength of joints to watch
Concerning the fatigue strength of joints to watch, the strength of a joint as shown in the fatigue provision of the current design standard[5] is used for railroad bridges in principle. However, as for the strength not specified in the provision, the Guidelines for Fatigue Design for Steel Structures and Explanation[6] are referred to.

(2) Stress acting on joints to watch
Stress used for fatigue assessment is service stress. Generally speaking, assuming that the history of live loads in the past and live load conditions assumed for the future and axial loads and wheel bases of typical trains which can be defined at this point are live load (if there is no special specification, the current load will continue), stress waveforms are obtained by simulation using this load. The stress waveform thus obtained may be used as service stress as it is. However, actually acting stress is smaller than the design value and generally conservative, so it is recommended that the product obtained by multiplying the calculated stress waveform by actual stress ratio is used as service stress [1, 4].
If the maximum stress range calculated by loading of trains whose axial loads and wheel bases are known is σcs, and the actually-measured value under the same condition is σma, the actual stress ratio (α) can be shown as follows.
$\alpha = \sigma_{ma}/\sigma_{cs}$
Consequently, the service stress waveform used for evaluation can be obtained by multiplying the calculated stress waveform used for evaluation by α.
Actual stress ratios are used even in current designs[5] .

(3) History of live loads
The history of live loads (or the history of stress) is necessary for the evaluation of cumulative fatigue. However, it is difficult to obtain such data in many cases. Three kinds of live load histories are allowed to be used for railroad bridges.

(A) History of annual passing tonnage (standard method)
(B) History of types of all trains and traffic volume (accurate evaluation)
(C) Only projected passing tonnage and age of a particular railroad line are known (same as design)

The system has input data files which permit automatic input.

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Maintenance of Structures along National Highway N2 in Switzerland

Maintenance des ouvrages d'art de la route nationale N2 en Suisse

Erhaltung der Kunstbauten der Nationalstrasse N2 in der Schweiz

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SUMMARY

This paper describes the concept for the rehabilitation of structures on the Federal Highway N2. This highway, built between 1965 and 1980, is one of the most important road links across the Alps. Survey of conditions, assessment of conditions, forecasting of future behaviour, and corrective measures are discussed. A method of weighted parameters, with which the development of corrosion in reinforcement can be estimated, is described

RÉSUMÉ

L'article décrit le concept pour la remise en état des ouvrages d'art de la route nationale N2 du canton d'Uri, une des plus importantes transversales alpines. Celle-ci a été réalisée par étapes entre 1965 et 1980. Le recensement et l'évaluation de la condition des structures en béton, l'estimation du comportement futur et les mesures effectuées pour la remise en état sont présentés. En particulier une méthode est discutée qui permet une estimation de l'évolution de la corrosion de l'armature.

ZUSAMMENFASSUNG

Beschrieben wird das Instandsetzungskonzept der Kunstbauten der schweizerischen Nationalstrasse N2 im Kanton Uri, eine der wichtigsten alpendurchquerenden Verbindungen Europas, welche in den Jahren 1965 bis 1980 abschnittsweise erbaut wurde. Eingegangen wird auf die Zustandsaufnahmen der Betonstrukturen, die Zustandsbeurteilung, die Prognose über das zukünftige Verhalten und letztendlich auf Massnahmen der Instandsetzung. Insbesondere wird die Methode der Wirksumme beschrieben, welche u.a. erlaubt, den Verlauf der Bewehrungskorrosion abzuschätzen.

1. INTRODUCTION

The four-lane National Highway N2 in the Swiss canton of Uri, one of the most important routes across the Alps, was built and placed into service in several phases beginning in 1965 until its completion in 1980. The N2 is a true mountain freeway, located at elevations ranging from 430 to 1100 meters above sea level. The 70 km long highway includes numerous bridges and tunnels, the most significant of which is the 17 km long Gotthard tunnel at the southern end of the highway. After the Gotthard tunnel was opened in 1981, the N2 was used by 3.1 million vehicles per year. In 1994, this number has grown to 7 million vehicles per year.
Due to steadily increasing traffic and the action of deicing chemicals and airborne pollutants, many of the structures on the N2 are in need of rehabilitation. Much of this work is currently in progress. To minimize costs to the public arising from the closure of bridges and tunnels, rehabilitations must be designed to ensure that, apart from replacement of expendable components such as wearing surfaces and expansion joints, service life can be extended maintenance free for 50 years.
For concrete structures, this implies that structural components currently in rehabilitation must be capable of resisting the actions of chlorides and carbonation without major deterioration for the next 50 years. Effective rehabilitations are designed on the basis of a detailed survey and assessment of conditions, followed by a forecast of the expected behavior of the structure during the remainder of its service life. When shown to be necessary by such an investigation, appropriate corrective measures can then be implemented.

2. SURVEY OF CONDITIONS

Procedures for condition surveys must distinguish between homogeneous regions with no visible defects and regions with inhomogeneities such as cracks and actual visible defects (e.g. gravel pockets, moist areas, and spalls).
Condition surveys were often restricted to an inventory of inhomogeneities. The condition of reinforcing steel in the apparently intact homogeneous regions was not questioned. Nowadays, since service lives after rehabilitations of several decades are required, reliable information on the condition of reinforcing steel in these regions is required as a basis for the design of corrective measures. Loss of passive protection and incipient corrosion can take place even in homogeneous regions.
Surveys of inhomogeneities present no problems, since these normally occur in limited numbers. This is not the case, however, for the extensive homogeneous regions, which cannot normally be examined in their entirety. For example, the recovery of concrete cores should be kept to an absolute minimum. Questions regarding sample size and the significance of individual measurements can be answered on the basis of the principles of statistics. A combination of continuous measurements on a large sampling grid over the entire structure and discrete measurements on a smaller grid for selected concreting steps has proven itself to be effective.
The parameters to be measured should be decided in advance. The definition ot the parameters to be measured follows from the methods given in the following sections for assessment of conditions and forecasting. Non-destructive methods of measurements are preferable.
Due to restricted accessibility, condition surveys often require the use of expensive equipment capable of reaching under structures. Such equipment is often available only for limited periods of time. Traffic restrictions must also be kept to as short a time as possible. Condition surveys must therefore be planned in detail with regard to type, location, and number of parameters to be measured, to ensure that all of the required data can be collected in the available time.

3. ASSESSMENT OF CONDITIONS

The assessment of existing conditions serves as basis for decisions regarding possible immediate corrective measures. These decisions are made to ensure safety and serviceability.

Assessment of conditions is based on the interpretation of measurements made during the survey of conditions and can be carried out according to several different methods. Until now, such methods were limited to identifying areas with depth of carbonation greater than concrete cover or with chloride concentrations greater than 0.4% of cement measured by mass. It is now recognized that neither method allows reliable statements to be made regarding the effective condition of reinforcement.

Results of much greater reliability can be obtained through half-cell measurements and by application of the method of the weighted parameter sum, described in Section 5. Both can be used in homogeneous regions and for the assessment of cracks. They cannot be used, however, for the assessment of defects, especially for regions with large gravel pockets. This is because the method of the weighted parameter sum was developed only for use in homogeneous regions and at cracks. Moreover, the electrolytes required for half-cell measurements is normally lacking in gravel pockets. At the present time, defects such as these can only be assessed by individual exploratory openings.

4. FORECASTING

It is common nowadays to require bridges after rehabilitation to have a mainenance free service life of several decades. To enable decisions to be made regarding which corrective measures, if any, are necessary, a forecast of the future behavior of the structure is required. For structural components that are still intact, the loss of passive protection of reinforcement must be prevented. Concrete protection is an issue of considerable importance in this regard. For reinforcement already undergoing active corrosion, the further development of corrosion is of interest, particularly its speed and the associated loss of cross-section of steel. Only when these issues have been adequately addressed should appropriate corrective measures be implemented based on criteria of safety and serviceability.

Methods of forecasting include the $\sqrt{t}$ method, in which the increase of depth of carbonation is assumed to vary with the square root of time, and the previously mentioned method of weighted parameters. The former method predicts the time to loss of passive protection; the latter method predicts the time to actual onset of corrosion. These two events are not necessary simultaneous. For this reason, as shown in Section 5.2, only the method of weighted parameters gives reliable results. Neither method, however, allows any statement to be made regarding speed of corrosion or loss of cross-section. Relaible methods for predicting these phenomena do not yet exist.

5. METHOD OF WEIGHTED PARAMETERS

5.1 Description

The method of the sum of weighted parameters was developed within the framework of a research project carried out in 1990 and 1991 at the Federal Institute of Technology in Zurich under the direction of Professor Christian Menn [1,2]. Its primary objective was to develop a method for assessing the effect of cracking on corrosion of reinforcement in reinforced concrete and prestressed concrete structures. Since homogeneous regions needed also to be considered in order to determine whether or not a given crack could lead to corrosion, the range of application of the method could be readily expanded to homogeneous regions.

The method of weighted parameters is an empirical method based on measurements made on full-scale structures in service. Similar methods have often been used in other fields, for example to assess the risk of corrosion of stainless and other corrosion resistant steels based on weighted proportions of the elements in a given alloy.

Data used to develop the method were obtained from 39 structures aging from 15 to 90 years. The following quantities were measured at precisely defined locations: intensity of corrosion (depth of pitting), concrete cover, absorption of water in the covering layer in a 3 hour period, and chloride content at the level of reinforcement. In addition, the following quantities were measured at cracks: width of crack, type of crack (normal crack or crack with penetration of water), and orientation of crack (transverse or parallel to reinforcement). Each of these parameters has a direct effect on corrosion. Over 6'600 measurements were made. Except for absorption of water and chloride content, each of the quantities could be measured using non-destructive methods. Each parameter is weighted in accordance with Figure 1. The sum of the weights G_i is denoted S. In homogeneous regions, S is made up of the first four parameters. At cracks, all seven parameters are considered. The weighting functions were defined to optimize the correlation between the computed sum of weighted parameters and the measured intensity of corrosion (depth of pitting).

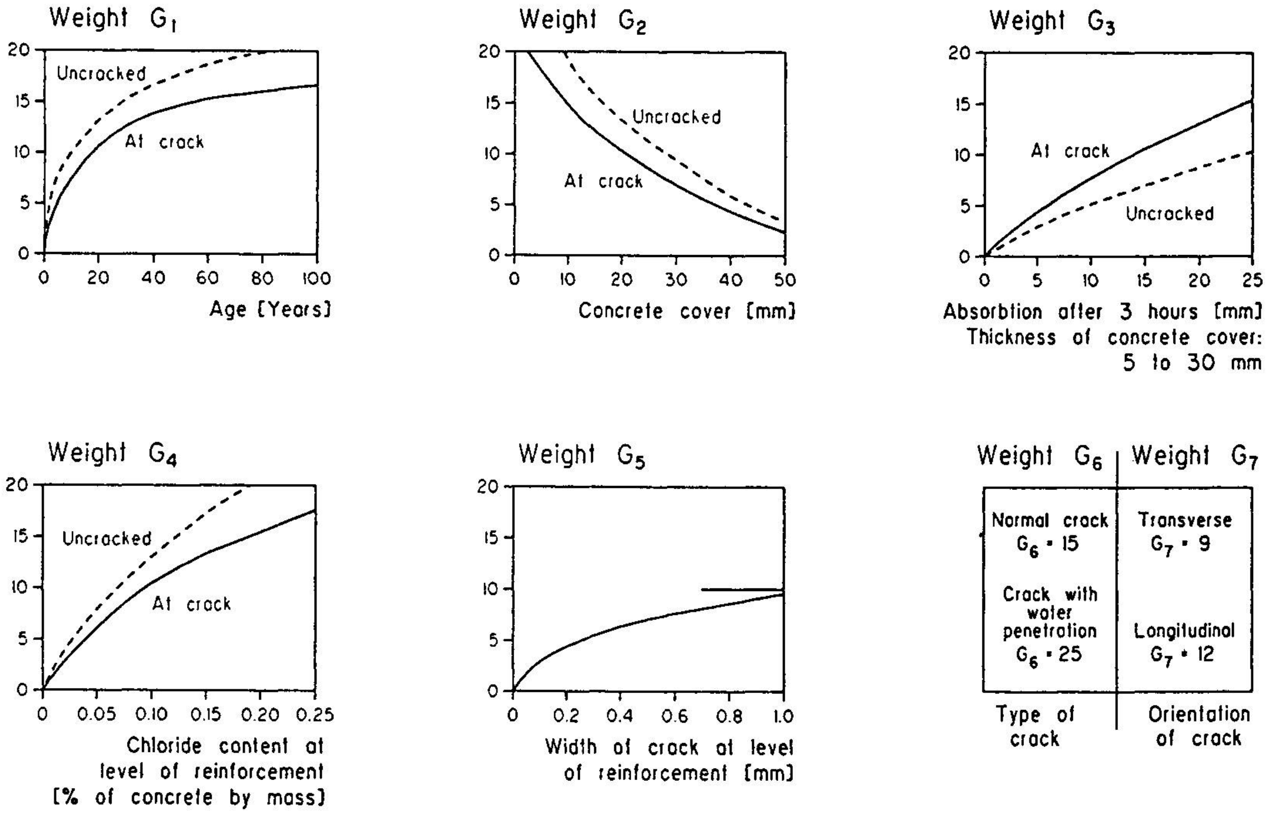

Fig. 1 Weighting functions

Based on these results, threshold values were defined for S in homogeneous regions and at cracks, beyond which corrosion of reinforcement could be deemed to begin. These threshold values are S=40 for uncracked homogeneous regions and S_R=65 at cracks.

It was observed that the effect of crack width on corrosion is minor. Of far greater importance is wether or not water can penetrate through cracks. Such cracks, which are recognizable by deposits on the surface of the concrete, are always associated with corrosion.

