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SESSION 1

Inspection, Records and Maintenance

Surveillance, protocole de mesures et entretien

Überwachung, Zustandsprotokolle und Unterhaltung

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Conflict between Structurally Deficient and Historically Significant Bridges

Conflit entre la sécurité des ponts et leur valeur historique

Konflikt zwischen den Sicherheitsanforderungen an Brücken und ihrem historischen Wert

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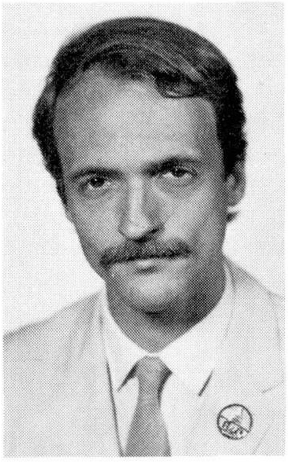

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SUMMARY
This paper highlights issues in the conflict between making America's bridges safe and secure and the desire to preserve selected examples of historically significant bridges for future generations.

RESUME
L'article illustre le conflit existant entre la nécessité de disposer de ponts sûrs et la volonté de garder, à l'intention des générations futures, des ponts de valeur historique.

ZUSAMMENFASSUNG
Der Artikel erläutert die bestehenden Konflikte zwischen der Notwendigkeit, über sichere Brücken zu verfügen, und dem Willen, zugunsten späterer Generationen Brücken von historischem Wert beizubehalten.

1. BACKGROUND TO THE BRIDGE ISSUE

The Historic American Engineering Record (HAER) [1] had been in business only six years when notice was taken of an article buried in the back pages of the July 19, 1975, issue of The New York Times entitled "32,000 Old Bridges Are Termed Unsafe." This article was an early warning that thousands of bridges built during the last half of the 19th and first quarter of the 20th centuries were threatened by massive federal programs to rid the primary and secondary road system of the United States of structurally deficient and functionally obsolete bridges. This did not mean that industrial archeologists, historic preservationists or historians of civil engineering were insensitive to the threat to life and property posed by unsafe bridges. But rather, we were concerned that the country was about to lose one of the most significant contributions made by civil engineers to the development of this vast land. What confounded the problem further was that few engineers, much less the lay public or historic preservationists, would recognize a historic bridge if they saw one. Like many other structures of the industrial revolution, bridges, especially metal trusses, at the time were not considered part of the historic patrimony; they were not viewed in the same context as great works of architecture. However, when viewed with an appreciative eye, bridges are wonderful expressions of the engineer's art. The truss bridge in particular was indigenous to America. No other country experimented with the truss concept as widely as we did during the 19th century. With unlimited wood, and the need to construct railroads and roadways as quickly and cheaply as possible to open up the frontier, the timber truss was a natural solution. Once the trunklines opened up the hinterland, people moving westward built a network of primary and secondary roads to connect their farms to market towns, and the towns to larger cities. The solution to crossing thousands of streams and rivers was the prefabricated metal truss which evolved from the wooden truss about the middle of the 19th century. Manufactured first in cast and wrought iron, and later in steel in a bewildering number of configurations, hundreds of patents were taken out during this period. HAER realized that many examples of these patented bridges remained among those defined as structurally deficient and functionally obsolete. Thus began intensive conscious raising efforts to sensitize the engineering profession, the preservation community, federal officials and the lay public to the historical significance of bridges, especially of the metal truss kind.

Fig.1. The Brooklyn Bridge, one of the most famous bridges in the world, celebrates its Centennial in 1983. Though no one would dream of replacing it, a cable corroded by pigeon dung snapped last year, killing a pedestrian; rehabilitation costs are estimated at $105 million. Jack Boucher, HAER.

2. HAER INITIATIVES TO FOSTER RECOGNITION OF HISTORIC BRIDGES

Articles were written, speeches were made and symposiums were given by members of the HAER staff. To arrest the attention of transportation engineers and Federal Highway Administration (FHWA) officials who pressed on with bridge replacement regardless of environmental or historical concerns, the question was asked - Is the bridge eligible for listing in the National Register of Historic Places [2]? While many viewed this tactic as obstructionist, and not in the tradition of cooperation between federal agencies, it was necessary on several occasions to delay the demolition of a bridge to allow the environmental review process, as mandated by law, to run its course. The intent was to promote the concept of comprehensive statewide inventories to identify those bridges that may be eligible for listing in the National Register. Having such inventories, it would be possible to advise the federal agency involved or the State or county highway engineer of the bridge's historical significance. Appropriate steps could then be taken at the earliest planning stages to mitigate any adverse effects. Mitigative measures would indicate which bridges should remain in situ and be sympathetically restored or strengthened; which might be dismantled and relocated for continued use elsewhere; and which should be recorded so their loss would not be total if in the final analysis, they could not be saved. This is the purpose of our historic preservation and environmental laws.

3. FHWA INITIATIVES FOLLOWING THE SURFACE TRANSPORTATION ACT OF 1978

Evidence that these measures were beginning to have an effect was revealed in 1978. The Surface Transportation Assistance Act of 1978 (PL 95-599, Sec. 124 & 202, 92 Stat. 2689) permitted the optional use of Federal Highway Bridge Replacement and Rehabilitation funds for inventories of historic bridges. In 1980, FHWA adopted a policy of encouraging states to conduct such inventories, and has recently moved to add a one-digit entry for historicity to the National Bridge Inventory Data Sheets. An adversary relationship between HAER, the Advisory Council on Historic Preservation, State Historic Preservation Officers, and bridge enthusiasts on the one side, and FHWA and state highway and transportation officials on the other, changed during this period to one of mutual cooperation. HAER, with the assistance of the SHPOs and FHWA, sponsored three regional Historic Bridge Symposia in 1979-80 that highlighted inventory methodology, ascertained historical and environmental significance, defined structural problems and strong points, and discussed the feasibility of preserving historic bridges. FHWA, with the assistance of HAER, produced "An Introduction to Historic Bridges," a 35 mm slide/cassette tape that is available to highway engineers and preservationists.

4. STATUS OF STATEWIDE HISTORIC BRIDGE INVENTORIES

By latest count, 28 out of the 50 states have completed or made significant progress on statewide historic bridge inventories [3]. This is a remarkable statistic considering the vast size of the United States, its many political subdivisions, and the fact that just seven years ago, the Commonwealth of Virginia was the only state that had completed an historic bridge inventory [4]. Most of the states are publishing the findings of their inventories thus adding to the scholarship on bridge building in America, and enabling regional comparisons to be made when necessary. Fast approaching is the day when it can be claimed that we have completed a national historic bridge inventory.

5. PROGNOSIS FOR THE FUTURE

Once the states that have not begun inventories come into line, the identification and evaluation phase will be behind us. Bridges determined eligible for the National Register will logically serve as the basis for preservation planning. For states that have completed inventories, approximately 10% of the bridges identified are eligible for the National Register. The remainder are of no historical interest. Preservation planning alternatives may entail: 1) Rehabilitation in situ; 2) Relocation and rehabilitation at a new site; 3) Adaptive reuse; 4) Recording prior to demolition.
regardless of the fact that inventories identify bridges that may qualify for these treatments, few bridges in the United States have been rehabilitated, relocated, or adaptively reused since the bridge rehabilitation program began. Based on the 4(f) statements [5] HAER has reviewed over the past two years, the primary mitigative measure has been recording prior to demolition. The reason is that few highway engineers seriously address the preservation potential of 19th and early 20th century bridges. In most cases they are stymied by modern geometric and loading standards established by the American Association of State Highway and Transportation Officials (AASHTO). FHWA has been reluctant to approve federal funding unless these standards are met. In other instances state and local highway departments will not assume legal responsibility for deficient bridges that could be bypassed and abandoned. Few local communities or private groups that may be interested in saving a bridge have the resources to upgrade a bridge to safe standards and then maintain it year by year, much less assume the burden of liability. Only in an extremely limited number of cases have non-highway interests gotten behind the preservation of a bridge and convinced highway officials that rehabilitation was feasible. Surprisingly, the few bridges that have been rehabilitated and continue to be used for vehicular purposes have been rehabilitated at a fraction of the cost of new replacement structures. Most of these efforts have had strong local supporters who have hired their own engineering consultants to reject the claims of deficiency and prove that it is feasible to rehabilitate to safe standards. However, local groups are reluctant to confront highway officials and few have the resources to hire consulting engineers.

Fig.2. Bollman's Suspended & Trussed Bridge (1869) was relocated from a main line of the Baltimore & Ohio RR to service the mill at Savage, Maryland. It is the only known example of its type and facilitated the rapid expansion of early American railroads westward. Robert Vogel, Smithsonian Institution.

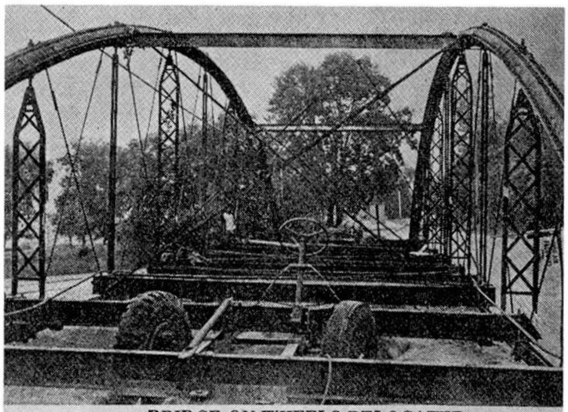
6. THE NEED FOR CASE STUDY DATA

Now that the identification and evaluation gap is being closed, the next goal will be to develop case studies demonstrating the economic and engineering feasibility of rehabilitating, relocating, and adaptively reusing historic bridges. We know there probably are more bridges than expected that have been rehabilitated or relocated to other sites. Reports on the results of statewide bridge inventories reveal that it was normal practice during the early decades of the 20th century to dismantle and relocate bridges. Needed is specific information on the techniques and costs of such procedures. We also need detailed information on rehabilitation measures, both those that take into account the historic characteristics of bridges and those that ignored them. We need examples and data on bridges that have been adaptively reused for purposes other than vehicular. Once cost data, engineering specifications, and illustrations of acceptable rehabilitation techniques begin to accumulate, it will be possible to advance the argument that bridges are imminently suitable for these measures, that it can be done without threatening human life and property, and at a savings over new construction. This is implied in the Highway Bridge Rehabilitation and Replacement Program. To date, replacement has been funded almost exclusively.

Also pointed out while monitoring bridge rehabilitation and replacement projects is the lack of understanding and sensitivity on the engineer's behalf towards historic bridges. Few engineers have been trained or have sought experience in preservation projects. There is little ethic to understand the profession's past accomplishments or to strive to preserve noteworthy examples of these achievements. An exception to this general observation is the landmark designation program of the History and Heritage Committee of the American Society of Civil Engineers (ASCE). And, it should be pointed out that once a state highway department becomes involved in an historic bridge inventory, many staff engineers develop keen interests and appreciation of old bridges. However, rarely does one find an engineering firm assuming a leadership role in a preservation project. The fact that architects and buildings rather than engineers and engineering structures have captured media headlines in these areas speaks for itself.

7. APPEAL FOR CASE STUDY DATA

The reason for seeking the opportunity to present this paper at the International Association for Bridge and Structural Engineering is that European engineers have a far better success rate for rehabilitating bridges than we have in America. Specifically being referred to are the rehabilitated bridges of Thomas Telford, and the first Ironbridge, constructed in 1779 at Coalbrookdale, England. Certainly notable examples in other continental European countries exist that I am not familiar with. We in America seek your assistance in lending us information on your accomplishments. Because we have such limited examples to point to in this country, we need specific information on rehabilitation projects that have been completed for historic bridges of all types. We need to know how you have addressed such issues as codes and standards, aesthetics, specifications, and costs. If such information is forthcoming, it will be forwarded to Howard Newlon, Chairman, Transportation Research Board (TRB) Subcommittee A1B03(1), Historic & Archeological Considerations in Transportation Planning [6]. After this information is digested into useful case studies, it is hoped that the Federal Highway Administration will extend the same level of support and assistance as was given to the National Historic Bridge Inventory. If the "Maintenance, Repair and Rehabilitation of Bridges" is as significant a subject to merit an international symposium, then it seems only logical that the techniques of maintenance repair and rehabilitation can be defined to ensure the preservation of historic bridges. If this comes about, then not only can we save limited financial and material resources, but we can also maintain notable achievements of the engineer's art, and the aesthetic character and environmental quality of our urban roads and rural landscapes.



BRIDGE ON WHEELS RELOCATED

Fig.3. Espyville Road Bridge (1873), a bowstring arch-truss fabricated by the Wroght Iron Bridge Company of Canton, Ohio, was braced, lifted from its abutments, placed on a wheeled under carriage, and driven to a new location over the Olentangy River near Caledonia, Ohio - an unusual, but simple alternative to demolition.

NOTES

[1] HAER was established in 1969 by the National Park Service, the Library of Congress, and the American Society of Civil Engineers to compile a graphic and written archive of historic industrial and engineering sites in the United States.

[2] The National Register is the official list of historic properties of state, local and national significance considered worthy of preservation maintained by the Secretary of the Interior.

[3] Chamberlin, William P., Criteria for Decisions Involving Historic Bridges. Scheduled for publication later this year by the Transportation Research Board as part of the National Cooperative Highway Research Program Synthesis series.

[4] Newlon, H. H. Jr. A Proposal for Initiating Research on History of Road and Bridge Building Technology in Virginia. Virginia Highway and Transportation Research Council, VHRC 72-P2, Charlottesville, 1972.

[5] Section 4(f) Statements emanate from the Department of Transportation Act of 1966 which states in part that the Secretary of Transportation shall not approve any program or project which requires the use of... any land from a historic site...unless (1) there is no feasible and prudent alternative...and (2) such program includes all possible planning to minimize harm...

[6] The TRB subcommittee on Historic & Archeologic Considerations in Transportation Planning was formed in 1977 to address the conflict between Transportation improvements and historic preservation. TRB is a program of the National Academy of Sciences, National Research Council.

Designing Service Life Into a Bridge

Prise en considération de la durée de service d'un pont, lors du projet

Die Erhöhung der Lebensdauer von Brücken als Aufgabe der Projektierung

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SUMMARY
In the past, bridge engineers have attempted to develop designs with durable materials that require minimum maintenance but, with few exceptions, little effort has been made to record their results. This paper presents several ideas for designs which extend service life and suggests that the National Bridge Inventory and Inspection Program required in the United States could be used as a valuable learning tool for improvement of bridge designs.

RESUME
Les ingénieurs ont de tous temps essayé de réaliser des ponts avec des matériaux durables et d'un entretien minimum. Rares sont cependant les cas où le comportement réel a été mesuré et protocolé. L'article présente plusieurs idées devant permettre de prolonger la durée de service des ponts. Le Programme national d'inventaire et d'inspection des ponts, appliqué aux Etats-Unis, offre un instrument qui devrait contribuer à l'amélioration des projets de ponts.

ZUSAMMENFASSUNG
Seit jeher haben die Ingenieure versucht, Brückenprojekte aus beständigem Material und mit minimaler Unterhaltspflicht zu realisieren. Trotzdem sind die Fälle selten, wo das wirkliche Verhalten gemessen und protokolliert wurde. Der Artikel gibt mehrere Ratschläge für eine verlängerte Lebensdauer von Brücken. Das in den USA angewandte Brückenbestands- und Inspektionsprogramm bietet ein Dokument an, das zur Verbesserung der Brückenprojekte beiträgt.

