Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 57/1/57/2 (1989)

Rubrik: Keynote lectures

KEYNOTE LECTURES

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Durability of Highway Bridges

Durabilité des ponts-routes

Dauerhaftigkeit der Strassenbrücken

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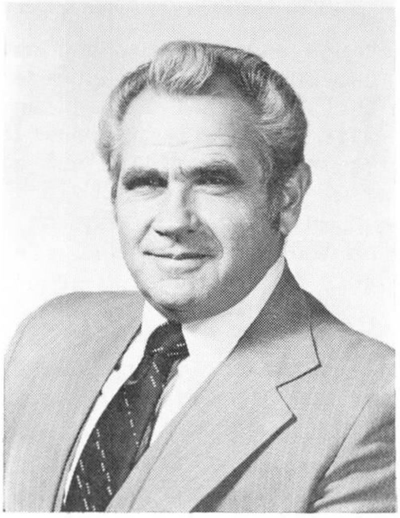

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SUMMARY

Every Bridge Engineer must plan, design and construct bridges, as if they were to safely service the traveling public forever. For only then can the bridge engineer feel that he has satisfactorily executed his commission. He must produce the best possible bridge and the lowest possible cost without sacrificing safety, quality or aesthetics. When he plans, designs and constructs with durability in mind his bridge will become functionally obsolete long before it becomes structurally deficient.

RÉSUMÉ

Chaque ingénieur des ponts doit concevoir, calculer et construire des ponts, comme si ces derniers devaient remplir leur fonction avec sécurité et pour l'éternité. Alors seulement, l'ingénieur a le sentiment d'avoir correctement accompli sa tâche. Il doit construire le meilleur pont pour le coût le plus bas sans sacrifier la sécurité, la qualité et l'estéthique. Lorsqu'il conçoit, calcule et construit un pont en ayant la durabilité présente à l'esprit, celui-ci sera obsolète longtemps avant de présenter des déficiences structurales.

ZUSAMMENFASSUNG

Jeder Brückeningenieur muss Brücken planen, bemessen und bauen, wie wenn diese dem Verkehr für ewig sicher dienen würden. Nur dann hat er das Gefühl, seinen Auftrag zufriedenstellend ausgeführt zu haben. Er hat die bestmögliche Brücke mit den kleinstmöglichen Kosten zu bauen, ohne Kompromisse zulasten von Sicherheit, Qualität und Aesthetik. Plant, bemisst und baut er jedoch schon mit der Dauerhaftigkeit als Ziel, so wird seine Brücke nicht mehr gebraucht, bevor ihre Lebensdauer erreicht ist.

1.0 INTRODUCTION

How long is a highway bridge supposed to last? The obvious answer is that it is supposed to last as long as it is needed. Predicting how long a bridge must remain in service is essential to bridge planning, design, construction, and maintenance. And yet predicting the exact service life of a particular bridge at a given site is impossible. Too many factors are beyond the bridge engineer's control.

Often, the useful life of a bridge ends when it becomes functionally obsolete. The bridge is in good condition, but it is no longer able to carry the traffic loads or volumes existing at that location. This can happen for many reasons. For example, if legal load limits change, or if vehicles are heavier than expected, or if traffic volumes increase as development occurs--the life span of a structurally sound bridge may be shortened. To cite another example, water flow through the bridge opening or the frequency of flooding may have increased to a point that is no longer acceptable. In that case, a new bridge is required to reduce the impacts on surrounding developments.

In the United States, 42 percent of our 577,710 structures are deficient. Of these, 102,531 (18 percent) are deficient only because changes at their geographical location have made them functionally obsolete. In urban locations and high growth areas, more bridges are replaced because of functional concerns than structural considerations.

Of course, some bridges deteriorate to the point where they can no longer carry the necessary loads safely. In the United States, 135,826 (24 percent) of all bridges on public roads are structurally deficient. These bridges have deteriorated to the point that major rehabilitation or complete replacement is necessary.

Ideally, no bridge would be structurally deficient. Every bridge rehabilitation or replacement project would be the result of functional obsolescence, not deterioration of our engineered product. We know how to correct deterioration before it reaches the point where a bridge can no longer serve the motoring public safely. With proper planning, design, construction, and maintenance, this should be possible.

So why have these 135,826 bridges deteriorated? The overall reason is that we do not live in an ideal world. In an ideal world, bridges would be given the attention they need to serve us well for many decades, even centuries. In the real world, we do not always have the luxury to make the right choices. Our predictions about traffic and loadings may prove to be incorrect so a bridge deteriorates faster than expected. Government agencies may not have enough money for all needed maintenance and rehabilitation projects. In the real world, maintenance is deferred, rehabilitation is put off, and a bridge that could have had an extended life of many decades has to be replaced instead. Recent studies by the Federal Highway Administration (FHWA) Bridge Division have shown that the average bridge in the United States is replaced when it is about 70 years old. By then, it would have been rehabilitated once.