The method is simple to use and can be implemented deterministically or probabilistically. In the latter application, all parameters are expressed in terms of normally distributed random variables with average μ_i and standard deviation σ_i. The corresponding sums $S(\mu_S,\sigma_S)$ are also normally distributed. This probabilistic formulation makes possible global conclusions based on individual measurements.

Deterministic consideration of homogeneous regions

$$S = \sum_{i=1}^{4} G_i \geq 40$$

Probabilistic consideration of homogeneous regions

G_i (μ_i, σ_i) normally distributed random variables

$$\mathbf{S\ (\mu_S, \sigma_S) \geq 40}$$

where $\mu_S = \sum_{i=1}^{4} \mu_i$ and $\sigma_S = \left(\sum_{i=1}^{4} \sigma_i^2 \right)^{0.5}$

and $G_1 = G_{age}$ with $\mu_1 = G_1$ and $\sigma_1 = 0$

An important parameter affecting corrosion, which could only be indirectly dealt with in the previously mentioned research project, is microclimate. Application of the method of weighted parameters is therefore limited to structures exposed to normal atmospheric conditions. It is not valid for special ventilation conditions (e.g. in tunnels) or for extreme conditions (e.g. in storage facilities for salt). In special cases, however, microclimate can be dealt with by calibration of threshold values to results of half-cell measurements or by confirming threshold values in general based on half-cell measurements.

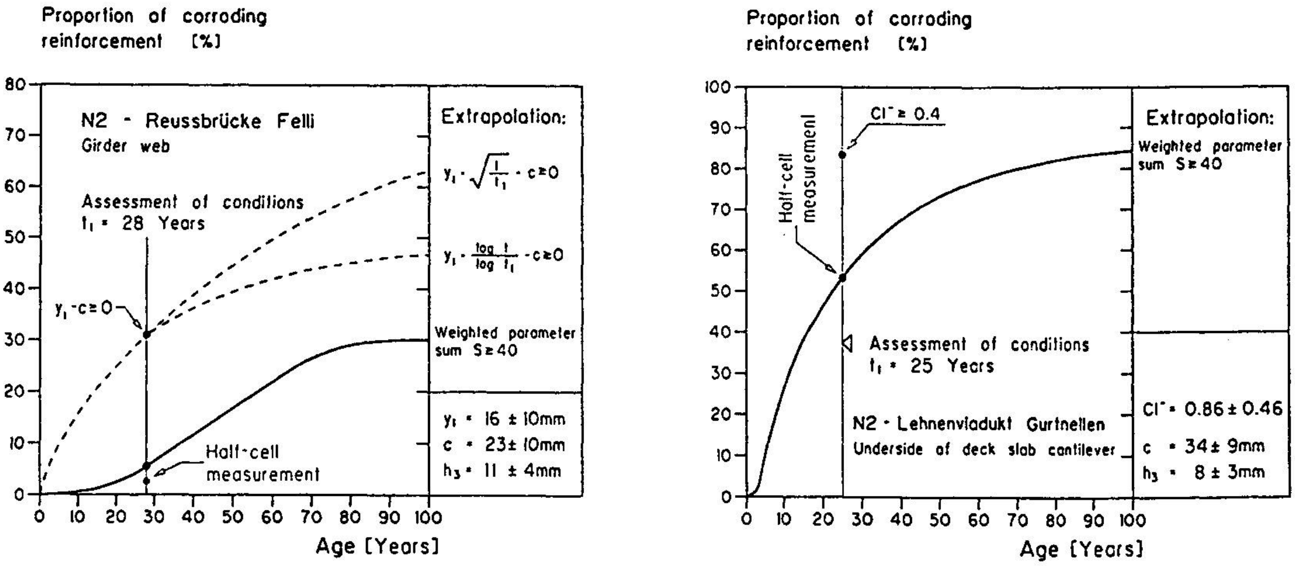

Fig. 2 Forecast of the development of corrosion of reinforcement: (a) Reussbrücke Felli, girder web; (b) Lehnenviadukt Gurtnellen, deck slab cantilever (y_1 = depth of carbonation, c = concrete cover, h_3 = water absorption, Cl^- = chloride content at the level of reinforcement (% of cement by mass). All parameters are normally distributed.)

5.2 Previous applications

The method of weighted parameters was applied for the first time to the assessment of conditions and forecast for the rehabilitation of two bridges on Highway N2 in the Swiss canton of Uri, Reussbrücke Felli and Lehnenviadukt Gurtnellen.
Figure 2a shows selected results for the left girder web of the southbound structure of Reussbrücke Felli, a T-girder bridge, which is exposed to carbonation. Also shown are predictions of carbonation computed by the √t method and by the method of weighted parameters. At age 28 years, there is a good agreement between half-cell measurements and the method of weighted parameters in the estimate of the proportion of reinforcement experiencing corrosion. This proportion is roughly 4%, even though 30% of the reinforcement is located in carbonated regions. Extrapolation with the sum of weighted parameters yields a plausible prediction as opposed to the √t method. Until the carbonation front has reached the steel with the thinnest covering layer, no corrosion is apparent. After roughly 80 years the proportion of corroding reinforcement reaches a limiting value. The proportion of corroding steel is grossly overestimated by the √t method. Probabilistic use of the method of the sum of weights yields results that are valid for the entire surface of the web.
Figure 2b shows an interpretation of results for the underside of the right deck slab cantilever of the northbound structure of Lehnenviadukt Gurtnellen. Due to leaks in the longitudinal joint between the northbound and southbound structures, this region is severely attacked by chlorides. Assessment of conditions was carried at age 25 years. There is good agreement in the proportion of corroding reinforcement (roughly 55%) as predicted by the sum of weighted parameters and as observed through half-cell measurements. The limiting value of 0.4% of cement content by mass, however, gives an overly high value of 84%.
Based on forecasts made using the sum of weighted parameters, decisions regarding areas requiring rehabilitation and areas requiring only protection of the concrete could be made for both bridges, to ensure a maintenance free additional service life of 50 years. As result of positive experiences gained on these two bridges, the method of weighted parameters is likely to be used on other stages of rehabilitation of Highway N2.

6. CORRECTIVE MEASURES

Apart from immediate measures resulting from the assessment of conditions, specific corrective measures can be designed on the basis of the forecast. Corrective measures range from protection of the concrete itself (various coatings or cladding with ceramic components), actual rehabilitation measures (removal and replacement of concrete, or cathodic protection), or even replacement of the structure. Unfortunately, electrochemical rehabilitation procedures (chloride removal or restoration of alkalinity) and use of inhibitors are not yet ready for field applications. The great advantage of such applications relative to currently used removal and replacement of the covering layer of concrete is that the original structure is not altered. Replacement of large areas of concrete using shotcrete generally results in a weakening of the structure, in spite of the considerable progress that has been made in shotcreting technology. Intensive research in the area of corrosion inhibitors is currently underway in Switzerland.

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Maintenance Facilities for the Honshu-Shikoku Bridges

Installations de maintenance pour les ponts Honshu-Shikoku

Wartungssystem für die Honshu-Shikoku-Brücken

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SUMMARY

When all the routes of the Honshu-Shikoku Bridges are opened, the total weight of the steel in bridge sections passing over the strait will reach 800,000 tons, and the area for repair painting is expected to be as large as five million m2. The Honshu-Shikoku Bridge Authority has provided vehicles and other equipment for inspection and repair of completed sections with the goal of saving labour in bridge maintenance. The Authority is also investigating ways of saving labour through use of various types of mechanised equipment. This report outlines the characteristics of maintenance of long-span bridges, existing mechanical equipment, and mechanical equipment currently under consideration.

RÉSUMÉ

Lorsque tous les ponts entre Honshu et Shikoku auront été construits, le poids total d'acier utilisé pour les ponts en acier atteindra 800.000 tonnes environ et la surface à repeindre à des fins de maintenance est estimée à quelques 5 millions de m2. La "Honshu-Shikoku Bridge Authority" prévoit d'utiliser des véhicules spéciaux pour la vérification et l'entretien des ponts déjà construits et étudie toutes les possibilités de mécaniser ces travaux afin d'économiser la main d'oeuvre engagée dans les opérations de maintenance des ponts de grande portée. Le présent rapport rend compte des efforts pour réduire le personnel d'entretien

ZUSAMMENFASSUNG

Nach Inbetriebnahme sämtlicher Abschnitte sind die Honshu-Shikoku-Brücken ein riesiges über das Meer spannendes Gebilde aus 800.000 Tonnen Stahl und mehr als fünf Millionen Quadratmeter Anstrichsfläche. Die damit verbundenen Wartungs- und Instandsetzungsarbeiten sind beträchtlich. Die für die Honshu-Shikoku-Brücken zuständige Behörde hat deshalb Arbeitsfahrzeuge und andere Ausrüstungen für Inspektions- und Wartungsarbeiten eingeführt, um bei der Instandhaltung der Brücke möglichst viel Arbeitskräfte einzusparen. Die Behörde untersucht darüber hinaus weitere Möglichkeiten der Arbeitsplatzeinsparung durch den verstärkten Einsatz mechanischer Ausrüstungen. Der vorliegende Bericht gibt einen Überblick über die damit zusammenhängenden Punkte.

1. INTRODUCTION

The Honshu-Shikoku Bridges, carrying both the highways and railways, are composed of a group of long-span bridges passing over the strait. The total length of the bridges is approximately 178 km. At present 60% of the total, or approximately 108 km, is in service.

The main categories of long-span bridge maintenance management are bridge inspection and bridge maintenance. Repair painting task occupies a large proportion of maintenance work, and this proportion is expected to increase as the bridge ages. When all the routes of the Honshu-Shikoku Bridges are completed, the total weight of the steel used in the bridge sections passing over the strait will reach 800,000 tons, and the area for repair painting is expected to be as large as five million square meters. In Japan in recent years many laborers have been leaving the construction industry, and the average age of those remaining, just as it is among the general population, is increasing. This had led to concerns about the productivity of the labor force.

The Honshu-Shikoku Bridge Authority (HSBA) has provided vehicles and other equipment for inspection and repair of completed sections with the goal of saving labor in maintenance of the bridges. HSBA is also investigating labor saving by using various types of mechanized equipment.

This report outlines the characteristics of maintenance management of long-span bridges, existing mechanical equipment, and mechanical equipment currently under consideration.

2. CHARACTERISTICS OF MAINTENANCE OF THE HONSHU-SHIKOKU BRIDGES

Table 1 shows the elements of bridges over the strait that comprise the Honshu-Shikoku Bridges and that are in use. The characteristics of maintenance services of the Honshu-Shikoku Bridges are as follows:

① The Honshu-Shikoku Bridges are a large bridge system whose construction required the overcoming of severe natural obstacles. Therefor, total replacement of the bridges is extremely unfeasible, and maintenance services that will last over the bridge s life for more than 100 years must be established.

② Most long-span bridges of the Honshu-Shikoku Bridges are on or near the sea. Maintenance services must deal with a highly corrosive environment.

③ Most of the bridges are large, complicated structures that incorporate both the road and railway transportation passing high above the sea, therefor, the inspection and repair work becomes difficult.

④ Alternative means of transportation are limited, so the bridges must offer a safe and dependable transportation corridor at all times.

Given the above characteristics, there are various design, construction, and maintenance considerations. Maintenance considerations are as follows:

① Maintenance facilities, including passageways and work vehicles for inspection and repair, are provided

② Inspection work is categorized as daily, periodic, and extraordinary, and the goals and contents of each job are clarified. To gather information for inspections, measurement devices such as wind direction and wind speed detectors, displacement gauges, and accelerographs, all of which also provides data for the traffic management and design verification, are installed on the main bridges. The bridges are in salty environments and are thus vulnerable to corrosion; they are also long and tall, which makes them difficult and expensive to repaint and maintain. Therefore, to reduce maintenance work highly anti-corrosive paints and coating specifications (long-term anti-corrosive paint system) are used.

The characteristics of the painting management system are as follows:

① The effectiveness of the long-term anti-corrosive paint system has not been studied over a long period of time, therefore, corrosion formation and deterioration patterns are not well understood. However, observations indicate that the rust tends to penetrate materials and not to spread out over the paint system. It thus necessitates to repair damaged areas as soon as possible. A scaffolding system that provides good access to all parts of the bridge is required.

② The painting of an entire bridge is a burdensome job that must be done efficiently in a difficult work environment. Therefore, safe and rational methods that minimize the impact of the work on the other environments are required.

Bridge Name	Bridge Type	Bridge Length (m)	Center Span (m)	Tower Height (m)
Ohnaruto Bridge	Suspension	1,629	876	144 *1
Tozaki Viaduct	Steel Box	1,009	190 *2	-
Muya Bridge	Steel Box	535	160 *2	-
Shimotsui Seto Bridge	Suspension	1,400	940	149 *1
Hitsuishijima Bridge	Cable-stayed	790	420	152 *1
Iwakurojima Bridge	Cable-stayed	790	420	152 *1
Yoshima Bridge	Truss	850	245 *2	-
Kita Bisan-Seto Bridge	Suspension	1,538	990	184 *1
Minami Bisan-Seto Bridge	Suspension	1,648	1,100	194 *1
Onomichi Bridge	Cable-stayed	385	215	77 *1
Innoshima Bridge	Suspension	1,270	770	145 *1
Ikuchi Bridge	Cable-stayed with Composite Box Girder	790	490	127 *1
Ohmishima Bridge	Two-hinged Steel Arch	328	297	-
Hakata Bridge	Steel Box	325	145	-
Ohshima Bridge	Suspension	840	560	97 *1

*1 Indicates the height of the tower from T.P. (mid-point in the Tokyo Bay tidal range)
*2 Indicates the length of the longest span.

Table 1 Elements of Bridges in Use

3. EXISTING MAINTENANCE FACILITIES

The Honshu-Shikoku Bridges in use have the maintenance and management facilities as the following.