1. INTRODUCTION

The service life of a bridge can be defined as that period of time over which a bridge can serve a useful purpose without excessive maintenance. Engineers would prefer the ideal condition of always building a bridge on a rock foundation, using materials that will last forever, and strong enough to withstand any natural force. The real life situation, however, is usually far less than ideal. Limited funding, availability of materials, mediocre workmanship, marginal designs and lack of or poor maintenance leave much to be desired. All of these shortcomings put severe limitations on what we can expect for the service life of a bridge.

It is not a general practice to plan obsolescence for a bridge. Usually a bridge is designed and built to accommodate a vehicular traffic demand and some expected flood conditions. It is then kept in service as long as possible because of the lack of replacement funds. The present long list of deficient bridges in the United States attest to the fact that we are losing ground on any well intentioned plans of maintaining our bridges to make them last forever. Improvements on present design practice to extend service life should be the single greatest present day challenge to bridge engineers.

2. INSPECTION PROGRAM

The nationwide bridge inspection program here in the United States is relatively new. It was started in the early 1970's and has served its initial purpose in locating deficiencies and prioritizing bridge replacement needs. Inspection teams were quickly assembled and after minor training were given inspection assignments. Professional expertise and reporting procedures were not consistent or uniform. Although the Federal Highway Administration has developed inspection training programs, a key area of concern today is the training and experience of the inspectors.

2.1 Lessons from the inspection program

This on-going bridge inventory and inspection program offers, however, a base for study of deficiencies and needed changes. Most bridge inspection reports give data on present structural conditions, safety features, and recommendations for needed maintenance, rehabilitation or replacement. With the help of a computer these reports can single out the magnitude of a problem. For instance, it was generally known that bridge decks were deteriorating at a rapid rate, but data from the inspection program told us the size and extent of this deficiency. An analysis of inspection data and existing designs can direct us to needed changes, not only in design, but also in inspection records and remedial action to be taken.

The State of Alaska assigns its design staff to inspection teams, which gives designers a chance to "see their designs in action" and hopefully improve the inspection effort, as well as correct design deficiencies. It is generally agreed that inspection data must be taken and recorded by knowledgeable individuals or its worth is questionable. Many believe that more professional engineers should be used for inspection. Our brief experience with the program tells us it can give good feed-back data for improving design and construction practices, as well as giving guidance for managing a maintenance program.

3. DESIGN FEATURES FOR EXTENDING BRIDGE LIFE

Our objective here is to discuss ways of designing service life into our bridges. In the past our experience, and oftentimes our intuition, has helped us to make decisions to "save our bridge," by using the right design, materials, or protection. Often bridge performance history has been of great assistance. To better illustrate this point, let us discuss several specific design features or considerations that could extend the life of a bridge.

3.1 Design for natural disasters

We have made progress by reacting to catastrophic failures. Bridge failures caused by floods, earthquakes and wind, have brought about changes, both in design specifications and the requirement of model performance testing.

Because of the concentration of many earthquakes in California, the State has been a leader in rewriting seismic design specifications, as well as retofitting existing bridges to withstand future occurrences. Bridge failures due to flooding, on the other hand, have not received as much attention, primarily because of the scattered nature of occurrences in time and location. Probably more bridges are destroyed by floods than any other single cause, but how many are destroyed annually is unknown. Analysis of bridge failures and historical flood data could give valuable guidance on providing protection to existing bridges, as well as some direction in future decisions. Information on how bridges fail during floods can give us important data for the design to resist pier scour, uplift, and drag forces.

In the past, some bridges destroyed by floods, wind, or earthquake have been replaced without learning from the failure. Today we are trying to study our failures and use these unfortunate occurrences to improve our designs. The replacement of the Tacoma Narrows Bridge and the new Hood Canal Bridge are good examples of using failures for extensive studies to improve the replacement structure.

3.2 Consider man-made disasters

Nature can wreak havoc to improperly designed bridges, but modern day traffic can also present hazards to bridge structures. Gasoline tanker trucks have burned under a structure causing its superstructure to sag and fail. Out-of-control heavy trucks have demolished vertical columns, and oversized loads have crushed structural members, both resulting in loss of service of a bridge.

Design planning for proper clearances and protection of vulnerable parts from the impact of errant vehicles are essential for the safety of a bridge structure, as well as the public using it.

Fortunately this type of disaster happens infrequently. However, a judiciously placed barrier or additional vertical clearance may reduce the chance of these occurrences without much additional cost.

3.3 Avoid obsolescence

Predicting future traffic needs is sometimes difficult, especially in developing areas. Selecting a bridge type that can be widened easily to provide for additional capacity may avoid complete bridge replacement. Many through truss bridges in good service condition are obsolete because of narrow roadways, which cannot be easily widened.

3.4 Plan for future rehabilitation

Long life for concrete bridge decks has not yet been proven. Protective measures have been researched and applied in the field and will offer an excellent data base for incorporation into the inspection program. As the years of experience accumulate on these systems, analyses of performance could be very informative. However, today many bridge engineers feel that after providing a deck protective system, the design of the bridge should allow the deck to be removed and replaced.

Conventional girder bridges usually allow the deck to be removed and replaced. But one area of concern is the future problem of deck reconstruction on segmental prestressed concrete box bridges. In this type of construction, the roadway deck is an integral part of the load-carrying superstructure, which cannot be conveniently removed during replacement. Some designers have suggested that extra tendon ducts be installed for future use if additional prestressing is needed while replacing the deck. Another viable solution for new bridges of this type is to add a secondary deck on an impervious membrane to prevent chloride penetration into the top flange of the main superstructure. This deck can be monitored and replaced when necessary, but without supporting or destroying the main superstructure. Initial studies indicate the cost of this secondary deck to be in the order of 5 percent of the capital investment. The benefit/cost ratio for such a system can be very high indeed for this type of bridge.

3.5 Adequate maintenance

Much bridge deterioration and attendant reduction in service life are due to poor maintenance. Commonly, bridge maintenance is performed only when an emergency occurs. This lack of maintenance is caused by several reasons: (1) insufficient or marginal funding, (2) lack of trained personnel and (3) designs too difficult to inspect or maintain.

Timely repairs cannot be made if troubled areas are not found or reported. Often such repairs will not be made if they are too complicated and expensive. Hence, it is important to design for ease of inspection and simplicity of maintenance and repair.

Other than lack of periodic painting of steel bridges, drainage and debris cause most problems in structural deterioration and traffic hazards. Salt water from clogged or broken drains and leaking expansion joints falls onto underlying supports causing discolorization and spalling of concrete and corrosion of supporting hardware. Minimizing the use of drains and providing adequate clean-out access of pipes and leak-proof expansion joints will make maintenance easier and help to extend service life.

To reduce the maintenance cost of painting, weathering steel has been used in recent years, but its performance has now been questioned. Apparently, it may not develop its proper "patina" when subjected to salt water, salt air or salt spray, and thus it could revert to the ordinary corrosion process. In the proper environment it should provide a long service life, but field studies on its performance are in progress.

3.6 Select appropriate bridge type

Maintenance and operation costs should be considered when selecting a bridge type. Some bridges have unusually high maintenance and operational costs. Movable highway bridges, constructed primarily to reduce profile grade and provide increased navigational clearances for water traffic are good examples of high costs, both to construct and maintain. A bridge of this type should be selected only as a last resort. Through trusses are vulnerable to oversized loads and constant maintenance is required to straighten and replace members.

Material selection is often related to or determines bridge types. The availability, cost and durability of a structural material must be considered with the environmental conditions at the location. Coastal regions, in particular, require increased maintenance for steel bridges and careful design precautions for concrete construction.

3.7 Minimize catastrophic failures

One of the primary reasons for establishing the National Bridge Inspection Program in the United States was to reduce the chance of another catastrophic bridge failure as experienced with the West Virginia Silver Bridge in 1967. Periodic inspection of critical load carrying elements of a bridge is believed essential for bridge safety, long service life, and to avoid a catastrophic collapse.

Steel fractures have closed at least three steel tied-arch bridges recently and several others are being watched closely for the appearance of cracks. This type of bridge generally possesses a non-redundant tie which is fracture critical; i.e., if it fractures completely the bridge will likely collapse. Fortunately, in the problem cases, only partial fractures have occurred before discovery and remedial action was taken.

Confidence in analysis, materials, and workmanship are commendable attributes, but practices that give repeated trouble should be changed. Designing bridges with fracture critical members should be severely scrutinized as to the savings realized and the margin of safety provided. In the tied-arch case, it is suggested that the use of stressed cables, as used in prestressed concrete, offers a viable alternate. Such cables, in combination with plate steel, would make the arch tie more redundant, thus helping to avoid complete collapse of a bridge.

When fracture critical members are present in a bridge structure to be inspected, special instructions and highly qualified personnel are needed. The seriousness and importance of this inspection cannot be overemphasized, and the reporting of any unusual findings is essential. Beyond the emphasis given to the finding of and reporting a deficiency, a great responsibility rests on supervisors to see that quick action is taken or failure may occur causing loss of life.

3.8 Minimize local failures

Cracking of a local area from either fatigue or brittleness usually does not gain the spectacular attention of a major failure. Nonetheless, these cracks are serious and reduce the service life of the bridge, if not repaired. Recent research has proposed a better understanding of these phenomena and suggests methods of avoid future problems.

Fatigue cracking usually results from a poor design detail or from a fabrication flaw. Both sometimes occur at the same point. Cracking is a function of the stress range and joint configuration, both of which can be controlled by the designer. Flaws serious enough to cause trouble must be controlled by a quality assurance program and detected by proper inspection during the fabrication and erection of the structure.

Similarily, brittle cracking is now understood to be a function of material toughness, temperature, and the stress intensity at a flaw. By specifying toughness for the lowest operational temperature at the bridge site, and relying on a good quality assurance and inspection program, the incidence of brittle fracture can be greatly reduced.

4. CONCLUSIONS

Providing long service life for our bridges requires following proven principles of design, fabrication and inspection. Selecting the appropriate type, keeping the details simple, and being aware of the unusual happening that can occur are important considerations. An adequate maintenance program properly funded will help perpetuate the quality built into the structure. And finally, to further emphasize the objective of this presenation a comprehensive and continuing inspection program will provide useful information for maintenance repairs and also serve as a learning tool to provide the necessary feedback to develop and improve our bridge technology of the future.

5. REFERENCES

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Symposium on Civil Engineering Structure Management Brussels – Paris, 1981 and An Example of an Ancient Bridge Rehabilitation

Colloque sur la gestion des ouvrages d'art Bruxelles – Paris, 1981
et Un exemple de rénovation d'un pont ancien

Kolloquium über die Verwaltung von Bauwerken Brüssel – Paris, 1981
und Ein Sanierungsbeispiel einer antiken Brücke

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SUMMARY
This article first presents a summary of the Symposium in Brussels and Paris, which took place on April 13 – 17, 1981 and was dedicated to the civil engineering structure management. It further presents an example of a rehabilitation of a bridge from the 18th century, the Wilson bridge, in Tours.

RESUME
Cet article donne d'abord une synthèse du colloque de Bruxelles et Paris, qui a eu lieu du 13 au 17 avril 1981, et était consacré à la gestion des ouvrages d'art. Il donne ensuite un exemple de réhabilitation d'un pont du 18ème siècle, le pont Wilson à Tours.

ZUSAMMENFASSUNG
Dieser Artikel enthält zuerst eine Übersicht über das Kolloquium in Brüssel und Paris, das vom 13. bis 17. April 1981 stattfand und der Verwaltung von Bauwerken gewidmet war. Anschliessend wird ein Sanierungsbeispiel einer Brücke aus dem 18. Jahrhundert, der Wilson Brücke in Tours gegeben.

The subject of this symposium was the management of civil engineering structures. It was intended to make the searchers and builders of several countries acquainted with the experiments and results in this field, of the utmost actuality, and to enable them to draw comparisons and conclusions.

Even though the problems may not be identical in the various countries where the need for more thorough and extensive knowledge is felt, they are similar enough. Such a growing internationalism of requirements and techniques should therefore be met by a corresponding development of the international cooperation in this field.

The international character of the organization of the French-Belgian symposium was very marked, since six countries besides France & Belgium were represented : Germany, U.S.A., United Kingdom, Italy, Holland and West Germany,

- either in the Program Committee, entrusted with the definition of the general organization of the symposium and the control of the technical level of the contributions and sessions,
- or in the functions of session chairmen or secretaries.

The symposium consisted in two parts :

- technical visits in Belgium, distributed over two days,
- the symposium proper, the conclusions of which are the subject of this paper, held in Paris for three days.

The organization of Washington symposium emphasizes the great interest of such international exchanges.

INTEREST OF THE SUBJECT – GENERAL RESULTS OF THE SYMPOSIUM

Numerous investigations and researches about the control, maintenance, repair and reinforcement of bridges have been carried out in several countries. The development of these works can be explained both by the high number of such structures, which, moreover, are key points in road networks, and by the evolution of technical, economic and political conditions.

The capital of civil engineering structures of our world is huge because they are a very ancient product of human intelligence. They are therefore invaluable, both as economical assets and as historical and cultural marks. Besides, the effectiveness of communications and exchanges, hence the economy of any country, depend to a large extent on the safety and quality of these structures, and heavy political or economic consequences may result from their being damaged or out of service.

The evolution of general conditions appears mainly :

- technically, in the ever increasing aggressiveness of loads and actions, and in the relatively rapid evolution of technology ;
- economically, in the restriction of investments, leading per force to some optimization of management ;
- politically, in an increased users' need for safety, leading to a definition of a balance of the accepted hazards and the efforts necessary for their limitation.

The wide extent and interest of this subject was demonstrated by the very high number of contributions from 20 different countries, which exceeded 110.

Though the major part of the contributions (90, out of which 50 were French) came from 10 countries of Western Europe, interesting contributions from North and East Europe, North America, South America, Africa, Asia and Oceania were presented.

More than 320 attendants, from 30 foreign countries, some of them very far, came from the whole world. The presence of over 200 foreigners clearly shows that the proposed themes actually correspond to present preoccupations of the persons in charge with the execution and management of the structures.

Six themes were studied :

- Safety and bearing capacity of structures.
- Checking and auscultation.
- Pathology and strengthening.
- Special techniques.
- Design and management.
- Management policy : present conditions and prospects.

Thus it is not only the various technical aspects but also the political aspect of the management of structures which have been dealt with, with the problems of organization and means, and the interaction with design, which emphasized the general character of the proposed subjects.

MAIN CONCLUSIONS

The technical conclusions drawn by the chairmen for the above six subjects have been published in the symposium report, third book.

The main general conclusions developed hereinafter stress some important notions which step out of the numerous results of the symposium and are fundamental for the attitude and general policy. They regard :

- the improvement of knowledge,
- the need to foresee and prevent events,
- the organization principles of a policy of maintenance.

The need of knowledge and the duty of information.

To assess the condition of a structure is not an easy task, as this condition is forever evolving along with the wear of materials and structures and the evolution of loads. As a whole, the behaviour of a structure is a complex phenomenon, but the evaluation of its safety is one of the main targets of the Engineer's action. Our ignorance is still very great in this field, hence the high interest of new techniques, notably auscultation (and specially the development of non-destructive procedures), and of thorough studies of the principles and methods of assessment of the bearing capacity of existing structures, which must take into account both the actual behaviour of the structure and economic restraints.