Even in the real world, though, this premature deterioration is not inevitable. The cover of the American Society of Civil Engineers' (ASCE) 1989 calendar has a picture of a covered wooden bridge built in the United States in 1866. It is still in service today. For September, the calendar used a picture of an Iron Bridge in Shropshire, England. This bridge, still in use, was built in 1779. These examples and many others prove that we can build durable bridges, if they are properly engineered, constructed, and maintained.

To achieve this durability, we have to explore what can go wrong and, more importantly, what can go right. We cannot control all the factors, such as geographic changes, budget limitations, or traffic volumes or weight. But to a greater extent, we can control the designs we use so they are capable of achieving maximum service life. We can also control the construction and maintenance procedures that will extend a bridge's life cost-effectively. In short, we, as engineers, should be able to select the best type of bridge for a given location, then combine proper materials, quality design, and pride in construction with protective strategies, including regular maintenance, to prevent premature deterioration, be it a timber, concrete, or steel bridge.

If we look at each stage in the life of a bridge we can find ways of increasing durability to extend effective service life. The first stage is planning.

2.0 PLANNING

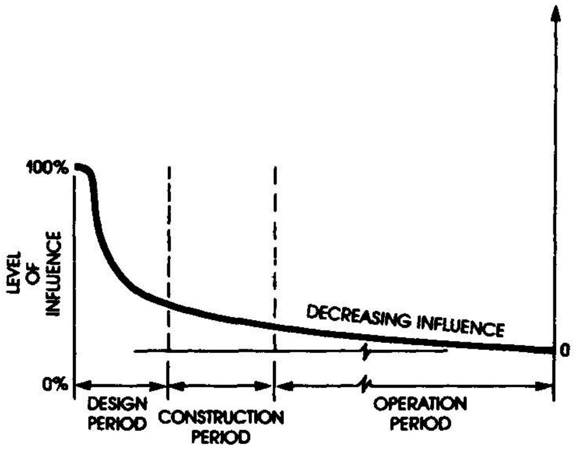
During the planning phase of project development, engineers determine the type, size, and location of the bridge. Site or other constraints dictate size and location. The type of bridge, however, is usually open, and the choice can have a significant effect on durability. We can see how by using an extreme example. We would not select a bridge for an Interstate highway that could not serve high volumes of traffic, much of it heavy trucks, well into the next century. True, some bridges may be the lowest first-cost solution. But that ignores the cost of replacements every 20 or 25 years and, more importantly, the cost of delays and inconvenience of traffic disruption each time. Therefore, in the planning stage, we would program a bridge-type with a higher initial cost, but one that incorporates more "durable" materials.

The planning phase is also when the impact of the environment on the bridge is first discussed. To again cite contrasts, we can see that a bridge carrying mostly automobiles over a slow-moving river in a warm climate should be different from a bridge carrying a traffic with a high percentage of trucks over ocean salt-water in a cold climate with snow and ice throughout the winter. While this example suggests the difference between Florida and Alaska, even bridges within an urban area, or a county, or State can be subjected to considerably different environments--for example, piers on solid ground or in the bed of a rushing river. During the planning stage, bridges must be programmed to incorporate materials suitable to the environment.

If these factors are not recognized during planning, and adequate funds are not made available for design and construction with durable materials, the resulting bridge will not last as long as it could have.

3.0 DESIGN

The design phase has the greatest impact on the quality--another name for durability--and cost of the bridge. In a publication entitled Quality in the Constructed Project, {1} the ASCE included a chart that illustrated the effect on quality: (Figure 1).



Opportunity to Influence Project Quality and Cost

Figure 1

The ASCE defines quality as meeting the needs of the owner within the available budget. For some bridges, this definition may appear to consist of two mutually exclusive terms. The owner may want a bridge that will last 100 years but may have a budget that appears to cover only a 50-year bridge. That is why experienced designers play such an important role. The designer must know how the various engineered materials, under the given site conditions, will perform. That way, the designer can get the most value, if not 100 years, for the available funds. To borrow an old definition of "politics," bridge design is the art of the possible.