3.1 Inspection passageways

The main inspection passageways are primarily located alongside the bridge girders. In addition, fixed scaffoldings are installed at tower entrances, bearings, and near navigation lights. Secondary maintenance passageways are installed to connect the main passageways, and the elevators are also installed in towers of suspension bridges and cable-stayed bridges .

3.2 Work vehicles for inspections and repairs

As shown on the Table 1, the types of bridges under discussion are suspension bridges, cable-stayed bridges, truss bridges, and box bridges. Therefore, work vehicles for inspections and repairs are of the following types:

① Work vehicles for inspections and repairs installed on the girders (suspension bridges, cable-stayed bridges, and truss bridges)
② Work vehicles for inspections and repairs installed on the towers (cable-stayed bridges)
③ Work vehicles for inspections and repairs installed on the main cables (suspension bridges)

Photographs 1 to 4 show some examples of these vehicles.

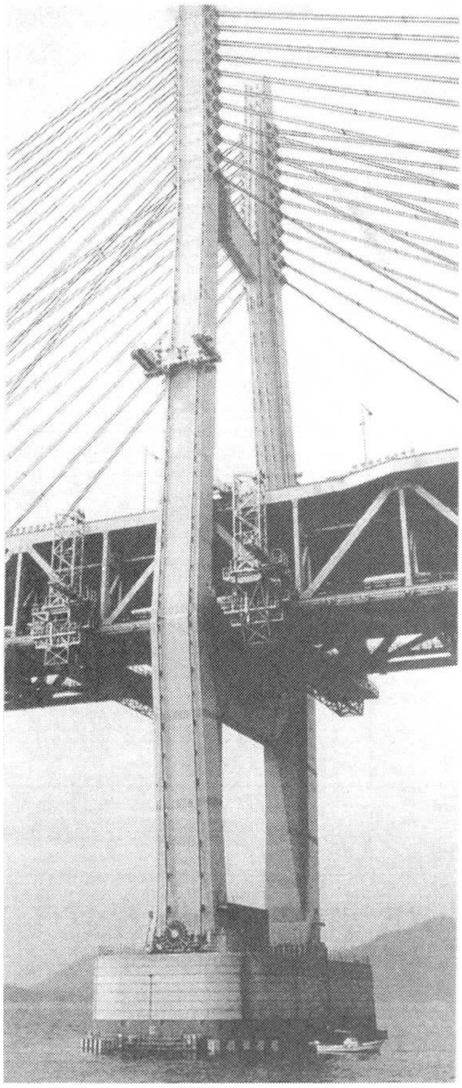

Photo 1 Work vehicle for inspecting girder and tower exteriors

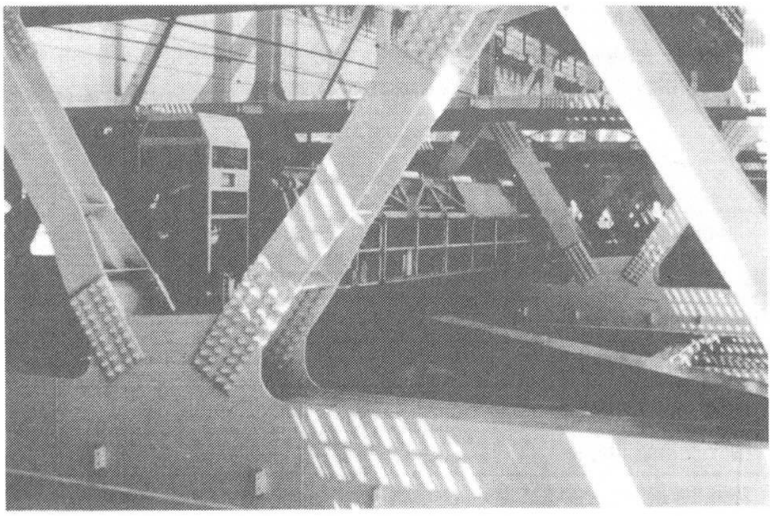

Photo 2 Work vehicle for inspecting girder interiors

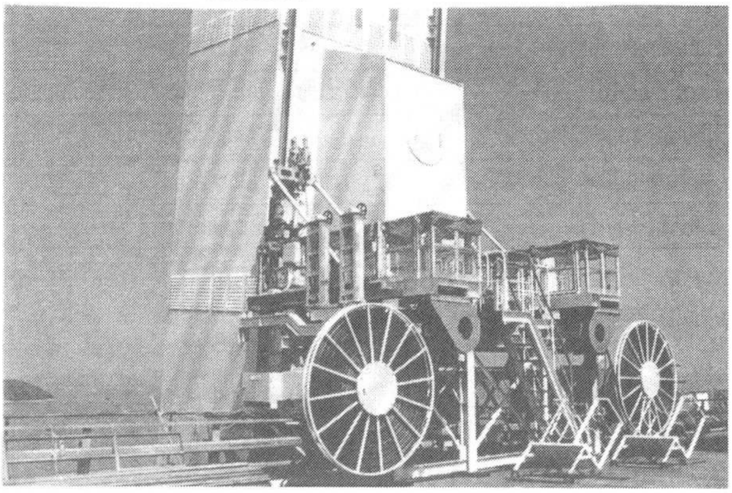

Photo 3 Work vehicle for inspecting roadside walls of the tower

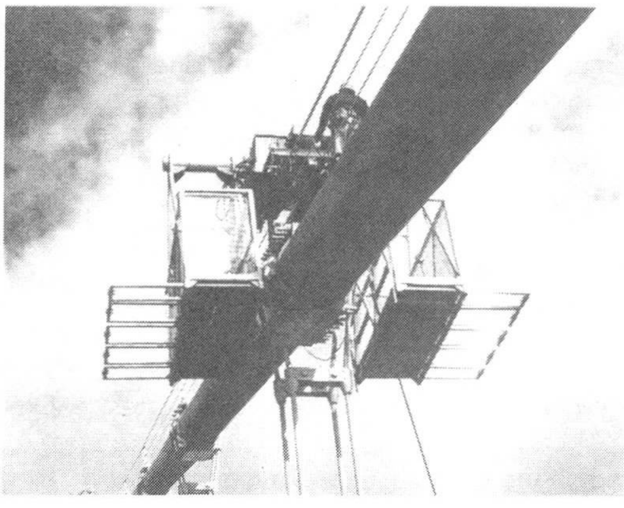

Photo 4 Work vehicle for inspecting cables

4. MECHANICAL FACILITIES UNDER DEVELOPMENT

4.1 Mechanical facilities for repair painting

4.1.1 Development goals

It is anticipated that the repair painting will comprise a large proportion of maintenance work. As described above, when the three routes are completed, the total area of sections that will need repair painting will be tremendously large, requiring a large number of painters. The following two problems are accompanied with this labor problem:

① Due to the strong winds and work heights, it is difficult to create safe working environments for painters.

② It is impossible to provide access by work vehicles for inspections and repairs to all members requiring repair painting.

Hopefully, all repair painting should have a good quality and consistency comparable to those achieved in a factory. Therefore, to minimize labor costs for painting while maintaining those quality requirements, an entire bridge mechanical facilities are being developed for repair painting.

4.1.2 Requirements

The requirements of the mechanical facilities for repair painting are as follows:

① For the time being, semi-automatic man-machine system with use of servo-assisted machines should be developed, and the fully automated system will be facilitated in the future.

② Existing work vehicles for inspection and repair should be used efficiently.

③ Devices on the vehicles should be suitable for general purposes and as light as possible.

④ The first and the second coating works should be focused for an entire bridge repainting, and the quality of such coating works should be as equal as that of the painting in the factory.

⑤ The systems should prevent from dispersion of dust of paint mist during surface treatment or painting.

4.1.3 Current situation of development

Development of mechanical facilities for repair painting began in 1990. By the end of 1992, those studies had been carried out such as collection of reference materials, and investigation on labor-saving equipment, applicability to the structures, the latest equipment for painting and surface treatment, and the main structures of mechanical facilities. At present, being studied are the latest system to prevent from the paint dispersion.

4.2 Mechanical facilities for inspecting the main towers of suspension bridges

4.2.1 Development goals

The main towers of the suspension bridges are over 100 meters above the sea level. To provide access to the towers for inspection, there is no other means than temporary facilities, such as gondolas. However, considerable manpower is required to set up such facilities, and the workmanship to conduct an inspection can be required in the great heights. These problems are particularly critical on the Akashi Kaikyo Bridge under construction, which is 300 meters above the sea level.

Meanwhile, visual inspection can be done from a distance with a small, light ITV. In addition, multi-joint manipulator systems have been developed for removing deteriorated paint and measuring coat thickness. By applying these systems, it should be possible to inspect the bridges from a distance.

Robots that can move along and inspect the walls of buildings are presently being developed. By using these robots as well as with the other technologies outlined above, development of the mechanical facilities for the main towers can be feasible, and thus the safety of inspection work can be improved, and manpower requirements can be reduced. In addition, through the use of interchangeable attachments, light repair work such as localized repair painting should also be possible.

4.2.2 Requirements

The requirements of the mechanical facilities for inspecting the main towers of suspension bridges are as follows:

① Access to discretional points on a main tower s wall.

② To provide workspace for inspection and recording the data on the coats

③ To provide workspace to remove eteriorated coats.

④ To provide workspace to perform simple tasks such as partial repair painting.

4.2.3 Current situation of development

Development of mechanical facilities for inspecting the main towers of suspension bridges began in 1989. Following this, in the same year the basic concepts were established for the facilities. Based on these concepts, in 1990 the basic design was developed to list up technical issues to be dealt with. In 1991 tests were conducted to solve various technical problems, and in 1992 the overall feasibility design was completed, which includes design of carriage system and inspection devices. At present, preparations are being made for conducting tests on the actual bridges. Figure 1 outlines the concepts being examined.

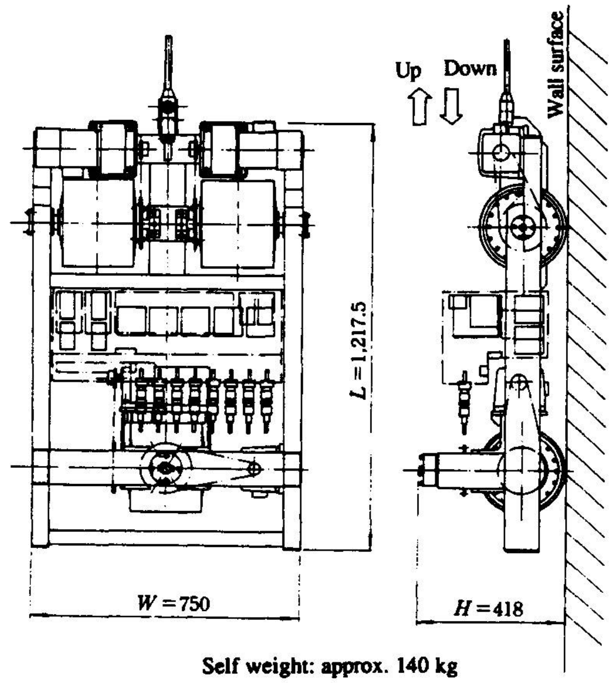

Fig. 1 Outline of the concept of the mechanical facilities for repair painting

5. CONCLUSION

The authors outlined the existing mechanical facilities and facilities being developed to save labor in the maintenance of the Honshu-Shikoku Bridges. It seems to need more time to complete development of the facilities and put them into practical use. Meanwhile, there also seems to need the other mechanical system to be used for the partial repair painting work and the inspection of the foundations 60 meters deep from the sea level. This will require the latest technologies of not only the civil and mechanical engineering but also the other fields concerned.

To maintain the nation's infrastructure in a good manner for as long as possible, corresponding to the needs of upcoming the aged society of Japan, a new technology for maintenance services shall be developed by the end of this century. Towards this goal, a technical committee has been established for development of mechanical facilities for repair painting. This committee has provided HSBA with invaluable guidance regarding development tasks. Finally, the authors would like to encourage the readers of this paper to provide us with valuable information regarding our goals.

Rational and Environmentally Compatible Maintenance of Old Steel Bridges

Entretien rationnel et écologique de vieux ponts métalliques

Rationeller und umweltverträglicher Unterhalt von alten Stahlbrücken

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Lars Have, born in 1958, obtained his civil engineering degree at the Danish Engineering Academy. During the last ten years he has been Project Leader for maintenance on some of the big bridges in Denmark. Today he is an expert on Surface Treatment and Maintenance in a leading Danish consulting engineering company.

SUMMARY

During the last couple of years there has been strong focus on environmental aspects of surface treatment and maintenance of steel structures in Denmark. This article deals with a solution in which environmental, economic and quality assurance elements are taken into consideration when planning and carrying out the maintenance of two of the biggest bridges in Denmark.

RÉSUMÉ

Au cours des dernières années, le Danemark a été sensibilisé sur l'environnement et ses aspects en ce qui concerne le traitement de surface et l'entretien des constructions métalliques. L'article présente une solution prenant en considération les aspects de l'environnement, l'économie et l'assurance de qualité. C'est la solution qui a été retenue pour le projet et l'exécution de l'entretien de deux grands ponts au Danemark.

ZUSAMMENFASSUNG

In den letzten Jahren wurden die Umweltaspekte der Oberflächenbehandlung und der Unterhaltung von Stahlkonstruktionen immer mehr in den Mittelpunkt gestellt. Dieser Artikel zeigt eine Losung, die sowohl Umweltaspekte als auch Wirtschaftlichkeit und Qualitätssicherung berücksichtigt bei der Planung und Durchführung von Unterhaltungsarbeiten an den beiden grössten Brücken Dänemarks berücksichtigt.

1. HISTORY

Most of the bigger bridges in Denmark were built during the nineteen-thirties. All the bridges were of rivetted construction, as that was the technology best known at that time.