Likewise, information must be spred in order to prevent difficulties met too often by managers. This need must be emphasized the more as it has often been underrated.

It has two aspects :

- regarding structures, the necessity of constituting proper engineering structures files, and uppermost of adequate management of the constitution and development of files and data banks ;
- regarding structure behaviour. The wide field of existing structures is an invaluable field of in-situ experience. While acknowledging the difficulty of using such experience with a sufficient scientific spirit, we must not forget that there lies a source of improvement of our knowledge, which is at the root of any management rationalization process and technical progress.

Forecasting and preventing.

It is generally assumed that a structure must have a long lifetime, while retaining relatively constant, sufficient service conditions to ensure the intended safety. In this field, errors and inadequacy are highly expensive.

Besides, a good management policy is a whole, starting at design level and proceeding throughout the structure lifetime. As numerous decisions must be made during that period, which imply choices the consequences of which are felt both immediately and in the future, the questions should forecast these consequences in order to get some optimization of the costs.

Prevention must be present at all stages :

– Design : this notion was dealt with in a specific theme, with much information on the steps to be taken or advocated in a project, as they are most effective when taken at that stage.
– Control : one of its main objects being to make it possible to carry out, in due time, the most adequate utilization and maintenance measures.
– Maintenance : it must be mostly preventive, as it is regular, scheduled maintenance only which enables to tend to economic optimization, by reducing technical hazards, improvised works and service breaks.

Organization – Financial requirements.

Several interesting notions were evoked in the discussions about management policy, many of which were general enough to be usable within the different frames of the organization structures of the various countries.

As regards organization, the basic notion is the uniqueness of the manager's responsibility. The manager of a road network should be held responsible for the structures of such a network. He must not leave technical specialists to deal with the choice of the applied methodology, the technical criteria for decision, the schedule of systematical rehabilitation of the structures, etc. Besides, it is important for a good understanding of all, and for a clear application of decisions, that a common language should be devised.

As regards the ever insufficient financial means, their limitation leads to an ever-increasing need of as effective and as rational a management as can be.

The problem of men has been stressed. In this field where technical progress cannot substitute the Engineer's craft, or the technicians' qualities, the adequacy of men is essential. This adequacy may result from specialization or from experience, but it is usually rare enough to call for an important effort, to develop a policy based on personnel stability and on training and teaching actions at every level, and intended to retain and promote competence.

Research

The present effort for studies and researches, regarding both theories and methodology, and techniques proper, clearly appeared in the symposium. This already important effort must be developed, and the following is to be noted :

– One should not hesitate, when dealing with ancient bridges restoration, to apply the most modern procedures, and techniques, as is already done with data processing, radioactive analysers, synthetic materials, etc...
– Generally, quality must be the major goal. Almost often, a compromise must be found between safety and quality requirements, and economic restraints. But in this compromise, technical progress is the tool to be used to meet economic requirements.
– The extent of this subject calls for international cooperation regarding researches and the works to be performed. The road is opened by O.C.D.E. works, A.I.P.C. actions, and the various symposiums, among which BRUSSELS-PARIS and WASHINGTON'S.

CONCLUSION

Through its various contributions and discussions, this symposium promoted a new advance in every aspect of the management of the structure capital : knowledge of structure behaviour, requirements and techniques to be applied in this difficult craft, necessary policy.

It was doubtless useful to all attendants, as each of them could benefit by the contact of the others and their experience, and the importance of the symposium's subject for the Engineer. Structure management is a field in which the Engineer's craft must apply, responsibilities must face a complex reality and difficult technical problems, and it must be kept in mind that the decisions can have very important economic and political consequences.

Finally, the symposium was successful in permitting information and experience exchanges, and in showing the need for further cooperation in this field.

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AN EXEMPLE OF AN ANCIENT BRIDGE REHABILITATION : TOURS BRIDGE

Tours' bridge was built in the 18th century, from 1765 to 1777, by Bayeux Sr., Ingénieur Général des Ponts et Chaussées, with the assistance of Vallée Sr., Bugey, de Voglie, Cadet de Limay and Vallée Jr.

This structure crosses the river Loire over 436,60 m from one abutment to the other. It includes 15 ellipse-shaped arches spanning about 24,50 m, with a span-to-rise ratio of three. It was thought, when completed, the most beautiful bridge in the world, and was currently considered as one of the major four bridges in France by the end of the 19th century.

The 14 piers rested on a series of vertical wood piles, hammer-driven through sand deposits down to limestone. Some foundations have been protected, ever since the bridge's construction, by adjoining wood piles, originally a cofferdam during construction.

The history of this bridge has been very eventful. Even before completion, the 8th pier suddenly sunk down, and had to be built over, together with both neighbouring arches. Sand removal between the piles which led to instability under the action of transverse loads, accounted for this collapse. Jean-Rodolphe Perronet, « Premier Ingénieur du Roi », then advocated building protections made of adjoining wood piles blocked by riprap around piers 8 to 12. Thus the only piers left unprotected were piers 2 to 6, which had been built on the old St Jacques island, but at that time the flow was running along the right bank.

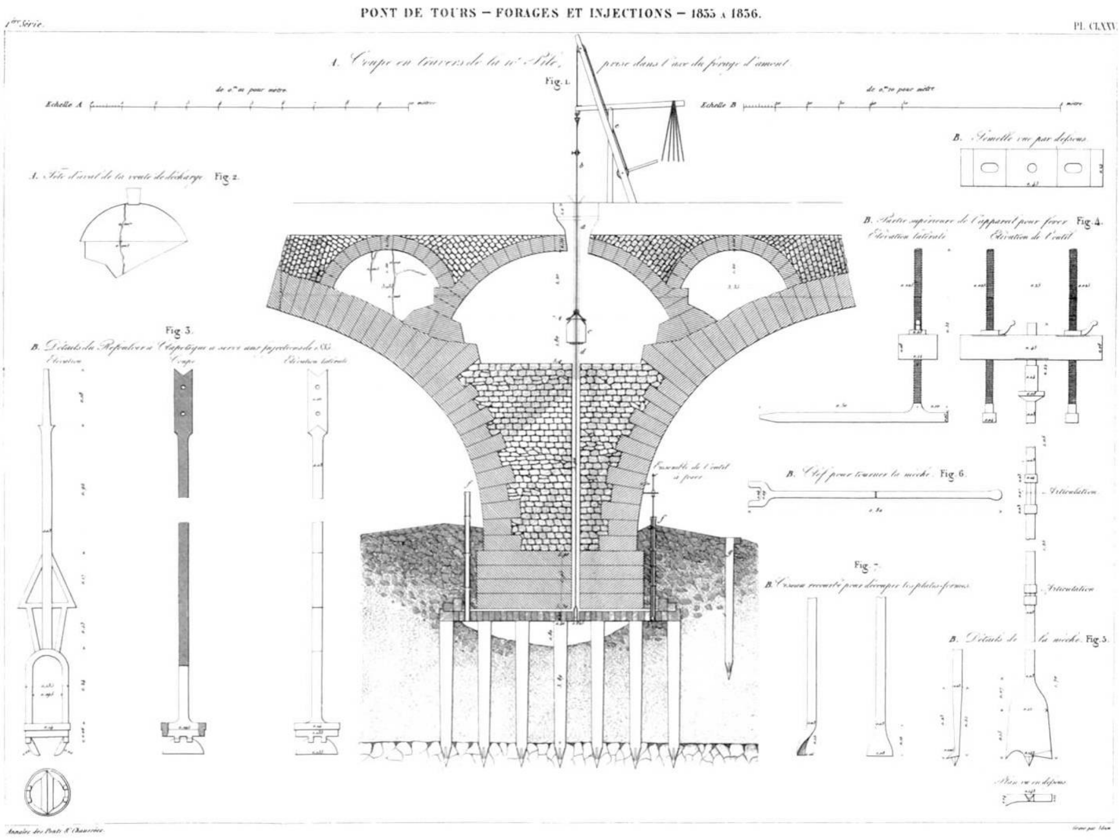


Fig. 1 : 1835 – Lime injections.
(drawing, in Annales des Ponts et Chaussées of that time).

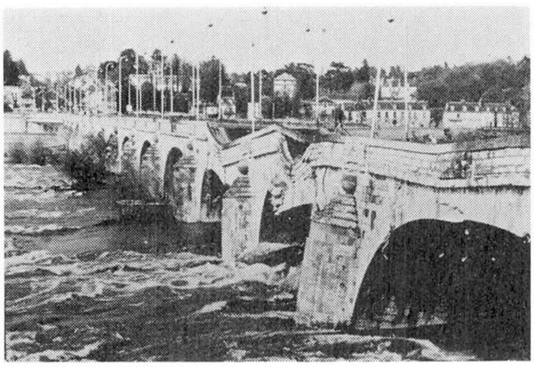
The collapse of the piers 12 to 14 and corresponding arches, on the 1789 river thaw, was also close to the right bank. Reconstruction works, slackened by the French Revolution, were completed in 1810 only.

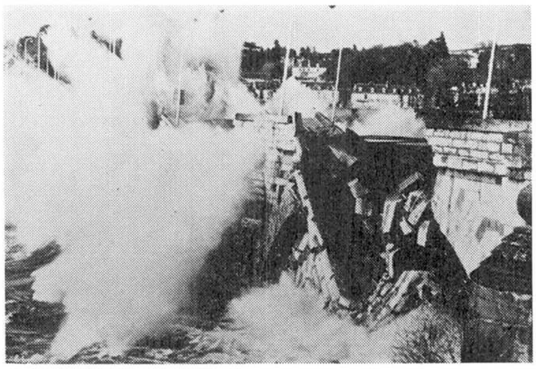
In 1835, piles 9 and 10 sunk noticeably, and disorders appeared in the masonry of arches 9, 10 and 11. Lime was injected to fill up cavities under the foundations of piers 9, 10 and 11.

In 1978, during borings performed to assess the condition of the foundations, elements of this history (pieces of the ancient wood plaftorms, masonry of the beds of the collapsed piers, lime injections ...) were found to confirm the information in the file records, even the measures mentioned in 18th and 19th century reports.

Finally, the bridge, called « Wilson bridge » between the two world wars, was injured by the second one. The French army destroyed the first arch in 1940 in order in hinder the German army's advance. It was reinstated later in the year. In 1944, in turn, the German army destroyed arches 9, 10 and 11, along with piers 9 and 10, to protect its flight. They were built over from 1946 to 1950, using slightly reinforced concrete, and the same ashlars as the original ones, though thinner with a somewhat different pattern, for economic reasons.

Then on April 9th, 1978, at 9.27 a.m., pier 2 sinks and brings down the upstream-faced part of the 2nd arch. At 2.15 p.m., the upstream-faced part of the 3rd arch collapses in turn. At 4.02 p.m., pier 2 sinks by one metre, and arches 2, 3 and 4 crash down. On april 10th, pier 4 sinks downstream, spans 5 and 6 fall and pier 5 tilts down. Finally, on May 3rd, pier 1's collapse induces span 1's fall. Most fortunately, there was no victim.





Photographs 1 & 2 : The collapse of the bridge, on April 9th, 1978, at 4.02 p.m. (Photographs by Pierre Fitou — La Nouvelle République)

The reason for this collapse was, once again, the removal of sand between the piers unprotected by adjoining wood piles, and the resulting transverse-force induced instability.

TEMPORARY STRENGTHENING

First of all, the engineers in charge with restoration works had to protect the part of the bridge still standing.

They had to clear the Loire's bed of all the masonry of the collapsed arches and piers, to prevent a shift of the flow which could endanger the remaining piers.

Much of the removed materials were used as a supporting shell built against pier 6, to enable it to resist the thrust of the 7th arch, left unbalanced after the fall of the 6th arch. However, as the thrust of an arch may range from 2,000 to 2,700 metric tons, depending on calculations and mainly on the masonry condition, this was not thought sufficient.

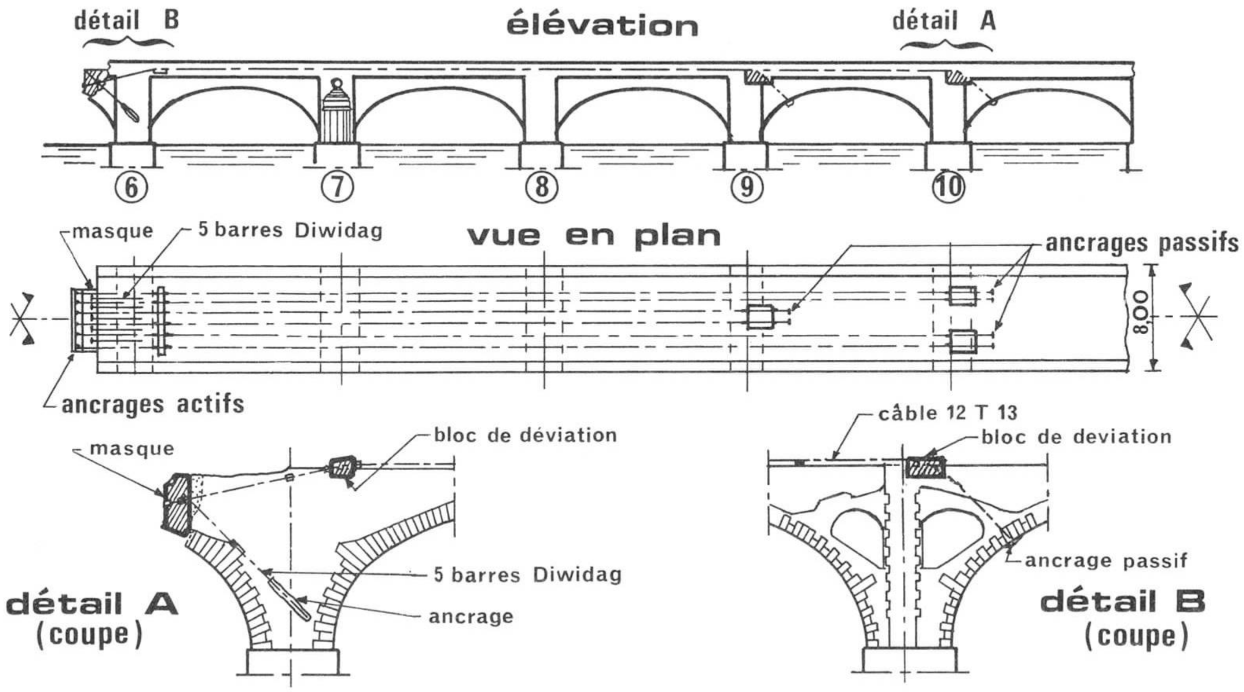
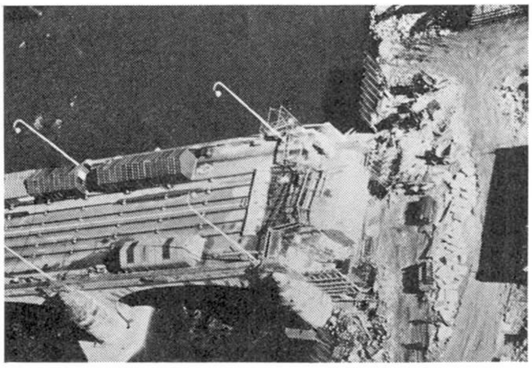
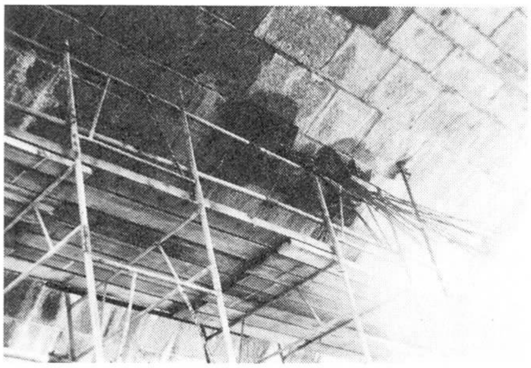


Fig. 2 : Pier 6 : temporary prestressing.