Bridge engineers decide on materials during the design stage. The two broad choices are usually concrete or steel. Within the concrete and steel industries, the pros and cons of each type are controversial. From the standpoint of durability, though, the type of bridge is less important in most cases than the choices made after the type is chosen. What the designer has to recognize is that each setting is different. The skill of the engineer comes in understanding the differences, and making choices accordingly. We will illustrate this point with a few examples, beginning with concrete.

Many engineers include high-strength concrete in their designs. These engineers think that high-strength concrete is more durable than lower-strength concrete. That sounds logical enough. And if stresses and strains were the only consideration, this assumption would be true. But the environment shows no respect for high-strength concrete, if such ingredients as "entrained air" are not included. Air entrainment reduces the strength {6} of the mix, if all other ingredients are kept constant (cement, water, etc.), but revising the mix design can provide both the needed strength and air entrainment.

Another factor that makes a major contribution to the durability of concrete bridges is the permeability of the final concrete mix. The lowest water-cement (w/c) ratio, compatible with workability, has to be specified for exposed concrete elements. Concrete with a w/c ratio of 0.5 (5 1/2 gallons per 94-pound bag of cement) has a higher permeability than concrete with a w/c of 0.4. The lowest practical w/c that can be placed is about 0.32 (depending on temperature), and then only with special equipment for consolidation. To get a durable concrete, therefore, the designer has to recognize the interrelationship of strength, permeability, and workability when specifying the concrete mix required for the project. The designer should also know that adding high-range water reducers, fly ash, retarders, silica fume, etc., may require a different w/c ratio to achieve equivalent quality levels.

As with concrete, the durability of structural steel is influenced by the decisions made during the design phase. To cite one example, designers who do not keep up with the latest in fatigue resistant design are potentially burdening their client with excessive rehabilitation costs to achieve expected service life. This can occur, for instance, when a structural detail develops a fatigue crack that grows until it becomes a critical flaw. If the structure is non-redundant and the member fractures, the entire structure can be lost. These cracks rarely start because of the design of the main load-carrying members. If proper detailing is not used for the secondary members, however, "out-of-plane bending" that is not accounted for in the design can, and often does, cause cracks.

Too often, designers incorporate fatigue-prone connections in new structures well after the technical literature has fully documented the weakness of the joint. In this case, the designer has made the choice of a bridge-type, namely steel, that can last many decades. Then a secondary choice may well cut that life short, with tragic consequences for any motorists on the bridge if the member cracks.

In making structural material choices, the designer must decide how to account for life-cycle cost in the analysis. Because of the rivalry between concrete and steel, this is always a controversial topic. No one answer seems to satisfy advocates of both types. Still, life-cycle cost is important to the owner of the bridge. Therefore, life-cycle cost must be important to the designer. It is influenced more by the designer's details than basic structural materials.

Life-cycle cost is the cost of all activities associated with a bridge during its life. It includes the cost of construction, but also the cost of any maintenance, rehabilitation, or reconstruction that may be needed during the life of the structure. Life-cycle cost allows designers to compare the cost of alternatives over the life of a bridge, instead of simply initial cost. A bridge with a low initial cost may be within a bridge owner's construction budget, but could be a poor investment if it requires rehabilitation three times during its service life instead of two.

In looking at the structures in the United States, we can see that any type of structure, properly designed, constructed, and maintained will have, comparatively, the same life-cycle costs. Therefore, the bridge owner's goal must be to develop a process that will allow only durable bridges to evolve.

Durability, in this regard, should be defined as a combination of engineered products or materials that will satisfy project needs at a specific site for a specific design life. This definition is useful because it makes clear the fact that "durable" does not always mean a "long-lasting" structure. Even though we know a concrete bridge, for example, could last 50 years or more, if the completed bridge will be replaced in 10 years because of functional obsolescence, concrete might be a poor choice.

In considering life-cycle cost, we sometimes find that the calculations are less persuasive than the experience of the designer. Should the steel be painted or unpainted (so-called "weathering" steel)? Should the concrete be reinforced or prestressed? Depending on who is involved, different selections will be made based on experience. An engineer who has dealt mainly with steel structures during his professional life would probably argue the advantages of steel in life-cycle cost. Engineers who have dealt mostly with concrete structures would probably think the facts favor concrete.

Some aspects of life-cycle cost, though, have been recognized. Concrete bridge decks are an example. Premature deterioration of bridge decks--deterioraation occurring before the end of the bridge's service life--has occurred in - localities where deicing salts are used to meet the need for winter travel. Because of the recognized effect of salt on reinforcing steel in concrete decks, experienced designers incorporate a "corrosion protection" system with higher quality concrete. That combats the influence of the salt, but with a higher initial cost. By calculating life-cycle cost, we can see that this extra cost is justified because the deck will now have a service life equal to the rest of the structure.