This type of construction is certainly not optimal for maintenance as the surface area is big, there are hollow spaces in several members and there are a lot of joints with more or less open gaps.

Two of the big bridges are the Old Lillebælt Bridge (length 850 meters) and the Storstrøm Bridge, which with its 3,200 meters is the longest combined railway/road steel bridge in Europe.

Both bridges have been under continuous maintenance since construction. It takes about 20 to 25 years to actually do the surface treatment of the steel structures from one end to the other, and after this it is necessary to begin again.

In the nineteen-thirties the bridges were painted with two layers of leaded alkyd, two layers of ordinary alkyd and one layer of bitumen. During the years up to now there have been added more and more layers of alkyd and bitumen. Since the beginning of the nineteen-eighties there have been brought into use totally new systems utilizing epoxy resin and also chlorinated rubber.

The total thickness and the condition of the existing paint, makes it today impossible to add more paint without first removing the old paint completely.

It was necessary to find a solution, where the renovation of the surface treatment could be carried out without dumping the lead-rich waste into the sea. This was partly due to ethical reasons and partly due to the strong focus on environmental aspects there is today in Denmark.

Another big problem with the maintenance of the bridges concerned the difficulty of actually carrying out the surface treatment. The persons doing the job until now have been like mountaineers, as they where erecting the scaffolding themselves. This was not only time consuming, but it was also not optimal for labour safety reasons.

2. PLANNING THE FUTURE MAINTENANCE OF THE STORSTRØM BRIDGE

The owner of this bridge, Danish State Railways, decided in 1991 that it was time for a total reconsideration of the philosophy for the maintenance of the bridge.

RH&H Consult was asked to start the planning for the future maintenance with a total inspection of every single steel element. The results of the inspection were put into a database, where among other things were registered the type of paint, the condition and the expected lifetime of the existing surface treatment.

It became clear during the registration that not only should the new maintenance philosophy take care of environmental aspects, it should also bring the renewal period for the surface treatment down from 25 years to 15 years, to avoid costly removal of a large number of elements in poor condition.

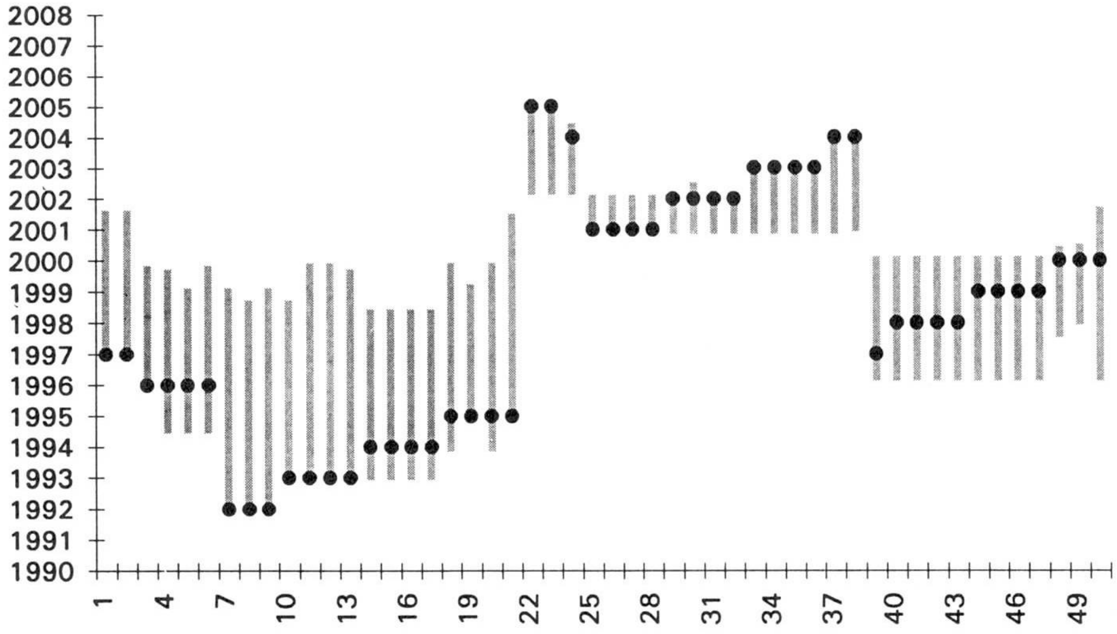


Figure 1 shows one of the results from the database. On the abscissa is shown the bridge span number from 1 to 50, on the ordinate is shown the weighted lifetime of the steel members in the spans. There are three different types of information: *Minimum* which shows the minimum lifetime of the existing surface treatment on the members, *Maximum* which shows the maximum lifetime, and *Dots* showing the planned maintenance. In an optimal case the dots should be somewhere between the Minimum and the Maximum points.

Now the task was divided into three main goals:

1) To find a solution where the waste from the surface treatment can be handled in a safe way.

2) To find a solution where the period for the surface treatment can be reduced from 25 years to 15 years, without significant extra annual cost.

3) To find a solution where the work with the surface treatment can be improved in a way which is safe for the labour force and economic.

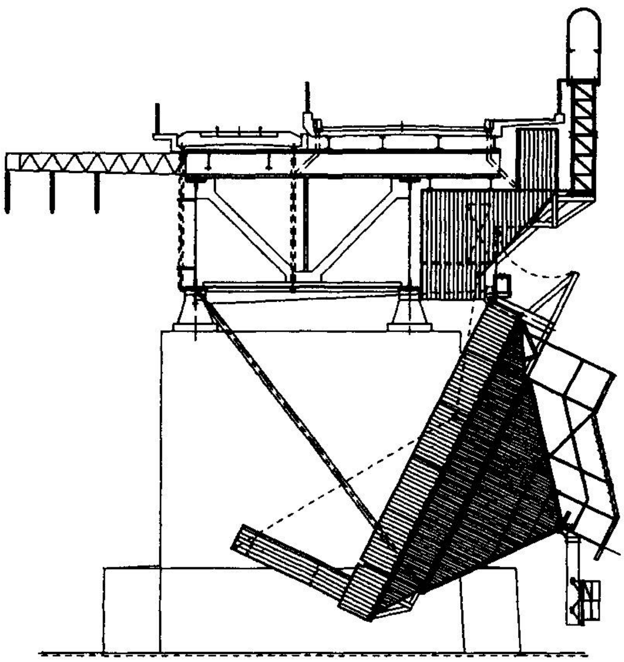
3. THE MOBILE PLATFORMS

During the investigation of the condition of the existing paint, it soon became clear that complete removal of the old paint was necessary (by sand blasting).

From that point it was also clear that the only solution was to have an easily movable scaffolding platform which should be enclosed so that the waste products would not disappear in an uncontrolled way.

In Denmark it is only possible to do outdoors surface treatment work about 6 months of the year. One of the positive side effects of having the whole working platform enclosed, is that the time available for surface treatment can be extended, as the climate inside the platform can be controlled.

There is already an existing market offering some standard solutions for mobile platforms. However such platforms were not found optimal for a number of reasons, mainly because the standard mobile platforms were not able to meet the geometric requirements, as it was impossible to maintain the whole 7 m high cross section of the bridge in one operation. Neither are they able to pass the 49 bridge pillars in a non- time-consuming way. Furthermore the standard mobile platforms were not designed to be mounted on a bridge for a period of 15 years, without maintenance of the platform itself.



RH&H Consult were asked to investigate the possibility of designing a mobile platform. The platform was to be able to meet all the special requirements for the actual bridge and was not to be significantly more expensive than the standard mobile platforms on the market.

Figure 2 shows the cross section of the designed platform in a situation just before passing one of the bridge pillars. The platform deck is lowered to a vertical position and the facade is folded also to a vertical position, the whole operation passing a pillar takes approximately one day.

It was decided to have hot-dip galvanized steel elements for the main structure of the platforms and all secondary elements such as the grid plates etc. were in aluminium to save weight. The covering of the platform sides was made of glass-fibre reinforced polyester to allow as much light as possible to enter the working area on the platform. Sand blasting tests were done both for the grid plates and for the covering. The tests showed that they could withstand direct sand blasting at a distance of 30 centimeters for more than 20 minutes, which was decided to be sufficient.

Under the platform is mounted a funnel (9x9 meters), so the sand can be collected in a controlled way on a barge anchored under the platform. The funnel is made of stain-less steel thin plate shaped in a trapeze. The funnel was designed as flat as possible with built-in vibrators, to minimize the bending moments, when the platform is turned into a vertical position for passing the bridge pillars.

The total working area on the mobile platform is approximately 325 square meters and the total weight is about 40 tons.

In order to optimize the work it was decided that two platforms were needed. The procedure for the work is that the platforms are placed at a distance of half a bridge span between the centre lines. At all times during the working period sand blasting is being carried out on one of the platforms and paint is being applied on the other platform.

A very similar mobile platform was designed for the Old Lillebælt Bridge.

Photo 2 shows the mounting of the mobile platforms under the Storstrøm Bridge.

While the platforms are passing the pillars, the barge with all the waste (sand grains mixed with leaded paint waste) is towed to shore. The capacity of the barge is designed to be able to carry all the sand needed to treat one whole bridge span together with all the equipment needed to undertake the surface treatment.

The traffic on the bridge is not disturbed at all while work proceeds on the surface treatment as all the equipment and containers are placed on the barge - and not on the bridge.

Two possibilities were investigated for further handling of the waste product: Either to deposit it in a special dumping area, were it could be controlled that the lead would not get into the groundwater, or as a new possibility to reuse the lead-rich sand in a constructive way in industry.

The investigation showed it possible to implement a new solution, that the lead-rich sand could be used in the brick industry. The sand is added to the clay needed for the bricks before the firing process, and thus sealed, will not give any negative environ-mental consequences in the future.

4. CONCLUSION

Now that the mobile platforms on both the Old Lillebælt Bridge and the Storstrøm Bridge have been in use for more than two years, it has been shown that not only is it possible to collect more than 90 per cent of the waste products, but it is also possible to speed up the work in a safe and an economic way.

For bigger bridges where one or more of the following requirements shall be met:

* Handling the waste problems with a minimum of environmental impact,
* having a more rational work procedure for the surface treatment,
* controlling the climate (extending the time available for surface treatment),
* improving the working conditions for the labour force,

the solution with a specially designed mobile platform is worth considering.

For the time being we are investigating a project, where similar mobile platforms can be used for maintenance of a big concrete bridge abroad.

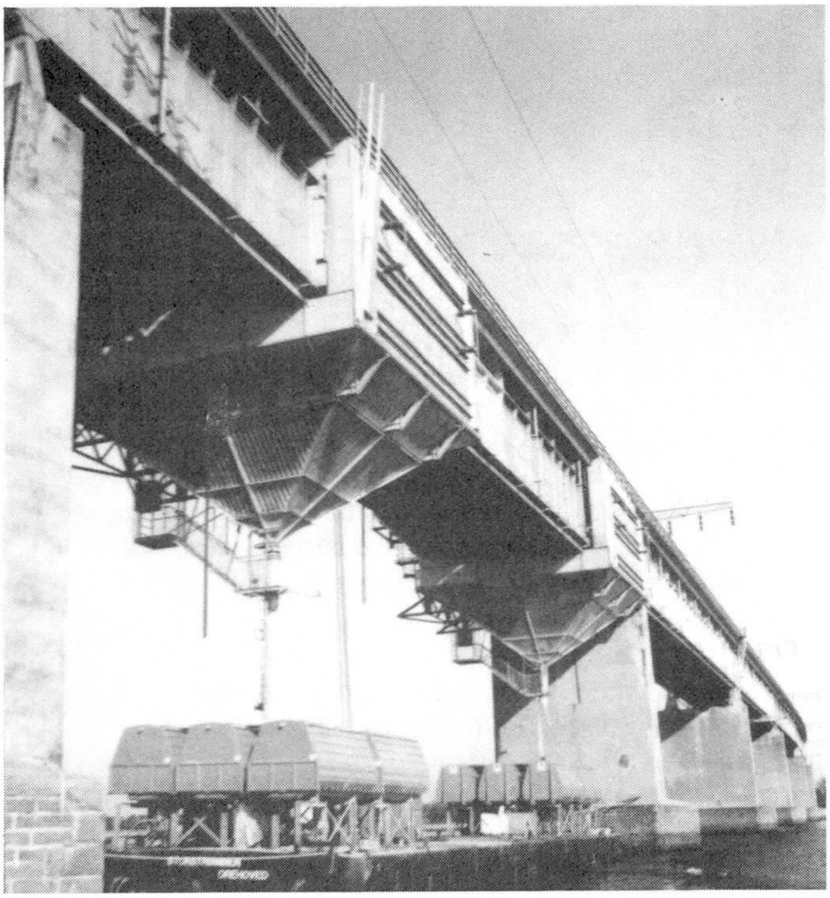


Photo 3 shows the entire system with the two mobile platforms at work on a span of the bridge. The barge with all the new and used sand is placed under the platform and can be accessed directly from the platforms.

The 1935 Little Belt Bridge, Denmark: Maintenance Experiments

Expériences de maintenance sur le pont de Little Belt au Danemark

Unterhaltsexperimente an der Kleinen-Belt-Brücke, Dänemark

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K.V. Christensen, born in 1947, received his degree at the Engineering Academy in Aalborg, Denmark. For 15 years he worked as supervisor for bridge, harbours and special buildings. Since 1991 he works in the Danish State Railways Department for the management of 2300 bridges.

SUMMARY
The design and construction phases of the Little Belt Bridge are reviewed. Special attention is paid to the design features enabling easy supervision and maintenance during the lifetime of the bridge. The displacement of the bridge piers due to the conditions of the seabed is described. An analysis of the impact on the superstructure is made. An estimation of the lifespan for the bridge is made based on the actual conditions of the bridge and assumed development in the traffic.