Six prestressing tendons, made of 12 strands of 13 millimeters, Freyssinet type, were therefore tensionned between the 6th and the 11th arches, and anchored in a reinforced concrete block cast against the standing part of the 6th arch, at the one end, and under the 10th and the 11th arches (2 tendons under the 10th, 4 tendons under the 11th) at the other end. They were laid on the deck and shifted down to the anchorages by deviators on either side. They were grouted with grease.



Photograph 3 : Temporary stabilization cables on the deck.



Photograph 4 : Anchorages under the 11th arch.

The stability of the anchor block of span 6 was ensured by a series of 5 embedded Diwidag bars.

This stabilization prestressing device reduced the thrust of the 7th arch by 650 tons approx.

Soil injections had previously been performed under piers 6, 7 and 8, in order to fill the largest cavities and to make the procedure safer.

FINAL STRENGTHENING OF PIERS 6 TO 14

But this did not constitute a lasting strenghtening of the still standing piers 6 to 14.

Since the Loire's bed in the bridge area is embarrassed with wood piles and masonry over some width on either side, the practical solution consisted in building a huge sheet-pile cofferdam, enclosing the remaining 9 piers and the right-bank abutment. The sheet piles (Larssen 3 S) were hammer-driven, throughout the sand, down to 1,50 m into the limestone.

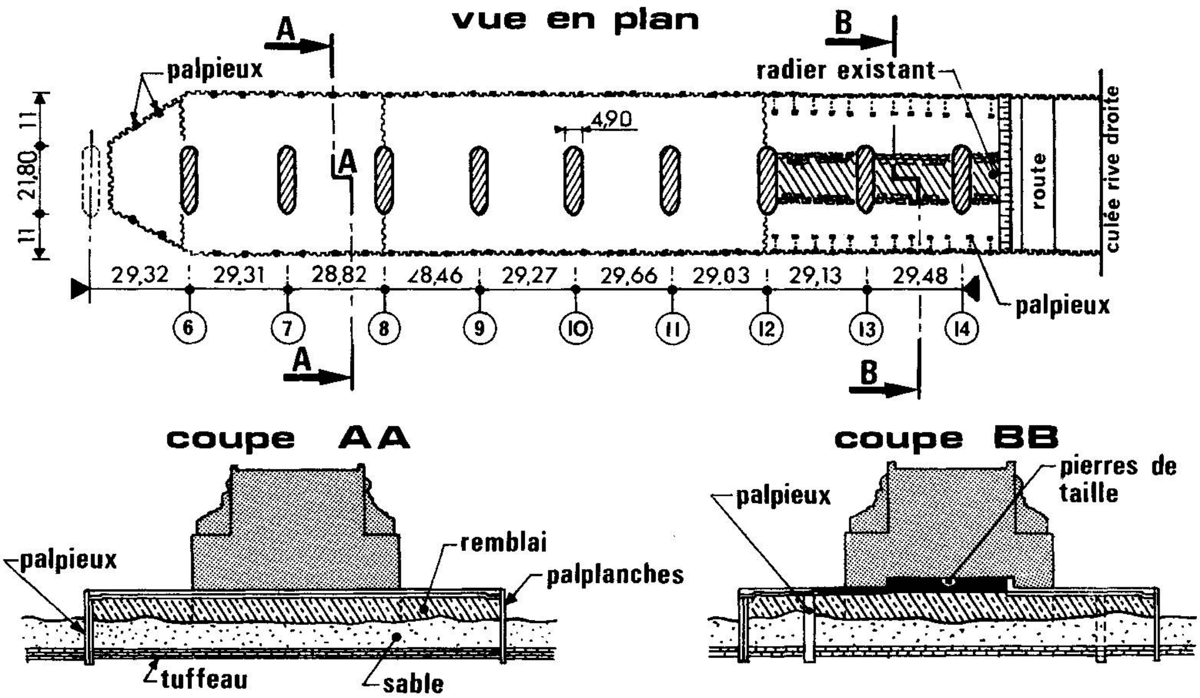


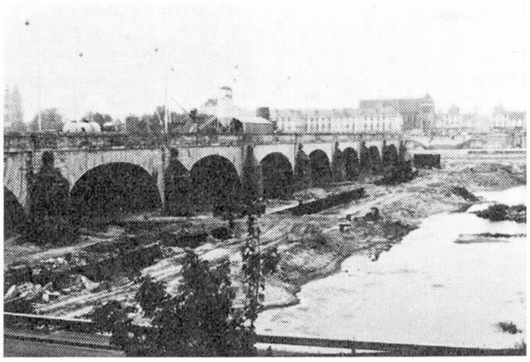
Fig. 3 : Drawing of the general cofferdam ensuring final strengthening of foundations.

An overall reinforced concrete slab, surrounding the piers, over the whole cofferdam, is intended to prevent the sand removal.

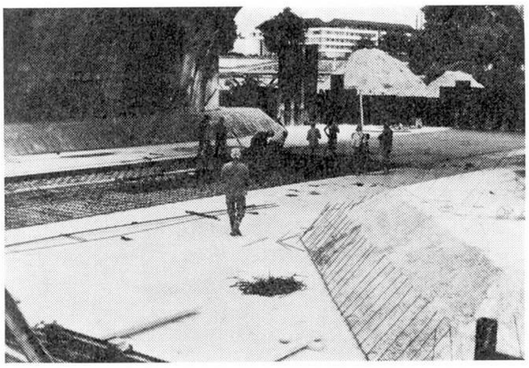
Under arches 6 to 12, the slab behaves as a tie between the upstream and downstream cofferdam walls. Moreover, these walls are stiffened by a pile box in sheet piling, every 6 metres.

Under arches 13 to 15, this solution was unpracticable because of high existing masonry raft. The concrete slab could not pass under the structure and it had to be interrupted. The stability of the sheet piling was ensured by frames, 4 metres apart, consisting of a pile box, included in the sheet pile wall, an 8 – m long tie, and a rear pile box, within the cofferdam.

After completion of this cofferdam, 40 metres wide and almost 300 metres long, and of the top slab, all the cavities under the piers were injected, even the small ones. The volume of injection could be reduced by a primary injection around each pier.



Photograph 5 : General view of cofferdam construction works.



Photograph 6 : Slab casting.

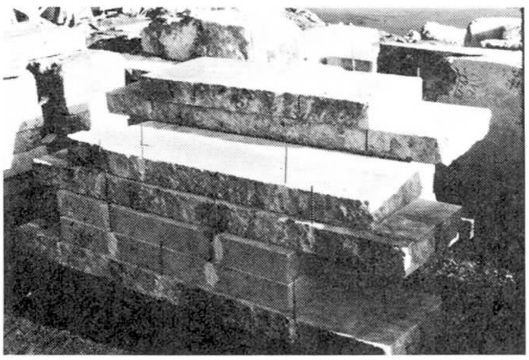
A lowered channel was built up, in order to provide for normal flow on low-water and, theoretically, for navigation.

RECONSTRUCTION OF ARCHES 1 TO 6.

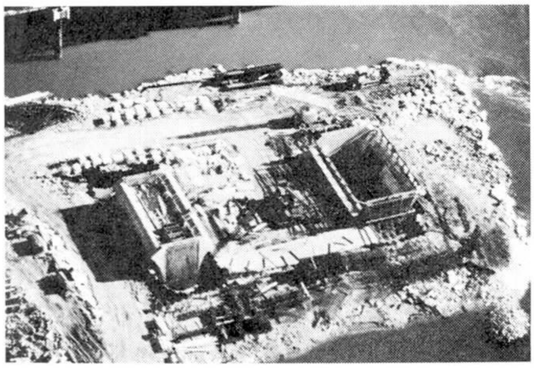
Finally, the collapsed 5 piers and 6 arches were to be reinstated.

It was decided, at the very beginning of the works, to build in reinforced concrete, with a thin stone facing. The concrete was poured direct onto the stone facings, laid on the bottom and sides of the formworks. Small stainless steel connectors, resin-bonded to the stone, provide for the stone facings and concrete adhesion.

The piers were conventionally built within sheet-pile cofferdams, using stone facings thick enough (min. 10 cm) to prevent too quick a flow-induced erosion.



Photograph 7 : Stone facings (from the soffit)



Photograph 8 : Piers 4 and 5 under progress.

For the deck, hinges at the springings of every arch are designed to prevent the important forces resulting from temperature shifts, and from concrete shrinkage and creep, from originating concrete cracking and possibly facing stone breaking.

The arch proper was cast in two steps, to reduce the centre size. The spandrels were built after arch completion.

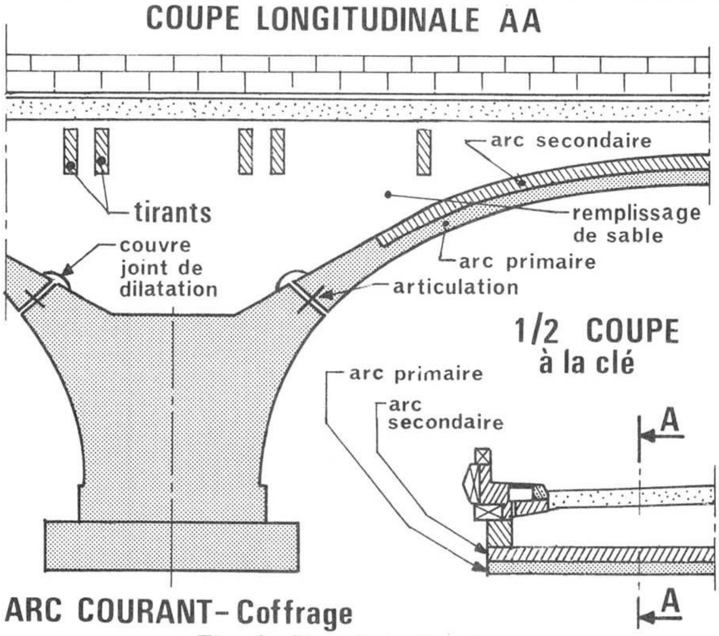
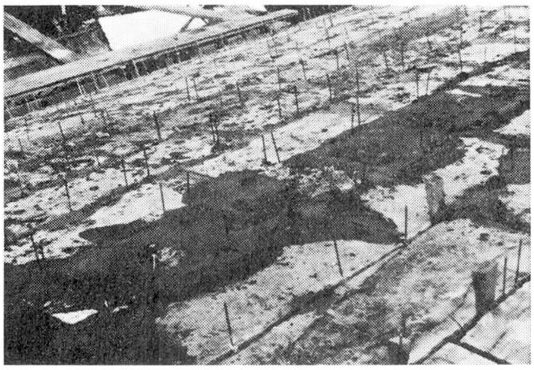
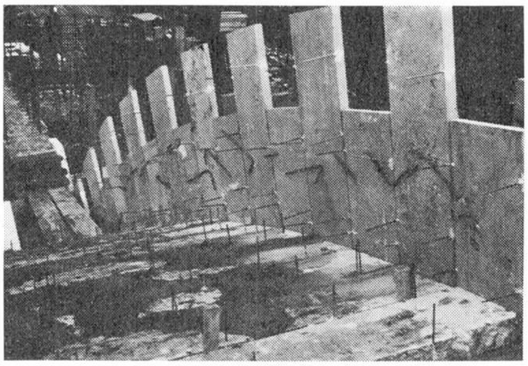


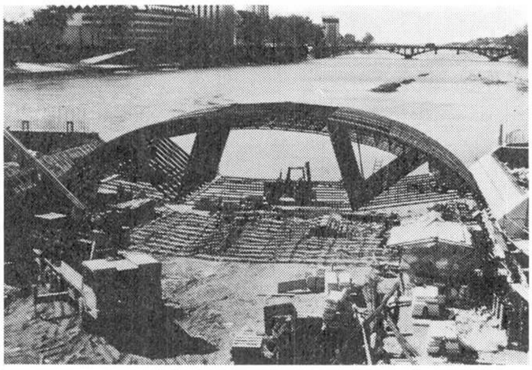
Fig. 4 : Drawing of arches.

Photographs 9 & 10 : Installation of facing stones on the centre.

The center was made of several elementary beams, assembled in sets of 3 beams, resting at the pier tops, right beneath the hinges, on temporary supports, hanging using Diwidag bars. The 3 beam sets could be moved transversally on the supports, then placed over another span, without any need for dismantling.

After deck completion, the arch watertightness was ensured, and sand filling was provided as pavement support.



Photograph 11 : A centre of Tours' bridge.

The main difficulty lied in connecting the older and the new structures.

A huge counterweight block was built close by the abutment to balance the hinge-supporting corbel, the hinge being placed at the arch haunch due to the deck widening. As for the widenings on either side of this counterweight block, they were held in suspension by prestressing tendons, the need for which appeared suddenly when large cracks were found in the masonry of embankment walls.

Nevertheless, the most difficult problem was the connection to pier 6. It was necessary to have the new arch of span 6 supported by the existing pier, but the temporary stability prestressing could not be removed before, and the thrust of the new arch was to substitute to prestressing forces progressively.

The partly destroyed masonry was cleared away. On either side of the anchorage block of the temporary tendons, a supporting block was designed to bear the lateral ends of the new span. When this new span was built, the temporary prestressing was removed, its anchorage block still untouched ; then it was destroyed in turn, any damaged masonry was cleared off, the supporting block was extended to the whole deck width, and span 6, hinged over the supporting block on top of the former masonry, was finally completed.

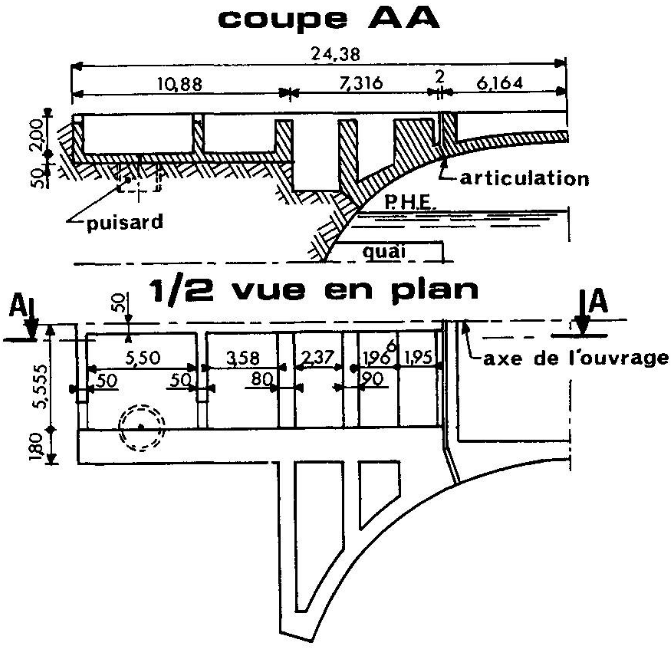


Fig. 5 : Abutment drawing.