We can see a similar debate over the life-cycle cost of painting. A structural steel member, if properly designed, detailed, maintained, and painted will last, in theory, forever. The 1779 Iron Bridge mentioned earlier is an example. But repainting steel bridges can be costly and it affects traffic, presenting safety hazards to workers and motorists. These costs have to be added to the life-cycle analysis.

Many designers think the answer to the painting problem is "weathering" or unpainted structural steel. That avoids the added cost of repainting. Moreover, used in the proper environment with appropriate details, "weathering" steel will provide an acceptable service life with minimal costs. "Weathering" steel, though, is not durable in all environments. In a marine environment, "weathering" steel experiences accelerated, premature deterioration, with resultant maintenance or rehabilitation costs for the owner. Because of windborne salts, this deterioration may occur even though the structure is miles from a seacoast. It may occur hundreds of miles from a marine environment, in fact, if roadway deicing salts come into contact with the steel. The designer must have a full understanding of the limitations of this material in calculating life-cycle costs.

Bridge joints are perhaps the single biggest cause of premature deterioration of bridge components. In addition, they greatly influence the rideability of the roadway surface. Here, too, the designer must make choices that will affect the durability of the bridge as well as its life-cycle cost.

One such choice involves handling water that passes through the joint. Because water is often laden with salt, it could cause the superstructure and the substructure to deteriorate. Experience has shown that joints will not remain watertight over the service life of the structure. Aging joints, by leaking, can affect durability. At the same time, replacing joints every 5 to 10 years to retain water-tightness is unacceptable, especially on high traffic routes. To meet these circumstances, a skilled engineer may consider provisions to control the water under the joint rather than try to prevent the water from penetrating. Properly detailed and maintained joints can control this water for the life of the structure.

For smaller structures, "jointless" bridges have been used with great success in some States. Tennessee, for example, {8} has built 400 foot long steel, and 800 foot long concrete bridges without joints. The State has not had any significant problems as a result of this design decision. Of the 577,710 structures in the United States, over 90 percent are less than 500 feet long and may qualify for a jointless design. Even though this design could increase durability, designers use it infrequently.

Bridge drains are another area where water flowing out of control may subject a structure to significant damage. They are used too frequently on highway bridges, probably because of the thinking that "more is better." In fact, the reverse may be true. With fewer drains, more water must flow through each one, thus "flushing" out the drains. Maybe the answer to many of our bridge problems is "jointless and scupperless bridges." An FHWA research report on Bridge Deck Drainage Guidelines {2} provides good advice for the engineer on deck drainage design.

The number of drains is an example of how a little decision can create a big problem. We do not want to slight the big decisions. A designer should not develop a structure where premature deterioration of any single element, from whatever cause, will require total replacement of the bridge. This is the basic idea of redundancy. If one thing fails, another will do the job. Designing for redundancy may increase initial project cost by a small percentage. That small increase may affect the competitiveness of the design in comparison with another structural system. Nevertheless, every designer and every bridge owner has to recognize the importance of redundancy. We are not comparing apples-to-apples if we try to decide whether to use a bridge design that can survive the failure of a critical member or one that cannot.

If the structure will cross a river or stream, the designer has several other choices to make that, obviously, can affect durability. A bridge must be able to withstand major floods. Many bridges cannot, though. More structures are lost in the United States because of floods than for any other reason. We may blame these losses on "acts of nature," and that is correct up to a point. But the losses often are a direct result of designer and owner decisions.

Scour resistant designs, for example, should be mandatory for structures that cross a body of water. If the bridge footing cannot be placed on a non-erodible base, such as competent rock, the designer must find ways to build in stability. The bridge must be able to withstand the "design flood" (usually a 100-year storm) without damage. In addition, it must be able to remain stable at even greater flood frequencies (say a 500-year event), although with a smaller factor of safety.

Because initial cost is, inevitably, a consideration, this stability must be achieved without increasing the cost exorbitantly under the guise of safety. To a degree, this is risk management. How much additional cost will the owner be willing to bear so the structure can withstand a 100-year flood, a 200-year flood, and so on.

A well-engineered foundation should be able to withstand a "design flood" or worse without any significant changes in cost or constructibility. If the designer makes all the other best choices, but does not give proper weight to scour resistance, he will have saddled the bridge owner with a structure that is not as durable as it could have been.

In 1988, the FHWA issued a Technical Advisory {7} providing guidance on scour resistant designs. Using the procedures described in the advisory will result in scour-resistant, and thus durable, bridges.