RÉSUMÉ
Le dimensionnement et les phases de construction du pont de Little Belt (1935) sont passés en revue. Une attention spéciale est portée sur les points du dimensionnement permettant une maintenance et une supervision aisée du pont tout au long de sa durée de vie. Le déplacement des piles dû aux conditions du fond marin est décrit. Une analyse de l'impact de la structure est faite, ainsi qu'une estimation de sa durée de vie basée sur les conditions actuelles du pont et le développement prévisible du trafic.

ZUSAMMENFASSUNG
Die Entwurfs- und Bauphasen der Kleinen-Belt-Brücke von 1935 werden betrachtet. Dabei gilt die Aufmerksamkeit solchen Entwurfsmerkmalen, die die Ueberwachung und den Unterhalt der Brücke während ihrer Lebensdauer erleichtern. Einen Problempunkt stellt die Verschiebung der Brückenpfeiler aufgrund der Veränderung des Meeresbodens dar, wobei deren Auswirkung auf den Brückenoberbau analysiert wird. Die Lebensdauer der Brücke wird im Hinblick auf ihren derzeitigen Zustand und die prognostizierte Verkehrsentwicklung abgeschätzt.

THE BRIDGE ACROSS THE LITTLE BELT

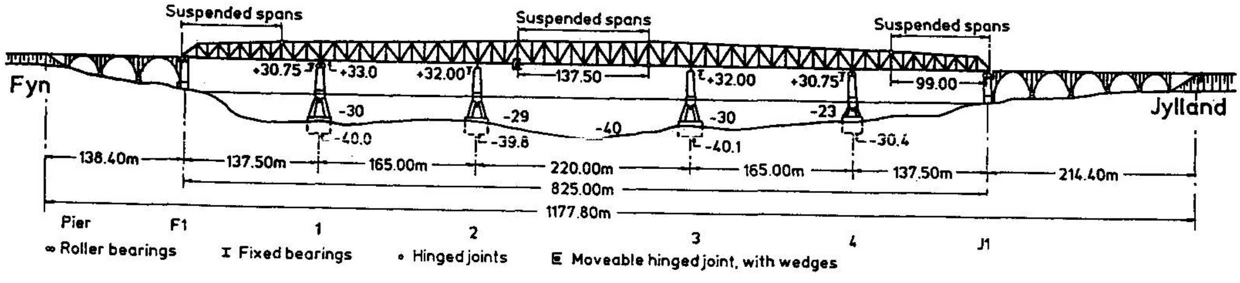

Fig. 1, Elevation

1 INTRODUCTION

The first thoughts, that were given on building a bridge across The Little Belt in Denmark, came up in 1880, when a new ferry connection was inaugurated.

Investigations were initiated to determine the optimal alignment for the railway, taking into account also the soil-conditions in the seabed of The Little Belt. Investigations on the quality of available steel and appropriate methods of construction were also made at this stage.

The seabed of the Little Belt consist of a special clay, that never had been discovered in Denmark before, and therefore was named "Littlebeltclay". It is a rich and dense clay, containing only a small number of stones (diameter 200 - 800 mm). Inspite it has been preloaded during the iceage it is still quite plastic. Several different outlines were made. In the final proposal the bridge was designed with 4 piers on direct founded caisons. To take into account the possibility of an uneven distribution of the settlement of the caisons, the superstructure was designed as a statically determinate structure.

The steel connections are very complex. Some include more than 30 parts. Every detail is worked out perfectly. The rivets were placed in such a short distance, that corrosion cannot part 2 plates.

Experience from shipbuilding was used to a great extent in the outline design and for choosing the methods of construction.

In May 1928 the design and the project for the Little Belt Bridge was put into an international competition with the request, that alternative offers would be of interest too. The evaluation committee, with participants from Germany, Sweden and Denmark, found, that the original tender design offered the best and cheapest solution.

In January 1929 contract was signed with Monberg & Thorsen Copenhagen and Grün & Bilfinger Mannheim in association with the large German steelsuppliers Friedrich Krupp Rheinhausen and Louis Eilers Hannover. The bridge was opened for traffic on the 14 of May 1935.

2 DESIGN AND CONSTRUCTION

The concrete caisons for the 4 piers were built on a slipway the same way as a ship. To be able to use the same slipway for all caisons, they were built upside down. This made it possible to shape the length of the skirt (made of pipes with a diameter of 800 mm) individually to fit the contours of the sea bottom.

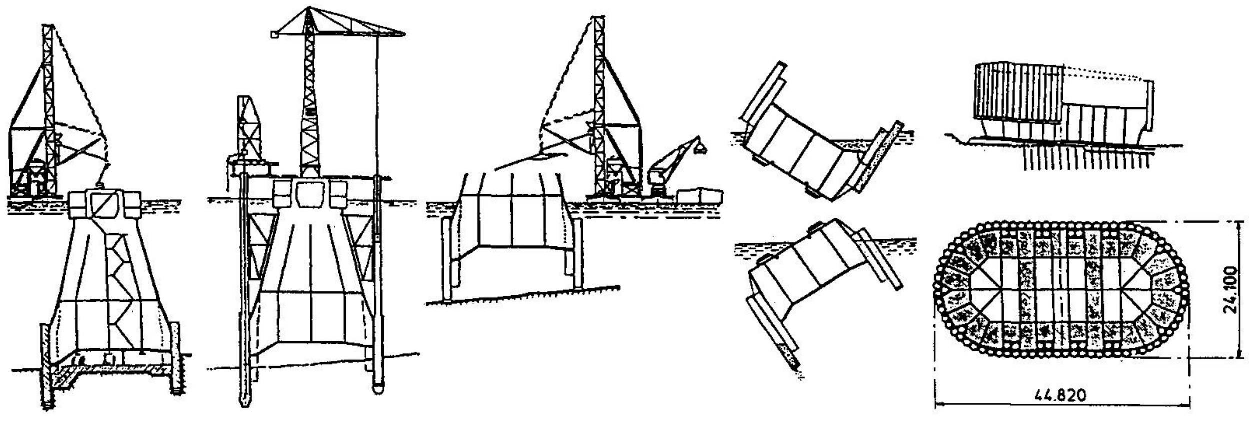

Fig. 2
The caisons were launched into the water (1), turned over by pumping in sand in the pipes and water in the working chamber (2) and increased in height (3) until the piers were tall enough to be placed in the final spot. The caisons were sunk into the seabed (4) by excavating from inside the hollow pipes, by means of a special drilling equipment, to a level beneath the pipes. There, special cutters were extended of the side of the drill, to make the diameter big enough. When holes were drilled in all the pipes around the caison, water was pumped into the outer cells in the pier, to make the caison sink to the wanted level. The Littlebeltclay was so impermeable, that soil could be excavated from inside the working chamber underneath the caison without having to create a pressurized chamber (5).

The riveted steel superstructure was assembled without use of falsework. On one side of each pier an erection bracket was placed and from there, the superstructure was cantilevered out to both sides.

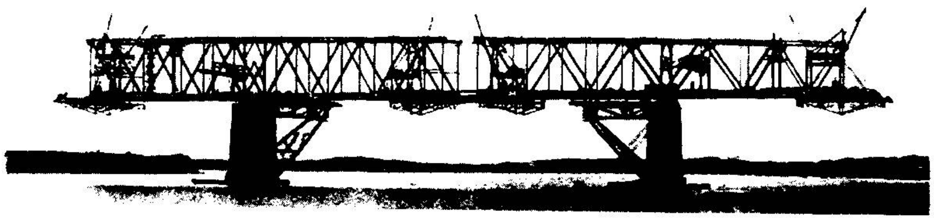

Fig. 3
The Situation from the construction where the cantilevered ends were just reaching each other between pier 3 and 4.

In the first and the last span there are fixed, hinged joints. In the middle span, there are 2 joints. One of the joints is moveable to equalize temperature expansions etc. There are - wedges for adjustments, so that jointconstruction for the railway and the roadway cannot be destroyed. See Fig. 1.
The bearings are placed on a steel plate and fixed horizontally by wedges. Plates are positioned below the superstructure, which enable lifting up the superstructure using hydraulic jacks. In this way it is possible to adjust the superstructure back into the right position if movements in the top of the pier requires it. The designer, Dr Anker Engelund has declared: The Little Belt Bridge can last for 300 years.

3 STRUCTURE STEEL

Steel was developed with strengths up to 540 MPa. New production methods and tests had proved, that it was possible to make a steel of uniform quality.

Composition in the Krupp steel

	C	Si	Mn	P	S	Cu
Krupp	0,21	0,29	1,41	1,19	0,021	0,45
Corten	0,12	0,25-75	0,20-50	0,07-15	0,035	0,25-55
St 52-3	0,20	0,35	1,3	<0,040	<0,040	

The Krupp steel has a composition with a large amount of Cu, as for Corten steel. That may be a reason, why there has been very little corrosion in the steel.

Out of tests from building periods and test results after a fire in 1946, it has been found, that the Krupp steel is comparable with modern St 52-3. In this way calculations can be based on the Danish Standard (recommendation) "DS 412".
It will always be of DSB's interest, if someone has new test results for steel like Krupp steel concerning the durability (brittleness and fatigue characteristics).

4 MAINTENANCE AND INSPECTIONS

4.1 Surveying, temperature, movements

Until 1953 surveying of the piers (vertical and horizontal) were made 4 times a year. Since then only once a year. From uneven compression of the Littlebeltclay the 4 piers up till today have got vertical movements of 125, 270, 425, 365 mm. Horizontal 20 - 180 mm towards North (Jylland), and 10 - 80 mm towards East. The gap in the moveable hinged joints has been adjusted several times by use of the Wedges. First time in 1937. Then in 1942 and 1986. In 1992 alignment of the pier no 2 is initiated.

It is very difficult to find instruments with adequate accuracy for the measurements of the small displacements related to the large distances. The measurements are furthermore influenced by the spatial variation in temperature in the superstructure (delta T = 10 - 15 °C due to heating from the sun), and the difference in the friction in the roller bearings.

Surveying with the use of a theodolite has been found to have the smallest deviation. But it is rather expensive. It takes a long time, and in this way temperature can change and have an influence on the results. GPS cannot be used due to "shadow" of the superstructure. Electronic distance measuring has been found to have so big a deviation, that it is of no use. Therefor we take many simple measurements to all the distances in the joints, and afterwards we compensate for the influence caused by different temperatures. (ruler and electronics connected to a computer is used)
In this way so many results are collected, that satisfactory precision can be achieved.

4.2 Adjustment in superstructure.

The horizontal movements in the superstructure caused by settlement of pier no 2 present some problems. The superstructure between pier 2 and pier 3 is compressed during the summerseason, which reduce the capacity to carry vertical loads. A program has been introduced to bring the top of pier no 2 back to its original position. Hydraulic jacks have been mounted in moveable hinged joints to produce a constant compression force of 3,7 MN in the superstructure between the two piers. At the same time 2 tackles pulls via 4 bars in the top of pier 2 towards the abutment with a force of 1.4 MN. For 3,7 MN the superstructure should be 12 mm shorter due to contraction. The piers is bend 2 x 2 mm = 4 mm. The total opening in the moveable hinged joints should be 12 + 4 = 16 mm. But it is only 9 mm. It shows, that secondary structures as girders and concrete in the roadway, is working together with the superstructures.

As a temporary arrangement the hydraulic system works without problems, and it is a were economical way, considering the high forces.

4.3 Fire

Fig. 4
Microscope picture x1000

In the period 1944 - 1946 several fires took place on the railway track on the Bridge. In 1946 the fire was so heavy, that several secondary girders carrying sleepers and rails had to be replaced. Test-elements were cut out of the girders. Microscope-analysis showed, that the temperature had reached 650 °C. The microstructure had not changed.
Material tests showed the following values: tensile strength 350 MPa ultimate strength 540 MPa, fatigue with a gap of 170 MPa 1,8 E6 cycles, impact test before and after artificial aging with 250 °C in ½ an hour showed values of 150 J and 140 J. These results shows, that the steel has the same characteristics as, when it was new.
Aging tests showed furthermore, that the steel will not become brittle. In 1963 the wooden sleepers were replaced with steel sleepers to decrease the fire-risk.

4.4 Maintenance of paint

It is found, that complete cleaning by sandblasting combined with new painting is the cheapest. With the use of different paint-systems, that have been available during the years (the producers are continually changing chemicals), we have found, that the average lifetime of paintwork is 20 - 30 years.

Details, like correct drainage of salty water form the roadway, is of great importance. Salty water reduces the lifetime of the painting to 5 - 10 years. The drainage is now connected to a new system of tubes letting the water out so far below the superstructure, that heavy winds cannot carry the salty water back to painted steel.

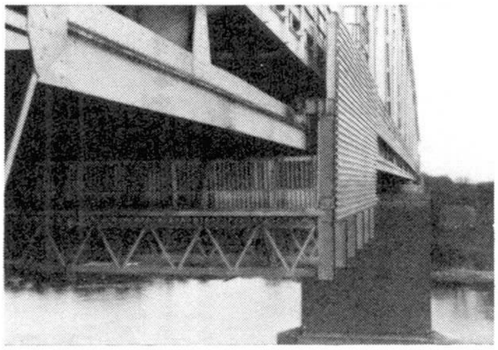

Fig. 5

During the lifetime of the Little Belt Bridge different simple uncovered scaffolds are used.
In 1990 a new big platform was mounted on rails underneath the superstructure. By use of frames and foam rubber it is possible to make a tight room, where the dust from sandblasting can be extracted and collected. By an artificial heating system the temperature can be regulated to a level so the paintwork during a day has been doubled.

The platform was primarily designed to collect the dust from sandblasting and the lead in the old paint, and in this way protect the environment from pollution. 90 % of the sandblasting sand is collected. By the use of the new platform we not only protect environment, but the paint work can be done in a more rational way, with lower costs and better quality. The price for a complete cleaning and new paintwork is 100 USD/m².