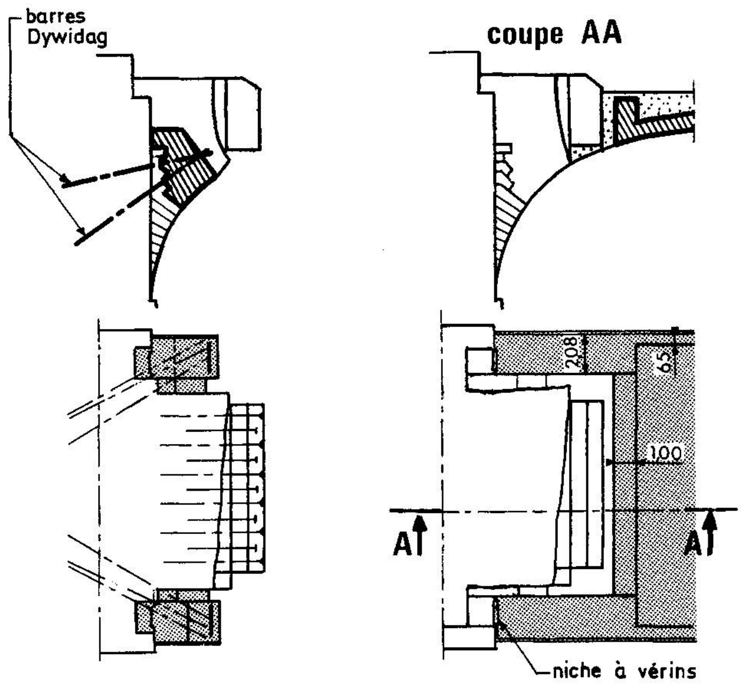
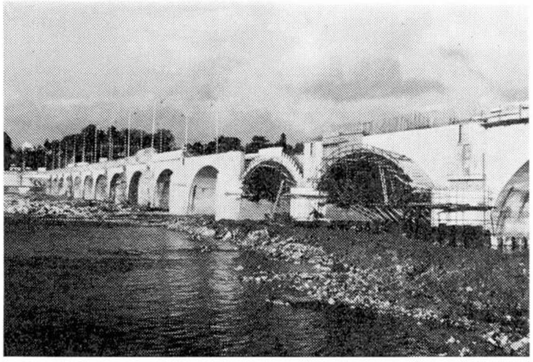


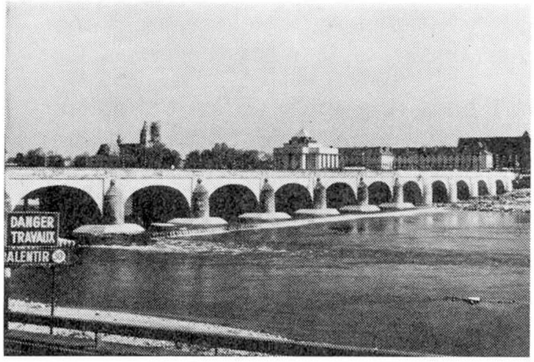
Fig. 6 : Connection to pier 6.

CONCLUSION

Now the reinstatement of Tours' bridge is over.



Photograph 12 : Completion of reinstatement works.



Photograph 13 : The restored bridge in Tours.

The overall cost of this operation, including the construction of two temporary bridges, is over 15 million U.S. $. The restoration of the 6 destroyed arches and the strengthening of the still standing piers, has been almost as expensive as a new bridge would have been.

But one of the most important of the 18th century bridges has been reinstated in its original appearence.

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Nihon Doro Kodan's Bridge Maintenance System

Programme d'entretien de ponts-routes au Japon

Brückeninstandhaltungs-Kontrollsystem in Japan

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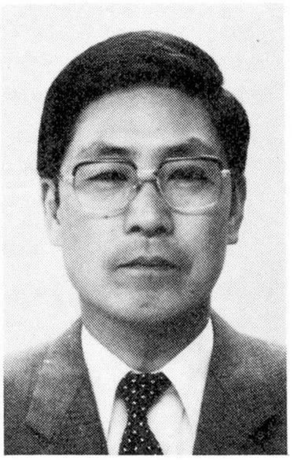

Born in 1935, graduate from Waseda Univ., Faculty of Civil Engineering Civil Engineer for planning design and supervision of Highway Projects at Nihon Doro Kodan for 25 years. Expert on large scale prestressed concrete bridge design and construction.

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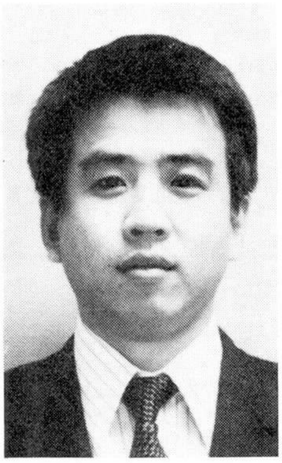

Born in 1951, graduate from Nihon Univ., Faculty of Civil Engineering Participated in the construction and administration of Express Highways for 9 years at Nihon Doro Kodan. Presently engaged in the inspection and repair services of bridges.

SUMMARY
The bridge maintenance system of Nihon Doro Kodan is introduced in this report. The maintenance and repairment works of bridge structures are one of the major maintenance works of the Japan's highway operations. The rating and repairment of damaged bridge decks are also explained as a main part of the above system.

RESUME
Le rapport présente le programme d'entretien des ponts dans le réseau japonais d'autoroutes. Les travaux d'entretien et de réparation des structures de ponts font partie des travaux essentiels pour l'exploitation efficace du réseau autoroutier. L'évaluation et la réparation des tabliers de ponts endommagés font également partie de ce programme.

ZUSAMMENFASSUNG
Der Bericht behandelt das Brückenunterhalt-Programm im japanischen Autobahnnetz. Die Unterhalt- und Instandstellungsarbeiten an Brücken sind ein wichtiger Bestandteil für eine wirksame Nutzung des Autobahnnetzes. Die Schätzung und Instandstellung der beschädigten Brückenbeläge sind in diesem Programm ebenfalls enthalten.

1. PREFACE

Japan has a plan for an Express Highway Network of 7,600 km that covers all the areas of its territories. The construction of this expressway network had been entrusted to a single organization that is Nihon Doro Kodan. At the end of 1982, 3,111 km will be in operation and additional 2,738 km will be under construction. Among the portion which has been opened to traffic, the earthwork section, the tunnel section and the bridge section are 86.0%, 2.2% and 11.8% respectively.

During these 20 years since the expressway was opened the deterioration of the expressway structures has become obvious. Accordingly the cost of maintenance and repairment has reached to about 260 million dollars (84,700 dollar/4 lanes·km) per year. The 11.7% of this total maintenance expenses, which is 30.5 million dollars (87,100 dollars/4 lanes·km), is spent for bridge structures. It is quite remarkable that 30% of the total bridge maintenance cost is allocated for the repairment of reinforced concrete bridge decks which are damaged seriously by the heavy traffic.

It is very important to find out in the earliest stage the signs of the damages in the bridge structures in order to take the necessary measures for the repairment. Nihon Doro Kodan is carrying out the inspection patrols under its "Bridge Maintenance System" which enables "the early findings and lower repairment costs".

2. OUTLINE OF THE BRIDGE MAINTENANCE SYSTEM

2.1 Record plan from the bridge inspection to the repairment

The flow diagram of the maintenance from the bridge inspection to repairment is shown in Fig. 1.

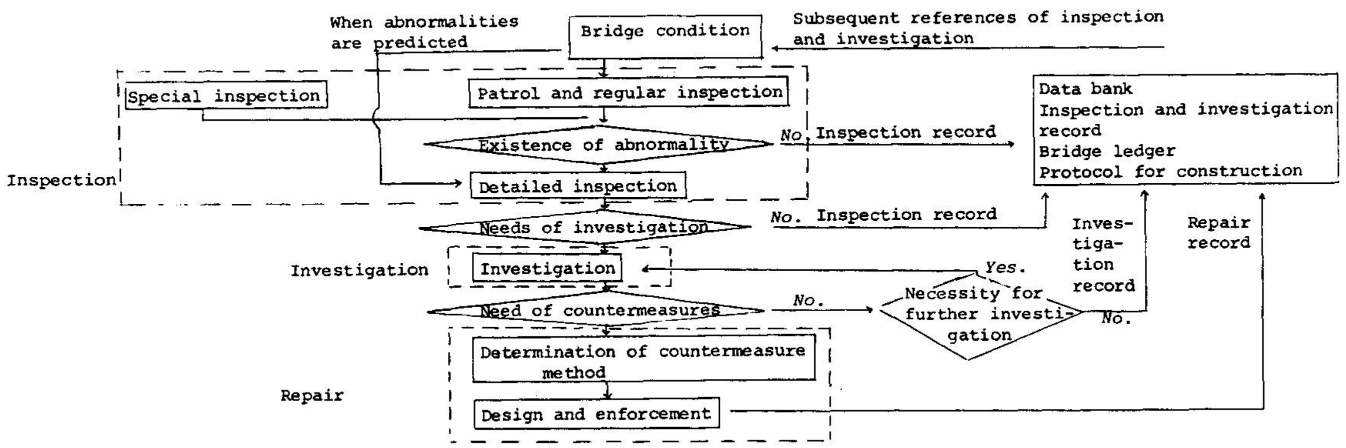

Figure 1. Flow diagram of inspection, investigation and repair works

2.2 Outline of bridge patrol, inspection and investigation

Actual conditions of the bridges are grasped through ordinary patrols, inspections, and investigations. The bridge maintenance works are carried out according to the degrees of its damages. The summary of this maintenance works are shown in Table 1.

2.3 Filing of records

The inspection results are summarized in a report paper; the construction record and the repairment history are written on the bridge ledger and these are put together in a micro film, stored in the data room. A photocopy from the originals are used in the regular administration. Shortly, together with the establishment of the Computer Center, the information transfer network that connects this Kodan's Head Office with the Operation Bureaus and offices will be developed. This network is utilized presently as an Information Control System that handles any kind and all sorts of information input or output, according to various demands.

	Item	Purpose	Method	Frequency	Personnel
1	Patrol	Early detection of abnormalities and damages in the upper surface of the brdige.	By patrol car; walking as occasion demands.	Once a day	2 persons
2	Regular inspection	Early detection of abnormalities and damages in the whole structure.	Approach to the bridge as near as possible while walking and direct visual inspection or using binoculars.	More than once a year	3 to 4 persons
3	Special inspection	Rapid grasp of bridge conditions in case of earthquakes	Walking or by patrol cars	As occasion demands	3 to 4 persons
4	Detailed inspection	Observe in detail the abnormal places detected during the patrol and inspection and decide the needs for an investigation.	Approach the subject place by means of inspection road, ladder, or construction scaffoldings and simple measure by visual inspection.	As occasion demands	3 to 4 persons
5	Investigation	Quantitative grasp of the degree of damages from the detailed inspection results and decide the needs of repairments.	Approach to the subject place by means of special constructed scaffoldings and by visual inspection, stripping off, measure, core testings.	As occasion demands	Required personnel

Table 1. Outline of bridge patrol,inspection and investigation

3. REINFORCED CONCRETE BRIDGE DECK INSPECTIONS

3.1 Regular inspections

Inspections of the bridge decks are carried out approaching as near as possible, by direct visual inspection or using binoculars for the following items; 1) cracks, 2) scaling off, 3) leakage of water and calciums, 4) reinforcement corrosions, 5) concrete construction joints, 6) cracks on the pavement. The inspections are recorded in the "Inspection and Investigation Record" regarding following items; 1) existence and location of cracks, 2) existence and location of damages other than cracks, 3) needs of a detailed inspections.

3.2 Detailed inspections

3.2.1 Purpose of the detailed inspection

The purpose of the detailed inspection is to judge the needs for an investigation, estimating the condition of the bridge deck damages and degradations by visual inspection and a simple measure, in case of detection of damages and degradations during the regular inspection.

3.2.2 Method of detailed inspection

Taking the deck panel (girder span x deck span) as a single unit, observation shall be carried out and recorded regarding the following items in order to estimate damages and degradations.

1) Sketch of main crack locations (cracks bigger than 0.1mm in width)
2) Condition of the production of scale out
3) Leakage of water and calciums
4) Condition of reinforcement corrosions
5) Condition of pavement's linear cracks and hexagonal cracks

3.2.3 Record of detailed inspection

The detailed inspection results are written in the "Inspection and Investigation Record" (Fig. 2) and the main points of the damage and degradation condition are recorded as illustrated in Table 2.

3.2.4 Criteria for damage ratings during the inspection

Based on the detailed inspection results, and using the rating criteria shown in Table 3, the rating of the damages in the inspection are made, taking the deck panel (girder span x deck span) as a single unit.

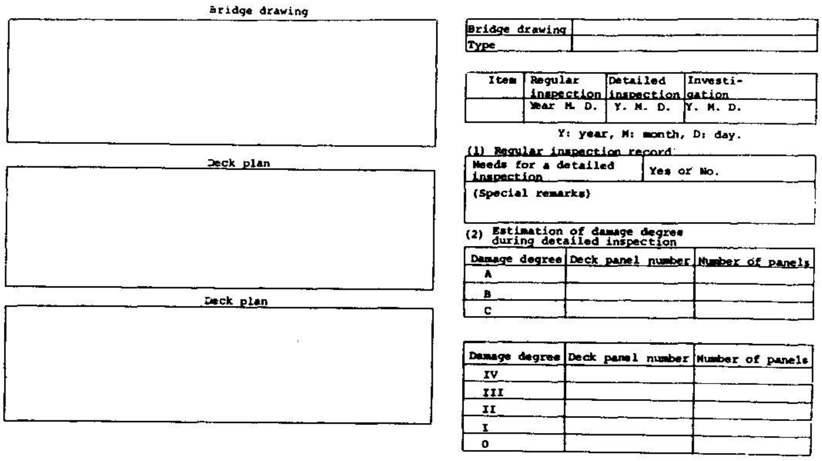

Fig. 2. Inspection and investigation record

Item	Indication method	Item	Indication method
Crack	Continuous lines	Leakage of water	R
Scaling out Abrasion	Continuous lines+dotted line	Calcium Separation	Y
Separation	H	Corrosion of reinforcement with openings	T
Hollows, poor cementations	M	Pavement cracks	one point dotted lines

Table 2. Classification of damages

Degree of damage	Floor system condition
A	Generation of bidirectional or hexagonal cracks. There are cracks in asuface portion of the pavement. Large generation of calcium separation.
B	Generation of unidirectional cracks, the crack spacing is more than 1 m. There are linear cracks in the pavement. Leakage of water and calcium separation found partly.
C	Generation of unidirectional cracks and crack spacing is more than 1 m. It is almost impossible to confirm the cracks.

Table 3. Criterion for estimating the degree of damage during the inspection (cracks larger than 0.1 mm in width)

4. INVESTIGATION OF THE REINFORCED CONCRETE BRIDGE DECK

4.1 Purpose of the investigation

In this detailed inspection, the deck panels estimated to have more than B rank of damage grade during the inspection (hereinafter called investigation panel) are investigated, the cracks are quantitatively comprised, and then the damage grade is estimated, including the conditions of damage and degradation other than cracks.

The procedure for making damage grade rating during the investigation is given below.