4.0 CONSTRUCTION

The best planning and design can go for naught during the construction stage--if the contractor is not "quality conscious," if the inspectors are not conscientious, if any one of a thousand details are not done as shown in the plans, the bridge will not be as durable as it should have been.

In some cases, durability and quality may be compromised, even before construction begins, by the procedure used in selecting contractors. To secure the benefits of cost competition, bridge owners select contractors by "low-bid." To stay in business, each bidder must minimize time and cost for the project, yet ensure the bid price will provide a product that meets the contract requirements. Bidders will not adopt a more costly or more time-consuming approach--they will stick to the specifications, no more and, we hope, no less. Thus, it is extremely important that the owner specify the type of structure and appropriate material specifications and procedures that have proven to be durable in other similar circumstances.

To be sure minimum quality level standards are met, the bidding documents must clearly indicate the requirements for the project. The criteria that will be used for acceptance or rejection must be clearly spelled out. Further, a balance must be struck. The contract documents should not over-specify material requirements or impose unnecessary construction restraints. And yet they must not be so ambiguous that the contractor will submit a bid thinking a lower priced product will be acceptable.

The bidder's level of experience is a consideration that is often overlooked, especially for state-of-the-art structures. The bridge owner and the contractor should be more conscious of experience. Many highway departments require financial prequalification before a contractor submits a bid, but few require technical qualification as well. The lack of technical prequalification has caused many problems when inexperienced contractors have used the claims process to try to recoup losses resulting from their not fully understanding the complexity of the work they bid.

Some bridge owners have begun requiring technical prequalification to minimize these problems. Industry, too, has recognized the need for technical prequalification. For example, the American Institute of Steel Construction has a three-level certification program for steel fabrication. Two of the levels deal with fabrication of steel bridge members. The Prestressed Concrete Institute has a four-level bridge member certification program. These programs require contractors (or precasters) to satisfy minimum quality control standards to become certified for the appropriate type of construction. Technical prequalification, combined with an adequate design and adequate contract provisions, could eliminate some of the problems we are seeing today.

Quality control is the responsibility of the contractor. Acceptance testing is the testing performed by the owner's representatives to be sure the contract provisions are met, and a durable bridge will result. Together these form the concept called Quality Assurance (Figure 2). The contractor must have an adequate quality control program. Just as importantly, the owner's representatives must understand the acceptance testing criteria and how to interpret the results to be sure the project will result in a durable structure meeting contract requirements.

Curing of freshly placed concrete offers a good illustration of the importance of quality construction. It is perhaps the least understood and most abused stage of concrete construction. This is especially true for bridge decks,

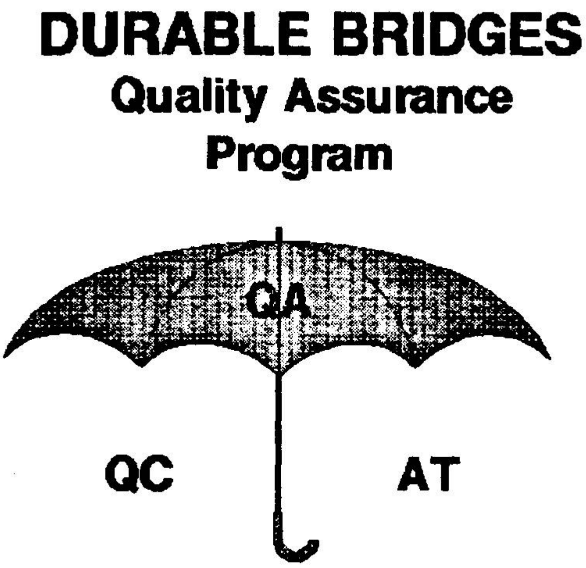


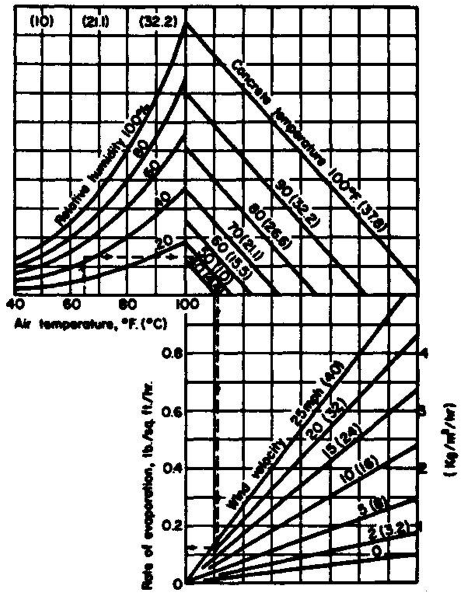
Figure 2

where large surface areas are exposed to ambient conditions. Timing is vital to curing, but proper application is also important to ensure controlled evaporation rate of hydrating water. Otherwise a less durable, poor quality product will result, with early bridge deck failures occurring even if everything else during the design and construction phase was done properly.