4.5 Stonecover

From ±3 m according to sea-level the piers are covered with a layer of 220 mm granite to protect impact from ice. In Denmark the temperature day - night in general fluctuates between - 5°C and +5°C in the wintertime. This causes solid surfaces like concrete to freeze in a depth of 50 mm. Therefore the cover-layer on the reinforcement is often demolished. Since the stonecover is more than 50 mm thick, the frost cannot reach the concrete, and the granite can stand millions of frost-thaw cycles.

4.6 Description of maintenance manual

In 1994 a new instruction manual for management, inspection maintenance work was made. All activities are listed, and every function of constructions, lights, lanterns, pumps, fog-detector, platforms, inspection waggon etc are made. By the help of a checklist we make sure, that all activities are carried out. Remarks are examined and repair- and maintenance work are performed.
Quality-management is at the same time described in the checklists. Information on executed works are registered so future generations can learn from past experiences. It is important, that the manual is updated every year.

4.7 Calculation of the lifetime of the Little Belt Bridge.

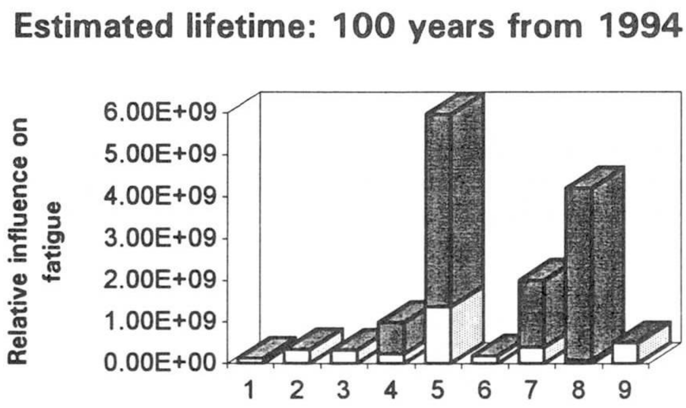

Fig. 6 ■ From 1994 to 2094
Train types: □ From 1935 to 1994
1-3: Steam trains, with 2 and 4 axled wagons
4-5: Diesel powered Freight trains
6-7,9: Light passenger trains
8: Fast passenger trains (IC3)

Heavier traffic loads can be foreseen when the construction of the Great Belt Bridge and Tunnel is completed. Taking into account the increase in number, weight and speed of future trains, new calculations of the lifetime for the Little Belt Bridge have been made.

From annual reports and old train timetables the total number and weights for the trains have been calculated. Preconditions for future heavier, faster or bigger trains are made.

9 standard trains for the past and for the future are set up.

In the Fig. 6 it is showed, how much each standard train already has used and in the future will use in fatigue calculations. (6.00E+09 is the same as 100%).

If the maintenance condition is kept like today, the remaining lifetime for the Little Belt Bridge will be at least 100 years.

5 Conclusive remarks

It has been a very interesting experience to participate in the maintenancework of the Little Belt Bridge, where the design includes so many features which enabling easy inspection and maintenance procedures.
It can be concluded, that it is very important to have a precise record of the history of a steel bridge (type, load and speed of the train and the road traffic, misfortune from cars and ships, fire etc, structures that corrode or are demolished and exchanged). Calculations are the most economical tools for making the decision: When do You have to replace an existing bridge.

Maintenance of the Structures of the Existing Severn Crossing

Entretien des ouvrages actuels de la traversée de la Severn

Unterhalt der Tragwerke der bestehenden Severn-Ueberquerung

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K. Sriskandan joined Mott MacDonald (MM) in 1988 after 20 years in the UK Department of Transport, where he was the Chief Highway Engineer from 1980-87. At MM he was the Manager of the Bridge Division and Project Director for the Maintenance Management of the Severn Crossing.

SUMMARY

In 1992, the operation and maintenance of the structures comprising the existing Severn Crossing passed from UK Department of Transport to a private company, who had won the franchise to also design, finance, build and operate a second Severn Crossing. Both crossings would revert to the Government at the end of the concession period. This paper describes the findings of a handover inspection, the requirements for routine inspection and maintenance, and for other repairs, and also the arrangements for managing all this work.

RÉSUMÉ

En 1992, la responsabilité de l'exploitation et de l'entretien des ouvrages actuels de la traversée de la Severn ont passé du Département des Transports Britannique à une société anonyme, qui a gagné la franchise pour la conception, le financement, la construction et de la deuxième traversée de la Severn. Les deux ouvrages seront rendus au gouvernement à la fin de la concession. L'article décrit les observations lors d'un contrôle de réception, les critères de l'inspection et l'entretien habituels, les diverses réparations, et aussi la gestion des travaux.

ZUSAMMENFASSUNG

Im Jahr 1992 wechselten Betrieb und Unterhalt der Tragwerke, die den Fluss Severn überspannen, vom britischen Verkehrsministerium zu einer privaten Gesellschaft, die auch die Konzession für den Entwurf, die Finanzierung, den Bau und den Betrieb einer zweiten Severn Brücke bekommen hatte. Beide Flussüberquerungen fallen nach Ablauf der Konzession an die Regierung zurück. Der folgende Beitrag beschreibt die Befunde bei der Uebergabeinspektion, die Erfordernisse laufender Inspektionen und Wartung, sowie die Vorkehrungen zu deren Management.

1. INTRODUCTION

The existing Severn Crossing was completed in 1966. It consists of the Aust Viaduct (a three span double box girder structure 156.7m long), the Severn Suspension bridge (length 1683m including anchorages [1], the Beachley Viaduct (length 745m) and the Wye Cable Stayed Bridge (length 409m) all with a total length of just under 3km. The Aust Viaduct has an RC deck acting compositely with the steel box girders, cross girders and side cantilevers. All the other structures are of single cell steel box girders with an orthotropic deck. Following a structural assessment in the 70's and early 80's, the entire crossing was strengthened and refurbished between '85 and '91 [2]. Some aspects of these works were not complete at the time of the Concession to SRC in April '92. The whole crossing was maintained by Avon County Council acting as Agent Authority to the DoT. They had set up a team of inspectors and maintenance personnel housed in a compound close to the Crossing and named it the Severn Bridge Maintenance Unit (SBMU).

2. MAINTENANCE ORGANISATION

Some 6 months before concession SRC appointed Laing Offshore (LO) as their maintenance contractor. LO would also manage staff from SBMU who SRC took over under the Concession Agreement (CA). At the same time SRC also appointed Mott MacDonald (MM) as their Engineer to administer the contract between them and LO and also to undertake the pre-concession inspection of the crossing as required in the CA. The DoT appointed Flint & Neill Partnership (FNP) to act as the Government Representative (GR) in matters relating to the operation and management of the existing Crossing.

3. PRE-CONCESSION INSPECTION

3.1 Objective

It was a requirement of the CA that a close visual inspection of the surfaces of all the structures be carried out in the presence of the GR. MM were instructed to represent SRC. The aim was to inspect the

- condition of structural members and attachments
- condition of paintwork
- signs of unexpected movement
- mechanical damage
- obvious signs of corrosion or deterioration
- completeness of items

and prepare the following:-

- inspection records giving observed conditions of all members
- defect schedule listing all known and observable defects (for this purpose MM defined 'defects' as departures from current relevant standards and specifications)
- condition report setting out the general condition and state of repair of M&E equipment
- our inventory of the assessts forming the existing Severn Crossing as transferred to SRC
- a list of items of outstanding or deferred maintenance

3.2 Access for Inspection

A close visual inspection requires access to within touching distance. Parts of the structures that were inspected without special access equipment were:

- inside of all the boxes
- inside of all towers and tower legs (ladders and inspection platforms are available)
- anchorage shoes of main cable of Severn Bridge and splay saddles
- surfacing, parapets, safety fences, bearings and expansion joints.

Gantries were available to inspect the external surfaces of the boxes of Aust Viaduct. However the corresponding inspection was delayed until the access gantries were available

- for the Wye Bridge and Viaduct in 1992/93
- for the Severn Bridge in 1994.

Inspection of the outside of the Severn Bridge tower legs was carried out by a specialist subcontractor using abseiling techniques.

Although gantries were available for painting the main cable of Severn Bridge, these are too slow for inspection which was done by men walking on the cable. The results of a full inspection carried out by SBMU in August 1991 were accepted for the purposes of the pre-concession inspection.

Special climbers were used to inspect the longer hangers of Severn Bridge when they became available in 1992.

Attempts to inspect the external surfaces of the Wye Bridge towers using a mobile hoist were thwarted by strong winds. In the end they were inspected with binoculars, as were the concrete surfaces of the anchorage chamber.

3.3 Findings of Inspection

3.3.1 As the main members of each structure of the Crossing were stiffened steel boxes, there were literally thousands of components to be inspected and recorded. Every plate panel, every stiffener and every weld was inspected. Fortunately a proven referencing system which identified each component uniquely, was in existence. It was therefore relatively easy to use proformas to record the findings.

3.3.2 Most of the defects found inside the boxes were weld irregularities, some weld cracks, local paint deterioration and some stiffener distortion. Most of these defects were in parts of the original structure and had been there for over 25 years. No action was taken on these except to record them on the inspection sheets. Defective welds were repaired in accordance with the maintenance manual and paint deterioration was made good at the next painting session.

3.3.3 No structural defects were found on the external surfaces. However there was paint deterioration over significant areas, particularly on Severn Bridge, due to lack of maintenance caused by unavailability of access gantries. Painting work has however started in 1994 following availability of the gantries.

3.3.4 The stay cables of Wye Bridge and the hangers of Severn Bridge were all new and were therefore in good condition. There was some loss of paint on the main cables of Severn Bridge. These have since been made good at repainting. There had been some corrosion and breakage of one or two wires of the main cable in the anchorage chamber. However, there has been no further deterioration since the whole of all four upper anchorage chambers were dehumidified.

3.3.5 Shortly before handover of the crossing an inventory was taken of all the equipment on and within the crossing. This was done by walking through internally and externally and ticking off items against a prepared list.

4. INSPECTION AND MAINTENANCE

4.1 Requirements

The type, nature and frequency of inspections to be carried out were all specified in a draft Maintenance Manual prepared by FNP. The CA allowed SRC to modify the procedures in agreement with the GR.

Structural members have the usual Routine Superficial, General and Principal Inspections except that the frequency of General Inspection is determined by the "Criticality and Vulnerability Ratings" (CR&VR) of each component. CR relate to anticipated fatigue endurance, tolerable crack lengths, tensile stress levels etc., whilst VR relate to propensity to deterioration due to corrosion, damage or wear. Frequencies of inspection are 6 months, 1 year, 2 years and 6 years for CRs of A, B, C & D respectively or VR's of 1, 2, 3 & 4 respectively. Only a few critical welds require inspection every 6 months. All cables, hangers, stays and connecting welds have CRs of B.

4.2 Inspections and Audit

All inspections are done through LO in accordance with the requirements of the Maintenance Manual. At the start results were recorded on proformas, but now they are recorded on hand held data capture devices and down-loaded directly into a computer. The computer data is accessible to MM who audit it to ensure that inspections have been done and that any defects found are repaired. Most of the defects found are weld cracks for which standard repair methods are available. If these are not available, method statements are prepared by MM and agreed with the GR before repair is put in hand.

4.3 Maintenance

4.3.1 Apart from the general good "bridge-keeping" to enable free movement of traffic, there are numerous items of routine maintenance that have been carried out. Some typical items are:

- lubrication of structural parts such as pins and strands on Severn & Wye bridges and tower column guide bearings on Severn bridge
- replacement of seals on Severn cable covers at towers and at main cable clamps
- replacement of worn parts on roadway joints, bend limiters, column guide bearings at lateral bearings on Severn Bridge
- replacement of parts damage by accident
- a complete maintenance of all access gantries whether in use or in storage.

4.3.2 In addition to routine maintenance, monitoring of some structural items is also being carried out.

Examples are:

- deck levels and tower tilts on Wye Bridge to decide whether loads in stay cables are changing
- levels on Aust viaduct to see whether there is any breakdown in composite action
- rocker loads on Severn Bridge to monitor effects of bedding down of new hangers and bearing wear
- humidity within shrouds surrounding the cables in Severn Bridge anchorages to

ensure a low (<25%) relative humidity
measurement and analysis of water from Severn Bridge cables to monitor effectiveness of protection and determine the presence of harmful chemicals.

So far the results have all been satisfactory and no corrective action has been needed.

5. REPAIR OF DEFECTS

5.1 Weld cracks

5.1.1 Most of the work has been in reinstating/repairing fillet welds in the orthotropic deck, joining trough stiffeners to deck or to the diaphragms. Standard repair methods have been devised. For the first, Fig 1(a), the existing 6mm weld is cut out over a certain length and replaced by a larger fillet weld which includes some preparation of the stiffener web. In the Second, Fig1(b), a shaped strap is fillet welded to the trough and also the diaphragm. Table 1 gives the numbers of these repairs on each structure from concession date to the present time.

Weld Type	Severn Bridge	Beachley Viaduct	Wye Bridge
Deck	18	24	8
X Girder	74	2	30

Table 1

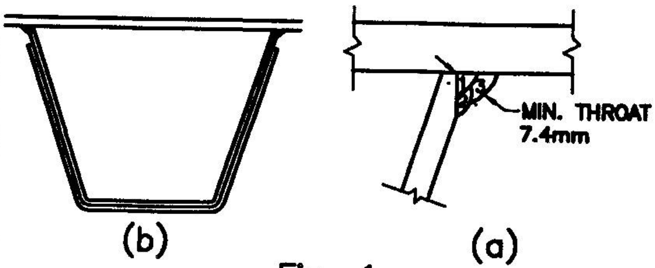

Fig. 1

5.1.2 In the Severn Bridge, temporary diaphragms were fitted at one end of each of the 18.3m long boxes to help float the boxes out. These were welded to the underside of the trough stiffeners and were not removed. Fatigue cracks began to occur at these welds early in the life of the structure. The repair method adopted was to free the trough from the stiffener, cut out a portion of the bottom flange of the U shaped stiffener containing the crack and bolt in two plates to the webs of the stiffener. There were in all 84 temporary diaphragms each welded to 36 stiffeners. So far it has been necessary to carry out repairs at 447 locations.