1) Confirm the location of main cracks sketched from the inspection results.
2) Determine the location of the places for measuring crack density of parts with remarkable crackings for each investigation panel.
3) Measure of crack density for cracks over 0.1mm in width, by the Grid Density Method.
4) Investigation of the condition of damage and degradation other than cracks, as occasion demands.
5) Rating of damage grade during the investigation.

4.2 Investigation of cracks

1) Draw a grid lines of 25cm in spacing on the decks bottom surface where the cracks are observed. Then from the number of crossing points, resulting from the intersection of the grid lines and cracks wider than 0.1mm, compute the crack density of the bridge's lateral direction (A) and the bridge's longitudinal direction (B). (Grid Density Method) Fig. 3.
2) Plot the crack density diagram as A/B and B/A ratio, and A+B (Fig. 4) for estimating the damage grade.

4.3 Investigation of damage other than cracks

1) Investigate the concrete's neutrality degree of the deck's inner part by using phenolphtalein.
2) Measure the natural period of oscillation and degree of deflection of the deck.
3) Measure the elastic modulus and strength of the concrete core by destructive tests.
4) Measure the crack depth by ultrasonic non-destructive tests.
5) Measure of crack depth by measuring the reinforcement strains.
6) Investigation of the upper surface of decks by removals of the bridge pavement.
7) Investigation of the pavements surfaces.

4.4 Criteria for damage ratings during the investigation

The criteria for damage ratings, as illustrated in Table 4, come from the crack density measured at the investigation.

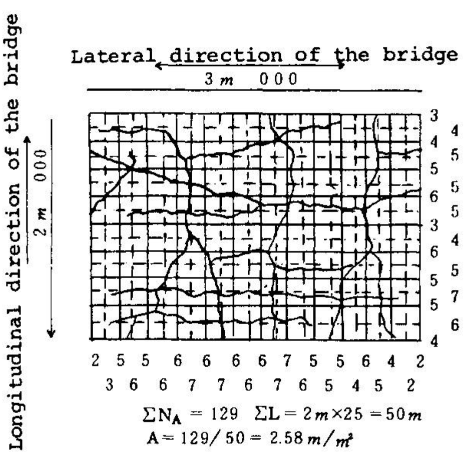

Fig 3. Example of crack density

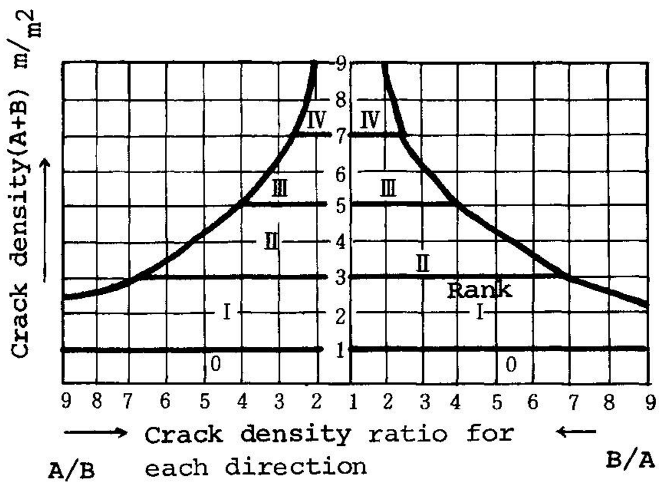

Fig. 4. Crack density diagram (For crack's width larger than 0.1mm)

5. REPAIRMENT PLAN OF REINFORCED CONCRETE BRIDGE DECKS

5.1 Repairment plan

According to the investigation results, the needs for a repairment plan are judged according to the deck damage conditions as follows;

Repairment plan

- Reinforcement: designed for increasing the decks load resistance capacity in order to avoid the crack's progress
- Water proofing: designed for water proofing of the cracked parts in order to avoid the crack's progress, concrete degradation, and reinforcement corrosions due to the penetration of water into the cracks.
- Prevention of concrete scaling out: designed for coating the floor system bottom surface in order to avoid scaling out of the concrete due to cracks.
- Replacement: complete removal of damaged decks and its replacement with new ones.

5.2 Rating of deck damages and repairment methods

The repairment methods of decks are decided from the estimation of damage degrees. It is necessary to select the proper repairment method according to the damage degrees and construction conditions.

The classification of repairment methods, according to the damage degrees is given in Table 5.

Damage of degree	Standard Crack density (m/m^2)	Average spancing (Reduced to bidirectional cracks)	Estimation of deck conditions
0	0 - 1.0 up to	200cm and more	Unidirectional cracks with spacing larger than 1m founded partly. The bidirectional crack density is still small and the load capacity of the deck is considered to be still high.
I	1.0 - 3.0 from to up to	200cm - 70cm	There is generation of unidirectional cracks, but the capacity as unidirectional slab is still expected
II	3.0 - 5.0 from to up to	70cm - 40cm	Generation of bidirectional cracks and the deck capacities decline in both directions. The leakage of water and the calcium separation are occasionally observed.
III	5.0 - 7.0 from to up to	40cm - 30cm	The bidirectional cracks develop with the crack corner's wearing and partly scaling out. The deck capacity drop remarkably in both directions. The leakage of water and the calcium separation become prominent. The cracks in the upper surface of the deck develop to produce concrete blocks.
IV	7.0 from to	30cm and less	The crack density reach the limit in both directions, and the load is supported almost only by the reinforcement grid effect, cracks are widened, and abrasion and calcium separation with muddy water are observed. When they progress, they cause holowing out and large scaling out. The damage of the upper surface of the deck is also progressed, and the pavement starts to peel off in some parts.

Table 4. Criterion for estimating the degree of damage during the investigation (cracks larger than 0.1 mm in width)

O It is advisable to make countermeasures
◎ Problem in need of countermeasures

Degress of damage	Repair plan		Method of construction
I II III IV	Rehabilitation measures		Stringer setting method, steel plate adhesion method, additional concreting method, spraying method, FRP method (concrete decks of steel and concrete bridges)
III IV	Plan to avoid hollowing out		Steel plate ahdesion method, FRP method
IV	Replacement	Replacement of some parts	Resin concrete, super high-early concrete, Reinforced concrete deck.
		Total replacement	Steel deck, steel orthofropic deck
II III IV	Water proof plan		Resin grouting method, water proof sheet method

Table 5. Classification of repair method according to the degree of damages

6. FUTURE SUBJECT

As the bridge deteriorations proceeds with the passage of years, it is necessary to improve above-mentioned "Bridge Maintenance System" furthermore. It is also very important to clarify the bridge's deterioration mechanism through theoretical studies in order to establish the proper repairment methods. Further, the urgent needs are pointed out with regard to the development of automatic equipment for estimating the degree of soundness of the bridge structures and the systematic compilation measures of the inspection and investigation records.

REFERENCE

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Survey of Structures by Using Acoustic Emission Monitoring

Surveillance des ouvrages par détection d'émission acoustique

Überwachung von Bauwerken mit Hilfe von Schallemissionsmessungen

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Jean-Louis Robert was born in 1939 in France. He graduated at INSA (LYON) as an Engineer in 1962. As a Group Head at LCPC, he is now working on investigations about the means for the survey and the control of structure cables.

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Marcelle Brachet-Rolland was born in 1936 in France. After personal investigations on stress corrosion in LCPC, she was the head of the Metal Section then the one of the Concrete and Metal Division. Now, she is a Technical Director at LCPC and in charge of the Civil Engineering Department at the Ministry of Research and Industry.

SUMMARY
The acoustic survey of civil works, based on the monitoring of waves emited when damaging materials, enables us to detect the fractures of elementary wires, internal or external ones, of tensioned cables and the active cracks in concrete. The equipment chain able to be on continuous service during several months were experimented. As the method is operational in the case of suspension and cable-stayed bridges, it still needs supplementary research for the interpretation of the received signals, in the case of prestressed concrete structures.

RESUME
La surveillance acoustique des ouvrages d'art, basée sur la détection des ondes créées par les endommagements des matériaux, permet de déceler les ruptures de fils élémentaires, internes aussi bien qu'externes, des câbles tendus ainsi que les fissures actives du béton. Des chaînes de matériel capables de fonctionner en continu pendant plusieurs mois ont été expérimentées. Si la méthode est opérationnelle dans le cas des ponts suspendus et à haubans, elle nécessite des compléments de recherche pour l'interprétation des signaux reçus dans le cas des ouvrages en béton précontraint.

ZUSAMMENFASSUNG
Die akustische Überwachung von Bauwerken durch die Aufnahme der durch die Werkstoffschädigung hervorgerufenen Schallwellen ermöglicht den Bruch von Einzeldrähten, innerer und äusserer, in gespannten Kabeln sowie die aktiven Risse im Beton festzustellen. Messgeräte, die während mehrerer Monate funktionstüchtig sind, wurden erprobt. Wenn diese Methode bei Hängebrücken und Schrägseilbrücken wirkungsvoll ist, sind für die Analyse der Schallemissionen bei Spannbetonbauwerken noch weitere Untersuchungen notwendig.

INTRODUCTION :

The pressing need of surveying the change of the conservation state of suspension cables in suspension bridges and the lack of non destructive means for detecting the fractures of internal wires of these cables, pecularly in their non free parts, gave us in 1968 the idea of using the waves resulting from the sudden release of the energy bound to the fracture of one wire in a tensioned cable.

The principle of the method, generally called "acoustic survey", lies in the fact that the waves created at the wire fracture propagate at a given velocity, in a given medium, and can be monitored with appropriate sensors at distances which depend on the released energy value and of the wave damping by the crossed media.

1. EXPERIMENTAL AND THEORETICAL INVESTIGATIONS

The investigations were experimental in a first stage and were completed with a theoretical approach.

1.1. Experiments

The experimental method consisted in inducing, at a given point, the individual fracture of internal and external wires in tensioned cables and in recording the produced waves (fig. 1) at various distances of the breaking point, by using accelerometers in order to determine the properties (frequency, amplitude, damping versus distance). In a parallel way, we searched a simple mean for producing similar waves in a cable, so that we could study the propagation conditions in a structure, pecularly the damping due to suspenders and suspender catches.

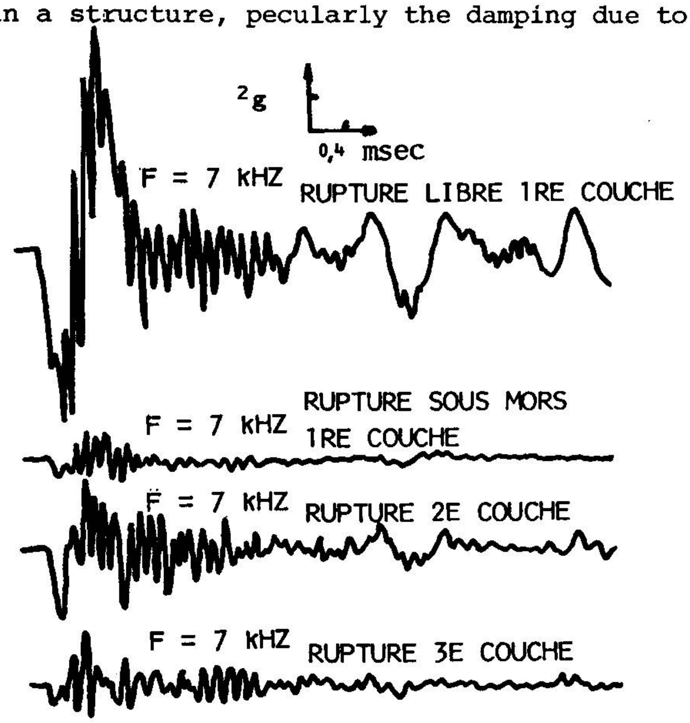


FIGURE N° 1 - Recording of the first wave in various cases of individual wire fracture in a cable, at 21 m far from the breaking point

1.2. Theoretical approach

The general theory of wave propagation in a cylinder [1] results in the POCHHAMER's "frequency equation" rather difficult to be practically used. Thus, an approximate theory was developed for describing the encountered phenomena solely in the practical domain which interested us : the wave length is great as compared to the cable radius. When transverse effects are token into account, it results in the differential equation :

$$c_b^2 \frac{\partial^2 u}{\partial x^2} - \frac{\partial^2 u}{\partial t^2} + \frac{\nu^2 a^2}{2} \frac{\partial^4 u}{\partial x^2 \partial t^2} = 0$$

which gives the propagation velocity :

$$c = \frac{c_b}{\sqrt{1 + \frac{\nu^2 a^2}{2} k^2}}$$

where C_b is the bar velocity $\sqrt{\frac{E}{\rho}}$, ν the POISSON's ratio, a the cable radius and k the wave number.

The experimental verifications are in good agreement with this theory which makes us take a propagation velocity equal to about 4 500 m/s, changing mainly with the frequency (geometrical effect due to the medium) and very little with the cable tension load.

2. EQUIPMENT

Since the first equipment chain made in 1971, which might enable, using sensors distributed along a cable, the propagation velocity and the damping versus distance to be determined, two new generations were designed and experimented on various structures. A particular attention was paid for the reliability of the whole set of the chain components which must be on continuous service on a structure during one year or 6 months, depending on the case. Now, the equipment chain is constituted of :

- a set of sensors connected in a series and fixed on the cable at ranges of 10 to 20 m, depending on the wave clamping proper to each structure. Every sensor has a monitoring element composed of an accelerometer and electronic circuits necessary for the transmission to a box centralizing the carried out measurements ;

- a box centralizing the data and processing, using a microprocessor, the signals given by every sensor (maximum number 100 sensors) and making it possible their recording with a printing machine (local result processing) or on a mini-cassette tape recorder (further study with a computer). The obtained information is as follows :

. date and time (hour) of the recorded event
. signal amplitude
. arrival time of the waves under a sensor. The initial time (zero) is given to the first impressed sensor, and so the propagation velocity can be obtained and the wave origin location be calculated

- at last, the microprocessor in the box makes it also possible to test periodically the right order of the set box-sensors.

3. APPLICATION TO SUSPENSION BRIDGES

3.1. <u>Structure n° 1</u>

It deals with a bridge having a 82 m long span, and having in each bundle four cables (66 mm diameter) continuous from one anchorage to the other one. Only the center span is suspended. After a total failure of the holding cable on the right side upstream, the acoustic survey was settled on the other cables, seeming to be intact, on the right side bank upstream and downstream. No new wire fracture was detected downstream but on the contrary, upstream two fractures for a day were, as a mean value, observed on the three remaining cables, on a length of 23 m and during 15 days (fig. 2), this time deviation was necessary for the immediate settling of a provisional suspension in order to prevent the total failure of the structure.

A destructive examination of the cable n° 4 which was the most damaged, after its removal (4 months later) showed out the presence of 55 broken wires in the controlled area. For 10 fractures, the bright aspect indicates that they were very recent.

3.2. <u>Structure n° 2</u>

For this structure, the situation was less critical and enabled an acoustic survey to be carried out during 6 months before the cables were replaced.

The bridge has a 160 m long span and 4 cables (67 mm diameter) in each bundle, continuous from one anchorage to the other one. In one of the downstream cables, about 20 wire fractures were observed in the second layer, and the acoustic survey was immediately settled on the 4 cables of the downstream bundle, on a length of 60 m which was evaluated to be the most critical for the whole structure.