The Portland Cement Association (PCA) addressed curing in its manual on Design and Control of Concrete Mixtures {3}. Concrete with exposed surfaces should not be placed if the evaporation rate exceeds, or is expected to exceed, a rate of 0.25 lbs/sf/hr. Figure 3 shows the PCA chart for calculating this rate. It considers humidity, wind velocity, and the temperature of the air and the concrete. Will the contractor measure these factors? Will the inspector be sure the measurements are taken? Will the construction manager catch this detail? If not, the results will be less durable concrete than the designer expected. Proper curing cannot make bad concrete good, but bad curing can make otherwise good concrete bad.

5.0 MAINTENANCE

Proper maintenance does not happen often enough. Because of reduced budgets or inadequately trained personnel, many organizations delay needed maintenance. Deferred maintenance that could have been performed at minimal cost leads instead to rehabilitation at major cost. All too often, we use our limited funds to rehabilitate a bridge that should not have needed rehabilitation for many years, and we replace a bridge that should have lasted many more years, all because of deferred--or ignored--maintenance. Deferring maintenance, therefore, is not only a false economy, but one that can directly affect durability.



Effect of concrete and air temperatures, relative humidity, and wind velocity on rate of evaporation of surface moisture from concrete.

Figure 3

The bridge designer, in considering life-cycle cost, should be able to tell the bridge owner the type of maintenance a bridge will need. The bridge owner should use this information to establish a maintenance program for the bridge before it is opened to traffic. Having the program is not enough, though. The bridge owner must stick to the schedule. This schedule should be like the maintenance schedule that comes with every new car--the owner ignores it at his own risk.

Something as basic as repainting bridges is often deferred. When painting is deferred, for whatever reason, the bridge owner finds that what should have been periodic simple surface preparation with a new top coat is not sufficient. That simple job must be replaced by extensive blast cleaning, priming, and top coating. That is how a forced economy for lack of funds becomes a false economy, whether funds are available or not. In addition, while "saving" money on repainting, the bridge owner is exposing the bridge to the harmful influences of the environment that can shorten the life of the bridge.

Often, funding for regular repainting is not available. Bridge owners, however, usually overlook the next-best possibility. Spot painting can help to protect the more vulnerable areas of the bridge, such as under joints, and to replace sections of paint that failed prematurely. This maintenance strategy is rarely used, but it can significantly reduce the cost of retaining durability.

As in the contracting field, certification of painters can make a major difference in the quality of work. In the United States, the Structural Steel Painting Council is establishing a certification program for painters to be sure minimum quality levels are achieved. Bridge owners who do not rely on the certification can only hope the low bidder selected for the job is capable of at least minimum quality.

"Weathering" or unpainted steel, mentioned earlier in the discussion of life-cycle costs, eliminates one maintenance problem, namely regular painting. However, bridges built with "weathering" steel need maintenance, too. Debris that collects on bridge members from pigeon nests, leaking expansion joints, wind blown dust, or other sources must be removed promptly. This material retains moisture and will cause accelerated corrosion. Salt-laden water coming through bridge joints evaporates, leaving salts that are highly corrosive. They must be flushed off. Some bridge owners have adopted a maintenance policy of washing their bridges, both painted and unpainted, at least once a year to extend their service life. This simple, basic practice is sure to pay high dividends in durability.

"Weathering" steel offers a good example of how a choice made during the design stage affects later stages. The designer may choose this type of steel to reduce maintenance costs and avoid traffic disruption. But that choice imposes special maintenance requirements on the bridge owner. If the bridge owner meets those requirements, the bridge will provide good service at minimal cost. If the bridge owner does not, the choice of "weathering" steel will lead to needless rehabilitation costs and possible replacement of the structure years before its useful life should have run out.

Concrete surfaces also require attention. Debris, for example, should not be allowed to build up and remain on pier caps or abutment seats. Something as simple as the failure to clear debris from drainage openings can prevent a carefully designed, carefully constructed drainage system from operating properly. Instead of moving through the proper channels, polluted, or salt-laden water may sit on the bridge for long periods or may drip over the side.

For surfaces under bridge joints, concrete sealers are recommended to provide the needed service life. In the United States, we often consult the Transportation Research Board's Concrete Sealers for Protection of Bridge Structures {4}. It provides the results of tests of numerous commercially available products that will seal the concrete surface and provide adequate protection.