5.2 Other Repairs

Other repairs that have been necessary are reinstatement of barriers and barrier posts that have been damaged by vehicle collision and also replacement of the shell grip in certain areas of the carriageway where it has lifted from the mastic asphalt.

6. WORKS OTHER THAN ROUTINE MAINTENANCE

6.1 Finishing Off Works

Typical items of work were unfinished painting inside and outside of the boxes, checking and adjusting clearances in the guide bearings (which were at every 6m of each of the 120m high and 406mm dia. tubular steel columns inside each of the towers of Severn Bridge) and fixing bend limiters at the upper end of the Severn Bridge hangers (bend limiters were already in place at the lower ends).

6.2 Access Gantries

6.2.1 At concession there were only three underdeck gantries in place on the Severn Bridge, the other having fallen off in an accident. These gantries had been out of use for some time and MM were appointed to design a refurbishment plan and oversee its execution and also take responsibility for the design of the gantries. Most of the refurbishment was to the electrical parts and the control systems. However MM also checked the structural design of the gantries. Strain gauging was used to determine the dynamic amplification of the loading and this was found to be about 15%. The design was found to be satisfactory and was used for the replacement of the fourth gantry. At the time of writing the gantries are all useable.

6.2.2 The tower access gantries for the Severn Bridge were also procured after concession. This was let as a design and build contract based on an outline design and performance specification. What was required was a 4 sided cradle and platforms suspended from the four corners of the towers with provision for removal and replacement of one part as the cradle passed the cross beams. The tender that was finally accepted (and is now fully operational) is a lightweight space frame based on the Beeche System in USA.

7. THE FUTURE

When these entrusted and additional works are completed, it is envisaged that the work, for the next few years, will be mainly routine inspection and maintenance with repair of cracked welds. In the longer term major maintenance such as refurbishment of expansion joints, replacement of bearings and even hangers may become necessary. However with diligent maintenance it is expected that these structures will be handed back to the DoT, in a good state of repair, at the end of the Concession period.

8. ACKNOWLEDGEMENTS

This paper is presented by kind permission of Severn River Crossing plc. Colleagues from Mott MacDonald Ltd have assisted with material for the paper, but views expressed are those of the Author only, and not necessarily those of any of the parties mentioned in this paper.

9. REFERENCES

1. ROBERTS Sir Gilbert, Severn Bridge: Design and Contract Arrangements. Proc. Instn. Civil Engs., September 1968

2. CHATTERJEE, S et al, Strengthening and Refurbishment of Severn Crossing, Proc. Instn Civil Engs Structs and Bldgs, February 1992

Heated Bridge Deck Construction and Operation in Lincoln, Nebraska

Construction et exploitation d'un tablier de pont chauffé à Lincoln, Nebraska

Beheizte Brückenfahrbahnplatte in Lincoln, Nebraska, USA

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Federal Highway Administration
Lincoln, NE, USA

Milo Cress, born in 1945, received his civil engineering degree in 1968, and masters degree in 1972, both at Colorado State University, Fort Collins, CO. He has worked for FHWA since 1973 in hydraulics, safety appurtenance design, and bridge structures.

SUMMARY

The construction and operation of a hydronic bridge/pavement deck heating system are described in this paper. The system is installed in the deck of a 367 m-long by 3.7 m-wide viaduct in Lincoln, Nebraska, USA. The system was monitored and performance evaluated for 12 months following installation.

RÉSUMÉ

Le document décrit le mode de construction et le fonctionnement d'un système de chauffage par circulation de fluide caloporteur pour le tablier d'un pont de 367 mètres de long par 3,7 mètres de large, qui se trouve à Lincoln, dans le Nebraska aux États-Unis. Le système est décrit; il a fait l'objet d'un suivi et d'une évaluation du rendement pendant les 12 mois qui ont suivi l'installation.

ZUSAMMENFASSUNG

Diese Veröffentlichung beschreibt den Bau und Betrieb einer Warmwasserheizung für das Pflaster einer Brückenfahrbahnplatte. Die Anlage ist in das Deck einer 367 m langen und 3,7 m breiten Überführung in Lincoln, Nebraska, eingebaut. Das System wird beschrieben. Die Anlage wurde nach dem Einbau über 12 Monate überwacht und die Betriebsdaten analysiert.

1. INTRODUCTION

Winter conditions impose difficult bridge deck maintenance problems, particularly in areas like Lincoln, in southeastern Nebraska, which has a normal annual snowfall of 881 mm. The maximum recorded snowfall for 24 hours is 264 mm and occurred in 1957. Between October 17 and April 20 each year, 185 days have an average temperature below 273°K *(1)*.

A new 367-m-long elevated pedestrian viaduct (Fig. 1) was constructed in 1992 over several railroad beds. Special Federal funding was available to install heated decks under an Intermodal Surface Transportation Efficiency Act of 1991 program; this deck was eligible and was a particularly attractive candidate because of its central location, heavy bicycle use, and potential use by the physically impaired.

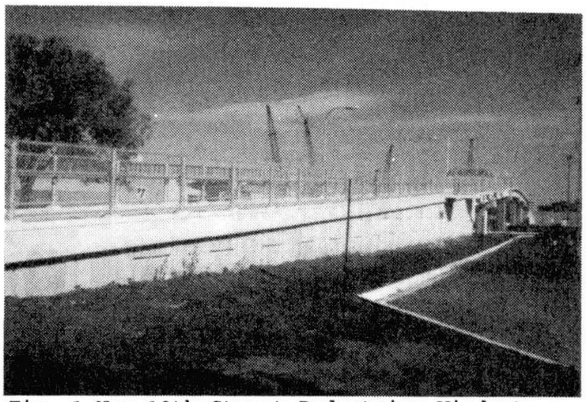


Fig. 1 New 10th Street Pedestrian Viaduct

The structure is a 5-span, 169.8-m-long precast-prestressed-post-tensioned concrete superstructure with an 165-mm-thick by 3.7-m-wide cast-in-place deck. The approaches, supported on mechanically stabilized earth (MSE), are 70.7-m- and 126.5-m-long and have 5 percent grade. The total top surface areas of the south approach, elevated structure, and north approach are 289 m^2, 696 m^2, and 614 m^2, respectively. The highest deck is 8.8 m above the boiler.

2. SYSTEM DESCRIPTION AND COMPONENTS

The hydronic deck heating system was manufactured by Delta-Therm Corporation®. A natural gas boiler heats a propylene glycol and water solution that is pumped on cue through hoses encased in the deck and warms the concrete deck enough to melt snow and ice. The heating system was installed from end-to-end of the viaduct, including approaches. Table 1 lists the major components.

• *Boiler Building*--4.6-m by 7.6-m prefabricated concrete, housing boiler and controls.
• *Hydronic Boiler*--Hamilton Engineering HE-3111 natural gas multitube hot water boiler, 908 kW input and 732 kW output.
• *Pumps*--Three Taco "1600" Series pumps with 1207 kPa operating pressure at maximum 422°K.
• *Polyvinyl Chloride (PVC) Distribution Line*--579 m of 152-mm-diameter Schedule 40.
• *Copper Distribution and Collection Manifold*--One of each at each of the 13 heating zones.
• *Heat Distribution Hose*--13.5 km of Delta-Therm 10-mm-diameter flexible hydronic hose.
• *Expansion Tanks*--802 L total volume.
• *PVC Collection Line*--579 m of 152-mm-diameter Schedule 40.
• *Heat Transfer Fluid*--21 kL, 35% propylene glycol/water, with corrosion inhibiter package.
• *Snow Sensing System*--Delta-Therm SMC 120A snow sensing system, including two deck surface heated moisture sensors and ambient air temperature sensor.

Table 1 Major Components of Heating System

The viaduct is divided into 13 heating zones, each about 121 m^2. The propylene glycol and water solution is heated to 327°K and pumped through the system under a pressure of about 207 kPa. The solution moves from the boiler into the 152 mm-diameter polyvinyl chloride (PVC) pipe for distribution to heating zones. PVC distribution and collection pipes are diagrammed in Fig. 2.

PVC pipes are buried in sand on approaches and supported on hangers under the elevated structure. The coefficient of expansion for the concrete superstructure is 0.0000108/°K; for the PVC pipe, 0.000052/°K. Providing for PVC pipe expansion was a primary consideration because there was potentially 343-mm total movement at each abutment in the PVC. A flexible expansion loop (Fig. 3.) is installed in each PVC near each abutment to accommodate expansion of both the concrete superstructure and the PVC. Each PVC pipe is enclosed in 51-mm-thick fiber-glass insulation beneath the elevated structure. PVC is not insulated in approaches. A PVC bridge pipe and valves, also displayed in Fig. 3, were installed near each abutment to enable shutting off the solution to and from abutment areas.

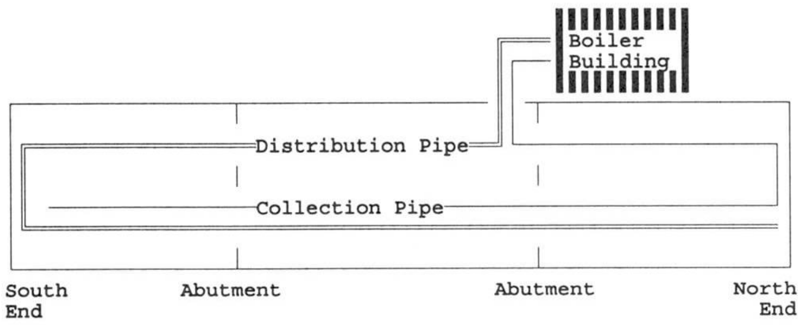


Fig. 2 Distribution/collection Network Schematic

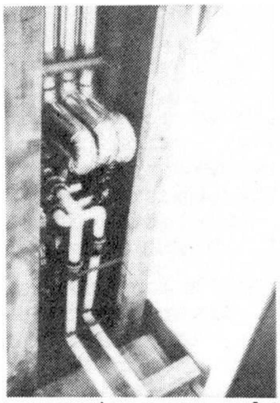


Fig. 3 PVC Expansion Loops and Valves Near Abutments

The boiler and controls are housed in a 4.6-m- x 7.6-m-prefabricated boiler building (Fig. 4) positioned adjacent to the north MSE abutment wall. The boiler was installed before the roof and can be removed through the service doors.

At each heating zone, solution is transferred in a 25-mm-diameter flexible plastic hose from the PVC distribution line to a copper distribution manifold (Fig. 5). The manifold distributes the solution to 10-mm-diameter hydronic rubber hoses spaced at about 114-mm centers within the concrete. These hoses run parallel from the distribution manifold to the extreme boundary of the heating zone and back to the collection manifold (Fig. 6), which is located adjacent to the distribution manifold (Fig. 5). The solution is then transported from the collection manifold to the PVC collection line in a 25-mm-diameter flexible plastic hose. Finally, the solution is returned to the boiler, where it is reheated and recycled (Fig. 7).

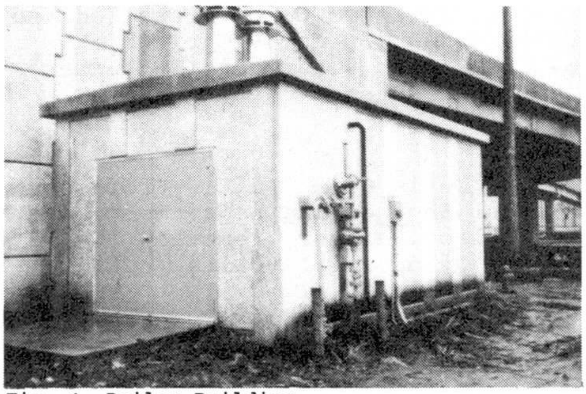


Fig. 4 Boiler Building

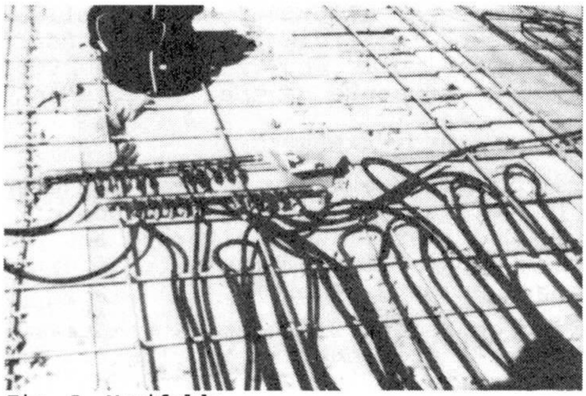


Fig. 5 Manifolds

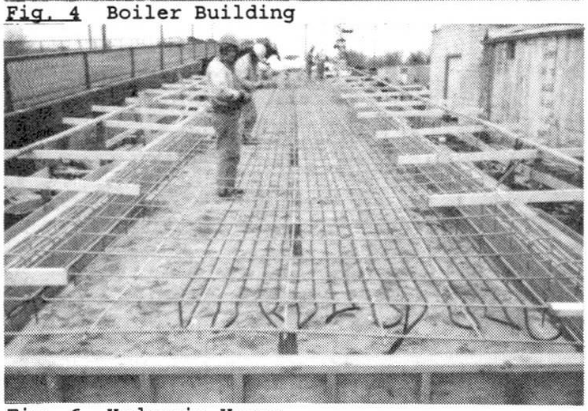


Fig. 6 Hydronic Hoses

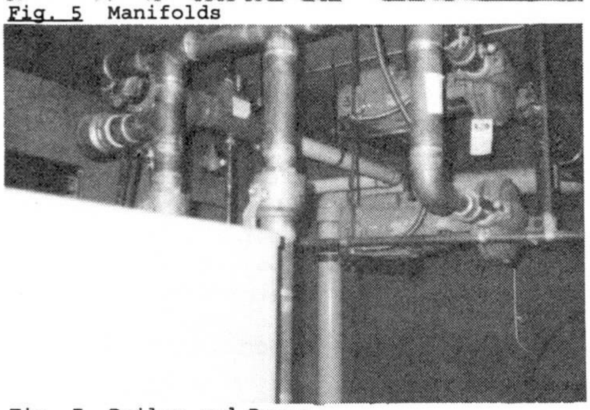


Fig. 7 Boiler and Pumps

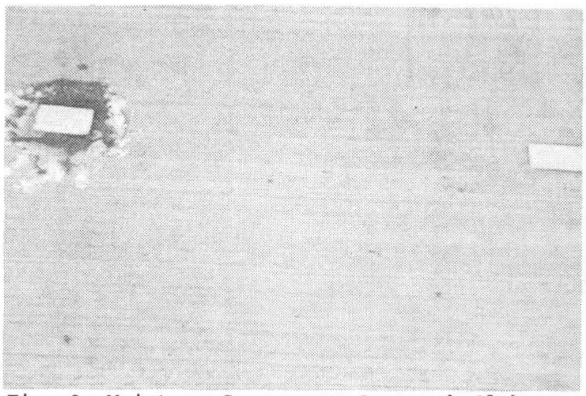


Fig. 8 Moisture Sensors on Approach Slab

The system was designed for a fluid flow rate of 454 L/min and to deliver 473 W/m^2 of heat flux to the deck.