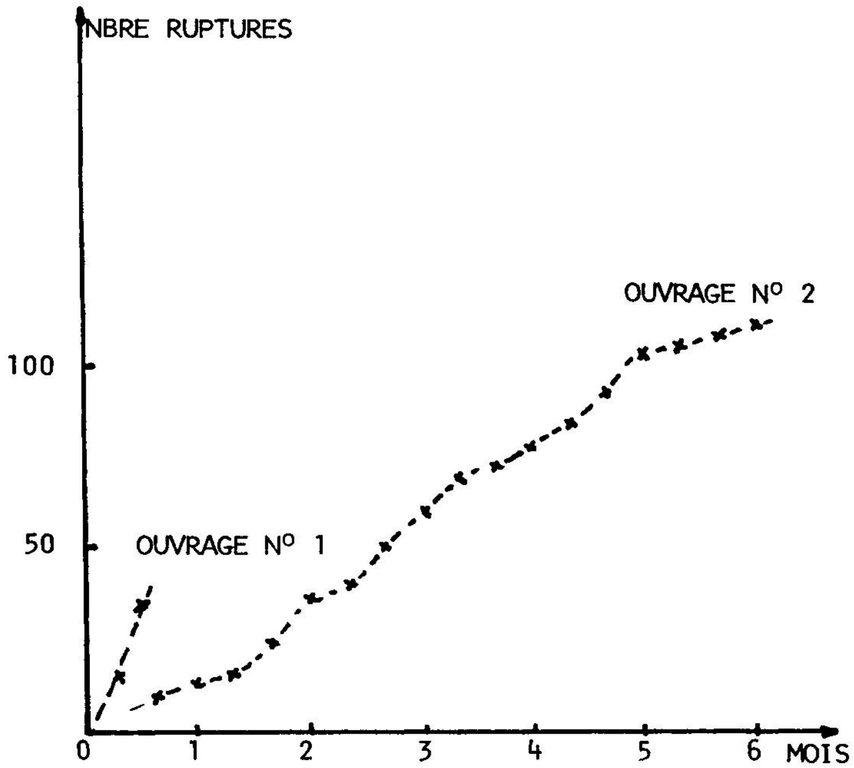


FIGURE N° 2 - Number of fractures monitored by acoustic survey of cables in two suspension bridges (on service)

In this area, the number of fractures monitored with the acoustic survey was 1 for a day, as a mean value, from July to December. Then the phenomenon seemed to be stabilized, starting from December.

After the cable removal, a 5 m long piece, where the acoustic emission had monitored 10 fractures, was examined : 63 fractures were observed in the internal layers (the external layer being perfectly safe). This result enabled us to verify the validity of the acoustic survey of the suspension bridge cables, which makes it possible to monitor the individual fracture of elementary wires at the time when it occurs, with a location precision in the order of 0,10 m.

4. EXTENSION TO THE SURVEY OF PRESTRESSED CONCRETE STRUCTURES

As the acoustic survey method is operational for the suspension bridge cables (or stay cables), it is not yet the case for prestressed concrete cables.

The two ways into which we lead our experimentation were as follows :

- monitoring the fracture of one wire in the prestressing cable
- monitoring the concrete crack growth.

They are full of promise, but the all encountered difficulties are note quite resolved.

In the first way, if the energy released at the fracture is high, the conditions of wave propagation in the complex structure of the bridge are not yet know enough so that a fracture is identified, with a faire assurance, starting from a recorded signal.

In the second way, more over, the released energy is weak and the result interpretation is ticklish.

4.1. Monitoring a wire fracture in a prestressing cable

The acoustic survey was used since September 1973 to February 1976 on a box girder bridge with 3 continuous spans 21, 30 m and 18 m long, for surveying 3 girder webs in the center span (30 m). During this time duration, 8 wire fractures were identified using the recorded signals. Before the structure was repaired a gammagraphy control was carried out on the whole structure. One fracture could be confirmed, but the 7 other ones unfortunately corresponded to parts of the structure where gammagraphy was impossible and the "autopsy" of the cable was not yet carried out.

4.2. Monitoring and survey of concrete active craks

The structure put under acoustic survey was a bridge on a motorway, with 4 spans (28, 46, 84 and 50 m long) built by cantilever method.

In a first step, the acoustic survey was distributed along the structure and enabled active cracks to be detected an located in 2 webs of the voussoirs in the center span (84 m long).

In a second step, the high density of sensors in the area with active cracks enabled us to localize 2 preferential areas of acoustic emission, of about 1 m^2 (fig. 3). The basic data on the properties of the waves emited by concretes and on their propagation conditions were not sufficient for the identification of the source of the received waves : opening or growth of cracks. But we are allowed to assess that these waves indicated the activity of these cracks because they were off since additional prestressing cables were tensioned (before cracks were injected).

Now, theoritical and experimental investigations are at hand for our knowledges to be improved on the conditions of wave propagation in concrete specimens, respectively sound, microcracked and cracked.

FIGURE N° 3

A - Sensor on a structure

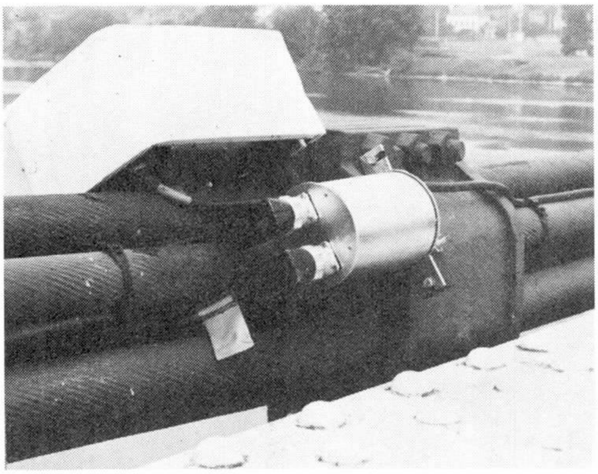
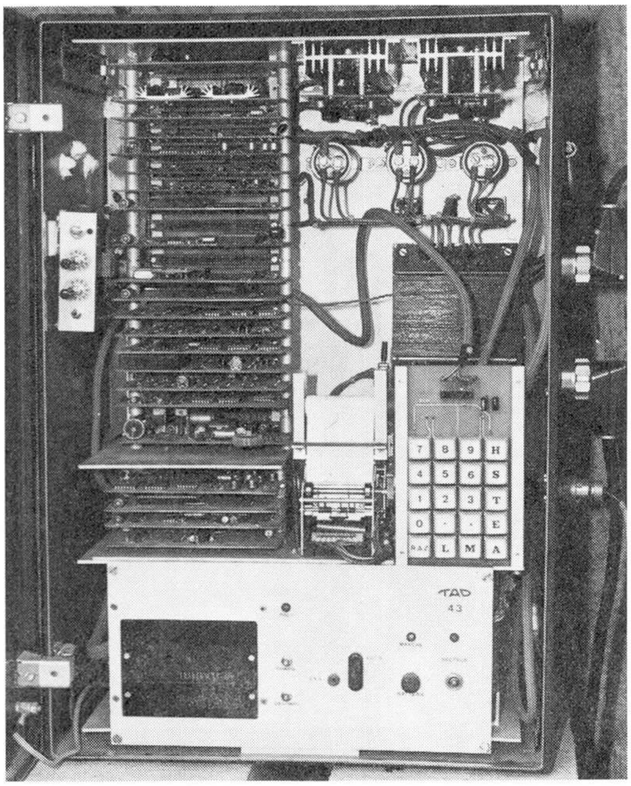


FIGURE N° 3

B - Central box



5. CONCLUSION

The acoustic survey of suspension and cable stayed bridges enables now the fracture of elementary wires to be detected in cables, which may induce the sudden failure of the structure. It is not excluded that it enable us to estimate the residual ligetime of a cable in a given structure, using the change of the wire fractures occurence and their location. In order to reach this purpose, systematic works are to be made for surveying cables in structures under construction or old ones and examining them after removal.

The case of prestressed concrete structures is more difficult. But it already appears that it is possible to monitor, using acoustic survey, the presence of active cracks and the pending investigations on the properties of waves emited during the initiation or the growth of cracks in concrete, and on the propagation of these waves in microcracked or cracked concrete should enable us to check the change of the concrete damage, thus to give a help in diagnosing the residual safety of a structure.

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Direct Measurement of Stresses in Concrete Structures

Mesure directe de contraintes dans des structures en béton

Direkte Messung der Spannungen in Betonbauwerken

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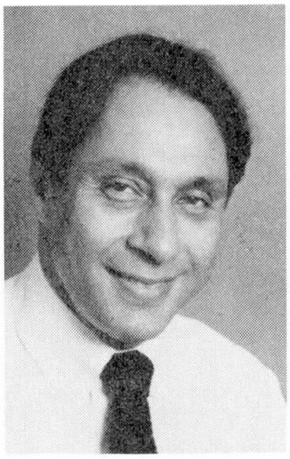


Charles Abdunur got his civil engineering degree, worked for five years on the design and supervision of several big projects, then prepared and obtained his doctorate in 1974. Since then, Charles Abdunur directs several research programs at a civil and structural engineering laboratory.

SUMMARY
To evaluate the absolute stresses in concrete structures, a direct method by partial stress release has been developed. It consists of cutting a slot in the concrete, restoring the initial strain field with an ultra-fine flat jack and measuring the pressure. The method has been thoroughly examined from its theoretical, technological and metrological aspects. It is now operational with an error margin of 0,3 MPa for both compression and tension. Following a thorough study of the shrinkage stress distribution, it is now possible to separate the two components of the measured absolute stress: applied and residual.

RESUME
Afin d'évaluer les contraintes absolues dans des structures en béton, une méthode directe par libération partielle a été adoptée. Elle consiste à pratiquer une entaille dans le béton, puis à rétablir, avec un vérin ultra-plat, le champ de déformations initial et à mesurer la pression. Cette méthode a été minutieusement examinée sur le plan théorique, technologique et métrologique. Elle est désormais opérationnelle avec une marge d'erreur de 0,3 MPa, qu'il s'agisse d'une compression ou d'une traction. Après une étude poussée sur la répartition des contraintes de retrait, il est possible de séparer les contraintes appliquées et les contraintes résiduelles qui forment ensemble la contrainte absolue mesurée.

ZUSAMMENFASSUNG
Eine Methode zur Bestimmung der absoluten Betonspannungen in Bauteilen mit Hilfe von Druckmessdosen wurde entwickelt. Bei dieser Methode wird ein Schlitz in den Beton geschnitten und das ursprüngliche Dehnungsfeld mit Hilfe einer flachen Druckmessdose wieder hergestellt und der Druck gemessen. Das Verfahren wurde vom theoretischen, technologischen und messtechnischen Standpunkt her gründlich untersucht. Es ist jetzt mit einer Fehlergenauigkeit von 0,3 MPa sowohl für Druck- als auch für Zugspannungen einsatzfähig. Eine umfassende Untersuchung über die Schwindspannungsabteilung hat es ermöglicht, die gemessene absolute Spannung in die Komponenten aufgebrachte Spannung und Schwindspannung aufzuteilen.

1. INTRODUCTION

In a concrete structure, showing signs of damage, the determination of the state of absolute stress is an essential element for diagnosis and for the evaluation of its residual strength. However, as these absolute stresses cannot possibly be determined through mere strain measurements, a direct method by partial stress release was considered. It consists in a local elimination of stresses, by cutting a slot, followed by a controlled stress compensation (fig. 1). In practice, the displacement reference field is first determined; a slot is then cut in a plane normal to the desired direction of stress determination; finally, a very thin flat jack is introduced into the slot and used to restore the initial displacement field. The amount of compensating pressure is an indication of the compressive stress in the direction normal to the slot.

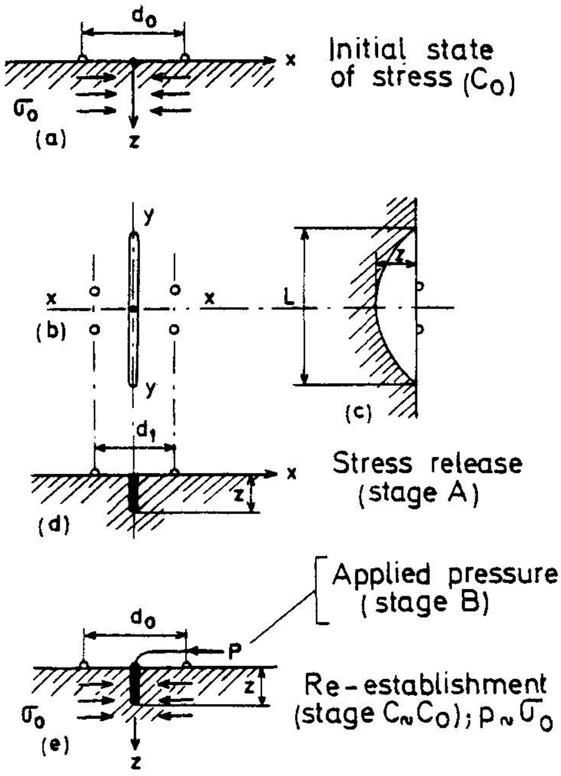


Fig. 1
Different stages of stress measurement by partial release

2. APPLICATION TO CONCRETE

Although this principle was easily applied in rock mechanics, its mere transfer to concrete has been repeatedly disappointing for two main reasons:

- The difficult nature of concrete as a material.
- The complications arising from the absolute need for the miniaturisation of this destructive operation.

To overcome these difficulties, the method was thoroughly re-examined from all its basic aspects that led to several imperatives:

- Behaviour analysis of the slot vicinity from a purely mechanics viewpoint.
- Dry cutting and simultaneous thermal stability to avoid the complete distorsion of measurements.
- Miniaturisation, considered absolutely imperative, but resulting in measurements increasingly sensitive to heterogeneity, hair-cracking, cut clearness and, above all, to the quality of the jack.
- Evaluation of tensile stresses occuring in zones where the applied compression is sufficiently low to allow the prevailance of internal stresses.
- Break down of the measured absolute stress to its two main components: applied and internal.
- Correction for cutting through reinforcement during stress release.

3. ORIENTATION OF THE RESEARCH

Three following basic objectives were fixed:

- To analyse the disturbance in the displacement, strain and stress fields induced by the presence of a slot in a medium subject to known stresses.
- To evaluate the restoration of these fields, using an ultra-fine jack.
- To establish a correlation between the cancelling pressures in the jack and the initial stresses.

The governing parameter is the depth of the slot.

4. EXPERIMENTAL PROGRAM

It followed three lines of attack where different tests often had to overlap:

- Development of specific instruments and procedures.
- Tests on plexiglass, using photo-elasticity and the Moiré-technique, to study the effect of the slot in a homogeneous and isotropic material.
- Identical tests on concrete models, using mechanical and electric gauges, to simulate actual cases and to study local effects.

5. DEVELOPMENT OF THE EQUIPMENT

The equipment included the release and cooling apparatus, the flat jack and the measurement apparatus.