We have already discussed the corrosive effect of deicing salts on bridge decks and some of the steps that can be taken to minimize this effect. Maintenance of bridge decks, however, may be needed for other reasons as well. The riding surface may rut or its skid resistance may be reduced by wear from high traffic volumes. Restoration of these properties is necessary under the maintenance program to ensure a safe, smooth riding surface on the bridge.

An asphalt overlay is the least costly of many ways of correcting the problem. If the concrete deck has an {3} adequate air entrainment system (as determined by ASTM Test Method C457) and a corrosion protection system, asphalt may be all that is needed. If either of these two characteristics is not present, an impervious overlay (concrete or polymer concrete) or membrane may be needed. The American Association of State Highway and Transportation Officials, the Associated General Contractors of America, and the American Road and Transportation Builders Association have set up a joint committee to develop comprehensive guidelines for overlays. The results will be published soon as a guide specification.

Another feature that inexperienced designers often overlook is "maintainability." For example, access to vulnerable parts of the structure must be convenient enough to allow effective maintenance. Access holes into closed spaces (box sections) must be large enough to allow easy access for personnel as well as equipment. It makes no sense to have to shut down traffic and remove a portion of a bridge deck to get inside a box girder for maintenance.

"Inspectability" is of equal importance. The designer must allow for easy inspection of the entire structure. This helps to ensure early detection of problems. Discovering a fatigue crack when it is 2 inches long allows easy, economical repair. Compare that to shutting down the bridge and installing falsework to repair a fractured element because the inspector could not inspect a particular detail. The designer should mentally "inspect" the bridge while designing it to ensure inspectability. That way, to cite another example, if he or she has a 36-inch girth, he or she won't detail 24-inch access openings.

6.0 TOTAL REPLACEMENT

At some point in the life of a bridge, it may no longer be cost-effective to continue maintenance. This can happen for many reasons. For example, perhaps the rate of deterioration is so great that it cannot be coped with. Or perhaps traffic volumes or other environmental factors have changed significantly, making the bridge functionally obsolete.

Deciding whether to replace a bridge or not is difficult. Cost, of course, is one reason. Another reason is that in most cases, the structure is carrying highway traffic that will have to be detoured during the replacement project. During the planning, design, and construction stages of a replacement bridge project, the same kinds of decisions must be made as in developing a bridge on new location. However, additional factors must be taken into consideration. For this type of work, the decisions made after the type of bridge is chosen may be even more important.

For example, the designer may choose higher cost materials such as polymer concrete instead of portland cement concrete. The higher cost materials can achieve higher strength in shorter time. To meet the project's time needs, precast elements may be favored over cast-in-place elements.

Contractors and engineers versed in the latest techniques for design and construction while maintaining traffic can, and have, produced fully satisfactory, durable bridges. Often, the bridge can be constructed in a remarkably short time. Because time is so important in these cases, bridge owners have offered significant incentives (namely bonuses) for early completion and penalties for late completion. These incentive/ disincentives have proven successful. They can help get the new bridge open faster than would otherwise be the case--and without sacrificing durability in the name of early completion.

Many times, only partial rehabilitation, such as bridge deck replacement, is needed. The question that has to be answered is what is the remaining life of the rest of the bridge? Will the beams, for example, last as long as the planned deck? If not, is the deck "over-designed" and, therefore, a poor investment?. In 1988, the Bridge Subcommittee of the American Association of State Highway and Transportation Officials adopted a guide specifications entitled Guidelines for Strength Evaluation of Existing Steel and Concrete Bridges {5}. Considerable professional judgment, coupled with these guidelines, will allow the proper decisions to be made.

7.0 CONCLUSION

We would like to able to say that all of the above items--and many we did not have time to mention--are accounted for in each and every project. But history has shown it has not happened. With the diminishing resources available to bridge owners (time, money, and trained staff) and the large number of bridges still in the "deficient" category, strict attention must be paid to the need for quality planning, design, construction, and maintenance. These project phases should be incorporated into a comprehensive Bridge Management System to be sure available resources are used effectively.

In closing, and in the words of English author, art critic, and social reformer John Ruskin:

> Therefore when we build, let us think that we build forever. Let it not be for present delight, nor for present use alone. Let it be such work as our descendants will thank us for, and let us think, as we lay stone upon stone, that a time is to come when those stones will be held sacred because our hands have touched them, and that man will say as they look upon the labor and wrought substance of them, "See, this our fathers did for us."