Automatic operation of the system is accomplished by moisture (Fig. 8) and temperature sensors. The system turns on when sufficient moisture collects on the sensing devices to make electrical connection, temperature of the deck is below 277°K, and ambient temperature is below 275°K. Moisture sensors on the deck are heated. The system turns off when the deck reaches a temperature of 286°K. Finally, the system can be turned on and off manually and the boiler shuts off automatically if system pressure decreases below 122°kPa.

3. CONSTRUCTION

The system was installed within the time allowed for viaduct construction without special construction equipment or personnel. Construction personnel were trained and specialized mechanical, electrical, and prefabricated building subcontractors were used. Local utility companies provided metered service at the boiler building (natural gas and 100- ampere, 110-volt electricity). Heating system installation added $161/m^2 to the cost of viaduct construction.

Construction began on the south MSE approach. Heating system components were installed following normal bridge construction sequence. Distribution and collection manifolds were positioned and tied securely in each heating zone. Hydronic hose was connected to nipples on the distribution and collection manifolds with circumference-screw clamps and stretched taut within the heating zone. The single layer of reinforcement was positioned on supporting concrete blocks over the hoses and tied. Hydronic hose was then tied to the bottom of the reinforcement. The heating zones on the elevated structure were similarly installed, with hydronic hose positioned between the layers of reinforcement. When the reinforcement and hoses were taut and tied, hydronic hoses were brought to 414 kPa air pressure, and concrete was poured in the forms, vibrated, finished, and cured following standard practice.

In the approaches, distribution and collection PVC pipes had to be installed and connected to the manifolds before the concrete slab was poured. PVC pipes, flexible expansion loops, valves, and PVC pipe insulation were installed under the elevated structure at the convenience of the contractor.

4. MONITORING AND EVALUATION

The monitoring and evaluation plan was prepared by Kevin Cole, Ph.D., Professor in the University of Nebraska at Lincoln Mechanical Engineering Department. The plan included installing monitoring equipment, collecting data, removing monitoring apparatus from the site after 12 months of data collection, and preparing a summary report.

Monitoring equipment included 18 temperature sensors and one fluid-flow sensor. Sensors were installed in five clusters of three. Each cluster included a sensor at the top surface, center, and bottom of the concrete. Clusters were installed on the centerline in the elevated structure 3 m and 6 m from the north abutment, on the centerline in the north approach 9 m and 12 m from the abutment, and in an unheated sidewalk adjacent to the boiler building. A sensor was installed in the supply pipe and return pipe to monitor fluid temperature and a sensor was positioned to monitor ambient air temperature. Finally, a volume-flow sensor was installed in the return pipe near the boiler. Sensors were wired to a data-acquisition board in a computer located inside a cabinet with temperature controlled by a thermostat.

5. SYSTEM OPERATION

The heating system was charged and operable in November 1994 and operated on December 6, 8, 20, and 31, 1994. The December 31 event, which consisted of a 76-mm snowfall, is described in detail below.

Ambient temperature was 275°K at mid-day on December 30 and dropped to 269°K during the following night. Temperatures remained around 269°K through most of the day on December 31, dropping to 265°K by 1800 hours, and to 257°K by 0700 on January 1, 1995. The temperature then rose to 268°K by 1600 hours. Temperature then began dropping, reaching 258°K at 0700 hours on January 2. The temperature reached a high of 271°K at 1600 hours and dropped to 260°K by 0800 hours on January 3.

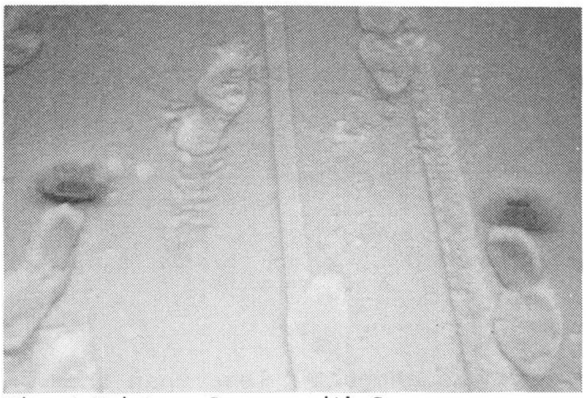


Fig. 9 Moisture Sensors with Snow

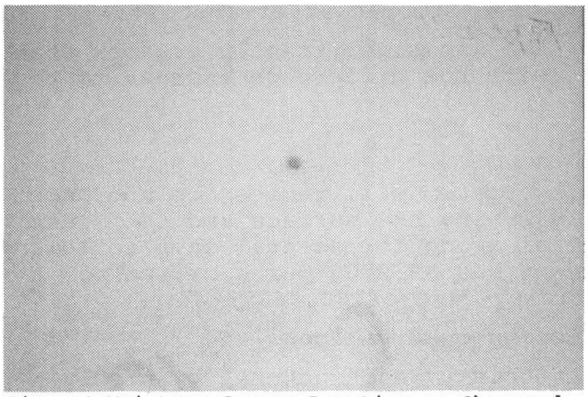


Fig. 10 Moisture Sensor Location as Observed

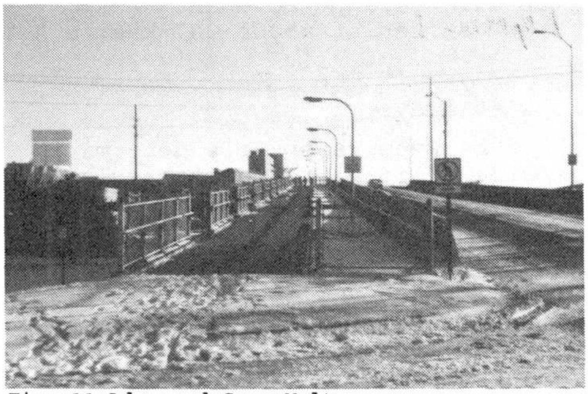
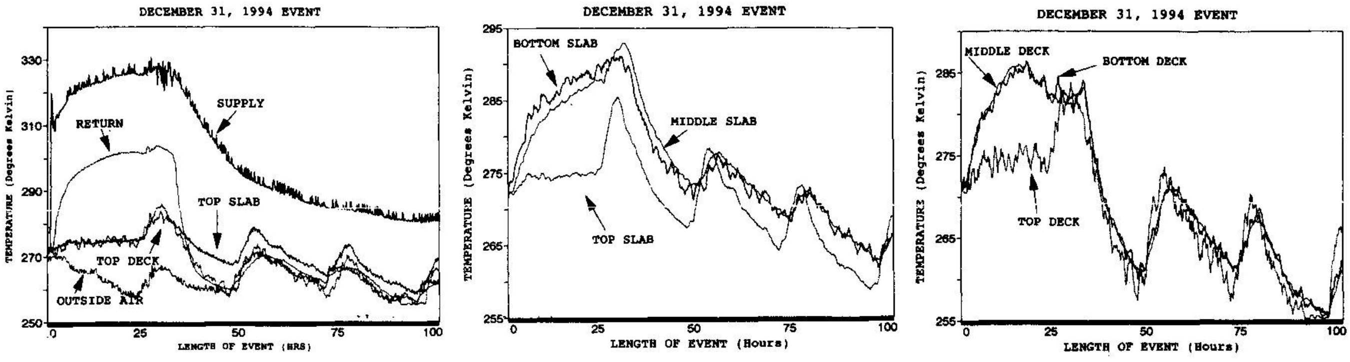


Fig. 11 Advanced Snow Melt

Light drizzle with very light snow flakes began early in the morning on December 30, 1994. This continued through most of the day. At 1200 hours the deck was wet, except at the control moisture sensors. Each sensor and about a 50-mm region around each sensor remained dry. Heat from sensors was evaporating moisture. At 1630 hours sensors had some ice accumulation that bridged the sensing elements. At 2330 hours snowfall was very light and about 20 mm of snow had accumulated on the deck. Sensors had no ice and were dry with adjacent snow accumulation (Fig. 9). At 0800 hours on December 31, about 32 mm of snow had accumulated on the deck and sensor location was slightly marked by dark spots on the snow (Fig. 10). Snow accumulation had formed a cap over each sensor and each sensor remained dry. The system did not start automatically because of this "igloo" effect. During investigation of the sensors, snow fell on the sensors, was melted, and the system started at 0955 hours on December 31. Gas and electric meter readings were 8 393 m^3 and 2 276 kWh, respectively. At 1840 hours, gas and electric meter readings were 8 996 m^3 and 2 320 kWh, respectively. Snow had been melted on about 40 percent of the deck and some spots on the deck were dry. At 1200 hours on January 1, 1995, about 38 mm of snow had accumulated on unheated streets and sidewalks. Gas and electric meter readings were 10 191 m^3 and 2 402 kWh, respectively. The deck was about 95 percent cleared with significant dry areas. The boiler was cycling on and off. At 1600 hours the gas and electric meter readings were 10 432 m^3 and 2 420 kWh, respectively. The deck was 99 percent clear and the boiler was cycling on and off (Fig. 11). At 1830 hours gas and electric meter readings were 10 516 m^3 and 2 421 kWh, respectively. Pump motors were running and the boiler was not operating. The system was manually turned off at 2330 hours and motors stopped. Subsequent investigation showed that system fluid was low and the siphon had broken.

Data collected during this event are displayed in Figs. 12 (a), (b) and (c). The flow meter was not functioning during this event.

The boiler shut off at 1418 hours on January 1, 1995. About 1 798 m^3 of gas was burned by the boiler by 1200 hours on January 1 during the first 26 hours of operation, and about 241 m^3 were burned between 1200 hours and 1600 hours on January 1. Most of the gas was burned before 1418 hours when the boiler first began to shut off. Based on the gas used and 80 percent boiler efficiency, 372 W/m^2 of heat flux was delivered to the deck during the first 26 hours of operation. Temperature drop between supply and return pipes was about 26°K during snow melting. Temperature of the concrete surface on both the elevated deck and approach slab remained at 273°K during snow melting, and then increased to 286°K after snow was melted and the system approached shutoff.



(a) Supply, Return, Outside Air, and Concrete Surface

(b) Top, Middle, and Bottom of Approach Slab

(c) Top, Middle, and Bottom of Elevated Deck

Fig. 12 Temperature Data

Temperature of the bottom of the elevated deck was about 2°K less than the middle of the deck during snow melting. The elevated deck temperature increased to slightly over 288°K during snow melting, then dropped after shutoff.

Temperature of the bottom of the approach slab was significantly greater than the temperature of the middle of the slab, with the difference increasing to about 5°K as the system approached shutoff.

6. CONCLUSIONS AND RECOMMENDATIONS

Our experience demonstrates that the heating system will remove ice and snow from the slab and deck surfaces--thoroughly drying the surface and eliminating the possibility for frosting and preferential icing for several days following a storm event. Cost of operation for this event was $9.25US per hour, using natural gas cost of $0.134US/m^3 and electricity cost of $0.04US/kWh.

Based on our experience, we offer the following observations:

- Expansion of PVC must be accommodated at joints in structures by highly flexible hose. Nipples or other appendages protruding from pipes in the sand approaches should be covered with material to allow slight movement. Also, joints of PVC should be wrapped with tape that can resist about 207 kPa pressure.

- Propylene glycol fluid should be colored with a dye.

- Valves and bridge pipes should be installed between reasonably determined large regions, such as the bridge and the abutment areas, to permit isolation when the system is charged with fluid. This enables isolation of leaks in the system.

- Standpipe devices should be installed for visual verification of fluid level in the distribution and collection pipes on the bridge and approaches, as well as in the expansion tanks. Valves should be installed at high points in all supply and return pipes to allow bleed-off of air during charging of the system with fluid. Valves should be installed at low points of the distribution and collection pipes to permit complete discharge of fluid from the system.

- The moisture- and temperature-sensing control system should include a device that senses when snow has been cleared from a significant portion of the deck surface. This would enable earlier automatic shutoff of the system, with potential savings of 10 to 30 percent per event.

- Finally, manual controls should be provided in the boiler building, wired to override the automatic control device operation. Wireless or landline control of system operation would be very advantageous.

REFERENCE

1. National Climatic Center, NOAA. *Climatological Data*. Asheville, N.C., USA