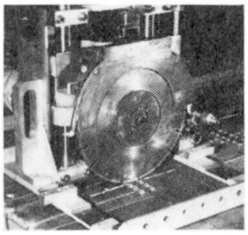


Fig. 2
Cutting machine

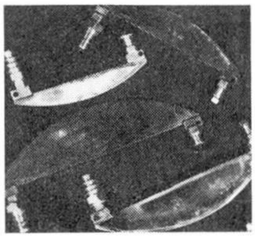


Fig. 3
Flatjacks

Cutting is carried out by successive passes which alternate with measurements. This involves the lifting of the cutting wheel and its reposition with great accuracy (0.1 mm); a special apparatus was constructed for this purpose (fig. 2). A very sharp and clear cut, with a uniform thickness, was thus obtained. Furthermore, a special cooling system was developed to favour dry cutting. The thermal stability thus achieved was excellent. The flat jack had to reconcile miniaturisation with strength and flexibility. A prototype 4 mm-thick jack (fig. 3) was designed by the author, constructed by a craftsman and successfully tested in the laboratory. In the measurement apparatus, the displacement field is materialized by a set of mechanical gauge bases. It is complemented by strain gauges forming the strain field for instantaneous measurements. Immediately prior to cutting, the readings taken of these two sets constitute their respective initial or reference fields.

6. THE IDEALIZED MODEL

The surface behaviour of a three-dimensional model was analysed on a series of plexiglass blocks by two complementary optical methods.

6.1 Qualitative analysis

On a plexiglass block, provided with photo-elastic coating, a first slot was cut parallel to the intended direction of loading. Under a uni-axial uniform compressive stress, hardly any disturbance was noticed (fig. 4 a). A second slot, perpendicular to the first one, produced a very clear disturbance in the stress field (fig. 4 b). The observations would favour the measuring of absolute bi-axial stresses.

(b)

(a)

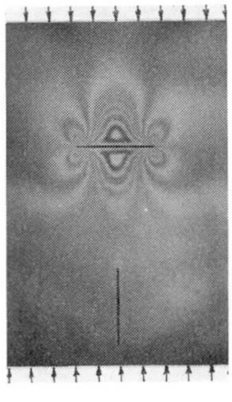


Fig. 4
No disturbance in slot (a)

(a)

(b)

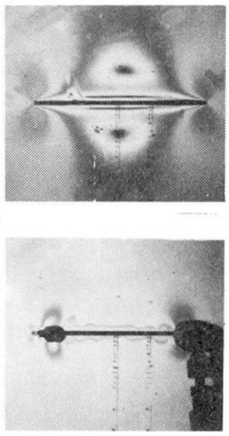


Fig. 5
- Disturbance
- Restoration

Another similar block, containing a slot, was also subjected to pure compression in successive stages. Fig. 5 a again reflects the extent of the disturbance in the stress field. Fig. 5 b, on the other hand, shows the high degree of its re-establishment, using a prototype flat jack. At each stage of loading, the cancelling pressure proved to be exactly equal to the corresponding applied stress.

6.2 Quantitative analysis

A third block, containing a slot, was equipped with a double Moiré-grating (fig. 6 a). It was then subjected to three phases of loading (fig. 6 b, c, d): Pure compression, a uniform pressure with a jack in the slot, finally a combination of the foregoing two. Fig. 8 a, b, c show the results obtained and efficacy of the flat jack in restoring the field. These results also confirm and complement those of the calculation carried out previously by finite elements.

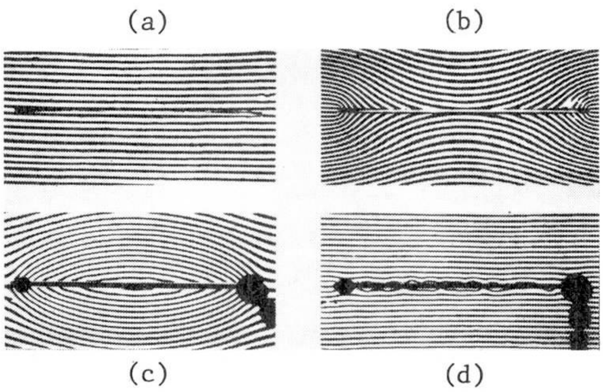
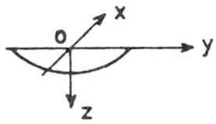
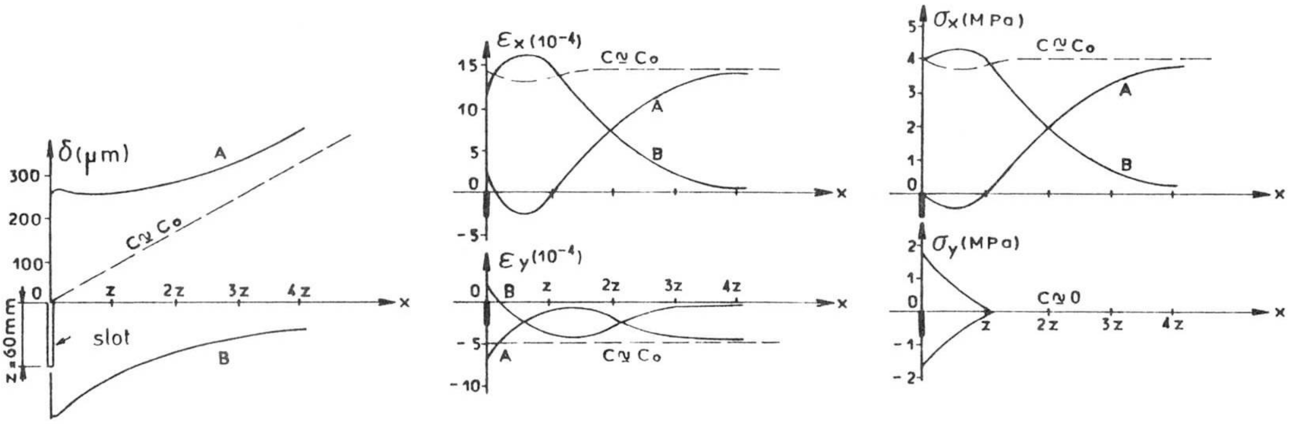


Fig. 6
Disturbance and restoration of the displacement field
(a) unloaded (b) external loading
(c) pressure in slot (d) combination of b and c

Fig. 7
Co-ordinate axes





a) Displacements; assumed positive towards the slot
b) Strain; contraction assumed positive
c) Stresses; compression assumed positive

Fig. 8 - Displacement, strain and stress distribution along an axis normal to the plane of the slot; obtained on a plexiglass model by the Moiré-technique. Cases of loading: A - Pure compression (σ_x = 4MPa); B - Pressure (4MPa) in the slot; C - Combination of A and B; C_o - Pure compression in a model without a slot. The slight distortion in the results is due to the delicate treatment of data and not to a supposed rigidity of the jack.

7. CONCRETE MODELS SIMULATING THE ACTUAL CASE ACCURACY OBTAINED

Now that the theoretical, technological and metrological problems are resolved, the way is paved for the application of the release method on concrete.

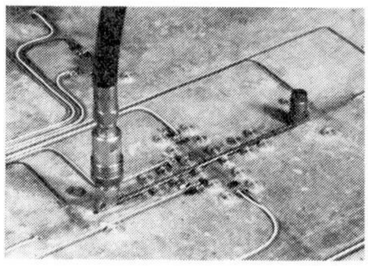


Fig. 9
Measurement apparatus on concrete

7.1 Compressive stresses

The tests undertaken on plexiglass by optical methods, were repeated on uncracked concrete models by extensometry (fig. 9). They were carried out within the elastic limit and at different slot depths. The results were in close agreement with those already obtained on the idealised models. Fig. 10 shows the essentials of this study, i.e. for a model subjected to pure compression, a maximum error margin of 0.3 MPa was found between the cancelling pressures and the actual applied stresses.

7.2 Tensile stresses

The principle of estimating compression by measuring the cancelling pressure could have the following corollary: Tension can be estimated through measuring a subsequent forced extension and the pressure that caused it, then by extrapolating down to zero displacement (fig. 11).

7.3 The stress gradient

Other tests were carried out on models subjected to flexure. At each slot depth, the measured stresses agreed fully with the theoretical ones, acting at the centre of gravity of the jack. Hence, by measuring the stresses at closely successive depths of the same slot, the gradient can be determined with a good approximation.

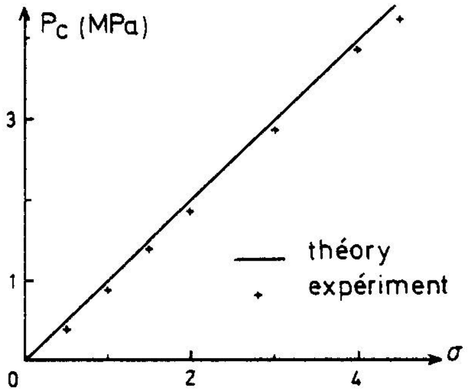


Fig. 10
Comparison between the cancelling pressure and the actual applied stresses.

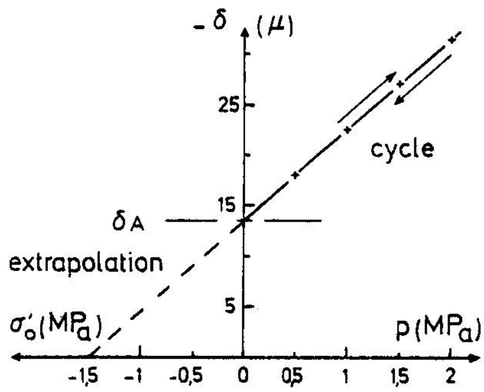


Fig. 11
Evaluation of tensile stresses, σ', by means of a pressure cycle p and corresponding displacement measurements, δ (δ_A: extension on stress release)

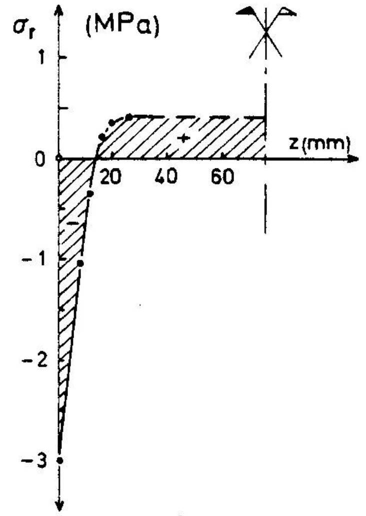


Fig. 12
Distribution of shrinkage stresses

8. THE ACTUAL CASE ON SITE

In all tests carried out so far, the cutting of the slot has been taking place before the application of external loading to eliminate internal stresses and offer a straightforward test of the release method. Now that the accuracy of this method is established, the more complex actual case on site can be tackled. It involves two supplementary problems: the internal residual stresses and the eventual cutting through a reinforcement bar.

8.1 Internal stresses; separation of stress components

The progress achieved in measuring a tensile stress and its gradient paved the way to the comprehension of internal residual stresses in concrete. A series of tests were carried out to analyse the effects of shrinkage. Fig. 12 shows an example of the stress distribution obtained. Shrinkage, as any other internal stress, obeys the law of the equilibrium of forces. When shrinkage and applied external stresses were both involved, the superposition principle proved to be valid. The absolute stress, measured on site, can thus be broken down to its components: the applied and the internal.

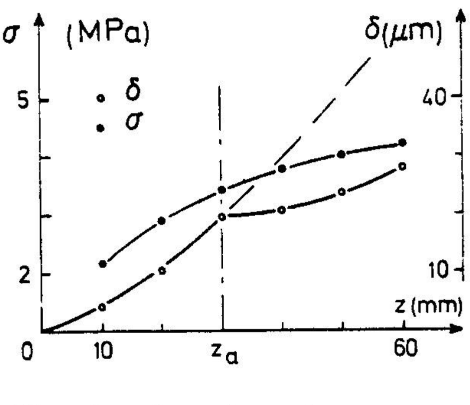


Fig. 13 - Cutting through a reinforcement bar at a depth z_a during stress release: an immediate effect on the displacement field, but not on the measured stress profile.

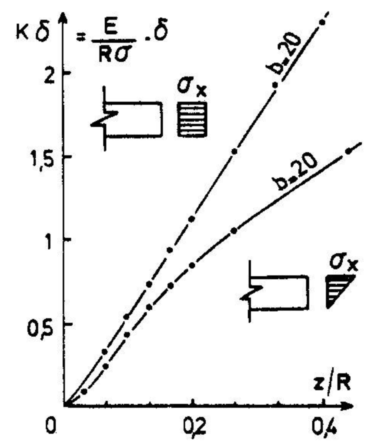


Fig. 14 - Dimensionless reference curves for evaluating the relative state of an unknown medium. The release criteria are expressed as a function of the depth z, for a slot of radius R.

8.2 Presence of reinforcement

All possible steps were taken to avoid cutting through reinforcement during the stress release operation. However, as exceptionally unfavourable cases may arise, tests were carried out to study the effect of such cutting. Fig. 13 summarizes the results. It shows a clear and immediate discontinuity in the evolution of the displacement field, but hardly any effect on the continuity and accuracy of the measured stress profile. It goes on as if the cutting through reinforcement had furnished the given medium with a higher rigidity facing the same stress field.

9. STATE INVESTIGATION OF A MEDIUM

After adequate development, the partial release method can now not only dispense with the constitutive law, but would even help to find it. Through a further analysis of the experimental data, the state of a given medium may be situated with respect to a linearly elastic, isotropic and homogeneous continuum. For this purpose, reference curves were established to define, with dimensionless criteria, a linearly elastic behaviour in the vicinity of a slot, whatever the modulus or the slot radius may be. For two types of stress distribution, fig. 14 shows the release characteristics as a function of a slot depth z and radius R; E is the modulus obtained from fig. 15 and σ the stress assumed equal to the cancelling pressure p_c. For the same slot of different depths, fig. 16 shows, as a function of position x, the response of the displacement field to a unit pressure of the jack. The actual curves can thus be traced and compared with their references. If a serious disagreement is observed, the medium may be cracked or plastified, depending on the direction and sense of deviation.

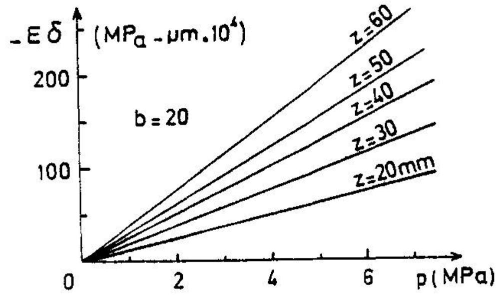


Fig. 15

Graphical estimation of the modulus E. Displacements δ, measured on a base b20, are induced by a pressure p, applied in a slot of different depths z and of a radius R.

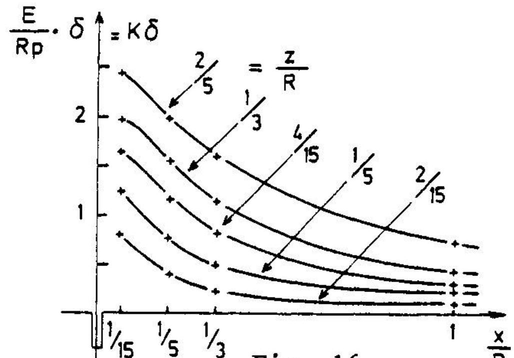


Fig. 16

Dimensionless reference curves for exploring a medium through a unit pressure in the slot (p = 1).

10. CONCLUSION

Progress has been achieved in the evaluation of actual stresses in concrete structures. A method by partial stress release was adopted. As far as instantaneous measurements are concerned, it is now operational.

For conciseness, the discussion was limited to the case of uni-axial stresses, where only one slot is usually necessary and sufficient. Other states of stress, much more complex, are equally accessible to measurement and with the same accuracy. Such cases, however, may require two or three slots in different direction to provide the number of points needed to construct the Mohr circle and determine the complete state of stress.

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