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General Considerations on Bridge Durability

Considérations générales sur la durabilité des ponts

Allgemeine Betrachtung über die Dauerhaftigkeit von Brücken

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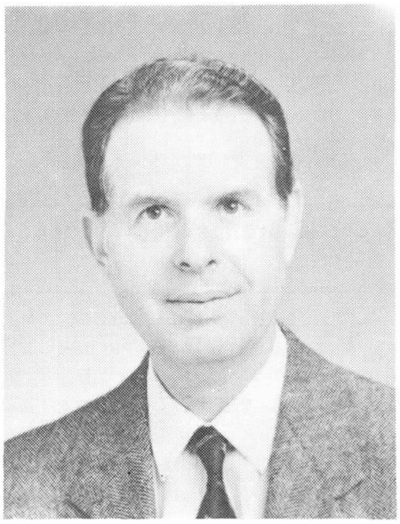

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SUMMARY

The life expectancy of bridges is somewhat variable, but economical considerations require it should be high, at least at the scale of a century. This may imply some changes in practice concerning design and contracting procedures, in order to improve quality, a condition of durability. Furthermore, the recent efforts of many countries in favour of maintenance must be further developed.

RÉSUMÉ

La durée de vie possible des ponts est assez variable, mais des considérations économiques exigent qu'elle soit élevée, au moins à l'échelle du siècle. Ceci peut conduire à des changements d'habitudes dans les procédures d'étude et de passation des marchés, en vue de promouvoir la qualité, condition de durabilité. En outre les récents efforts de nombreux pays en faveur de la maintenance devront encore être développés.

ZUSAMMENFASSUNG

Die Lebenserwartung von Brücken variiert von Fall zu Fall, sollte jedoch aus wirtschaftlichen Gründen in der Grössenordnung von 100 Jahren liegen. Diese Forderung bedingt gewisse Aenderungen der Projektierungs- und Ausschreibungsmethoden, um die Qualität, eine Grundbedingun der Dauerhaftigkeit, zu verbessern. Darüber hinaus sind die Anstrengungen zahlreicher Länder für einen besseren Unterhalt weiterzuführen.

1. ECONOMICAL CONSIDERATIONS

For bridges the concept of lifetime is of great importance, as otherwise the demands placed on public maintenance repair and replacement budgets would be too great. Bridge construction is an ancient activity of civilized societies ; as nowadays many old bridges are still suitable for service, we have been thinking for a long time that long lifetimes could be expected from bridges. Nevertheless we must admit today that the efforts of modern technology have aimed more to lower the cost of structures than to improve their durability.

An interesting report of the OECD, entitled Bridge Maintenance and dated 1981, gives some data, which we reproduce below, concerning the annual rate of bridge replacement in different countries.

Country	Rate of Bridge Replacement	Rate % per ann.
Belgium	No data. As a first approximation assume a life of 100 years	
Denmark	2-4 bridges per 1,000 at present.	0.2 to 0.4
Finland	18 bridges per 1,000 and 10 culverts per 1,000 during 1978.	1.8
France	142 bridges per year out of approx.50,000 (average for 1976, 77, and 78)	0.3
Germany	Overall replacement rate	0.6
Italy	5 motorway bridges out of 1,200 replaced during last 20 years	0.02(*)
Netherlands	1 bridge per 1,000 (due to technical obsolescence), on the State Highway System, which started in the 1930s	0.1(*)
Norway	16 bridges per 1,000 on National Roads (average of 1977 and 1978)	1.6
Sweden	Estimated at 6 bridges per 1,000	0.6
United Kingdom	Estimated at 4 bridges per 1,000	0.4
United States	3,620 out of 258,000 Federal Aid bridges being replaced over a period of 7 years.	0.2

(*) These rates relate to systems containing a high proportion of new structures

The reasons for replacement were not recorded, but some countries indicate that their rate was limited by the funds available. If we do not take into account the low rates, which concern highway system containing a large proportion of new bridges, neither the high rate, due to replacements necessitated by a change in vehicle regulations, the range appears to be between 0.2 per cent and 0.6 per cent per annum, with an exceptionnal high rate of 1.6 per annum in Norway.

A rate of 0.6 leads to an assumed serviceable life of 170 years, and the rate of 0.2 raises this assumed life up to 500 years, what is obviously far too much. But this approach takes into account only an average replacement rate, which should be available for long periods. Now in all industrialised countries many more bridges were built in the last few decades than in the past, and this fact tends to lower the average age of the stock of bridges. Three examples of age distribution are shown in Figure 1, concerning the stock of bridges of two German Länder and of the United Kingdom. They show that in these regions 90 per cent of the bridges are less than 50 to 80 years old.

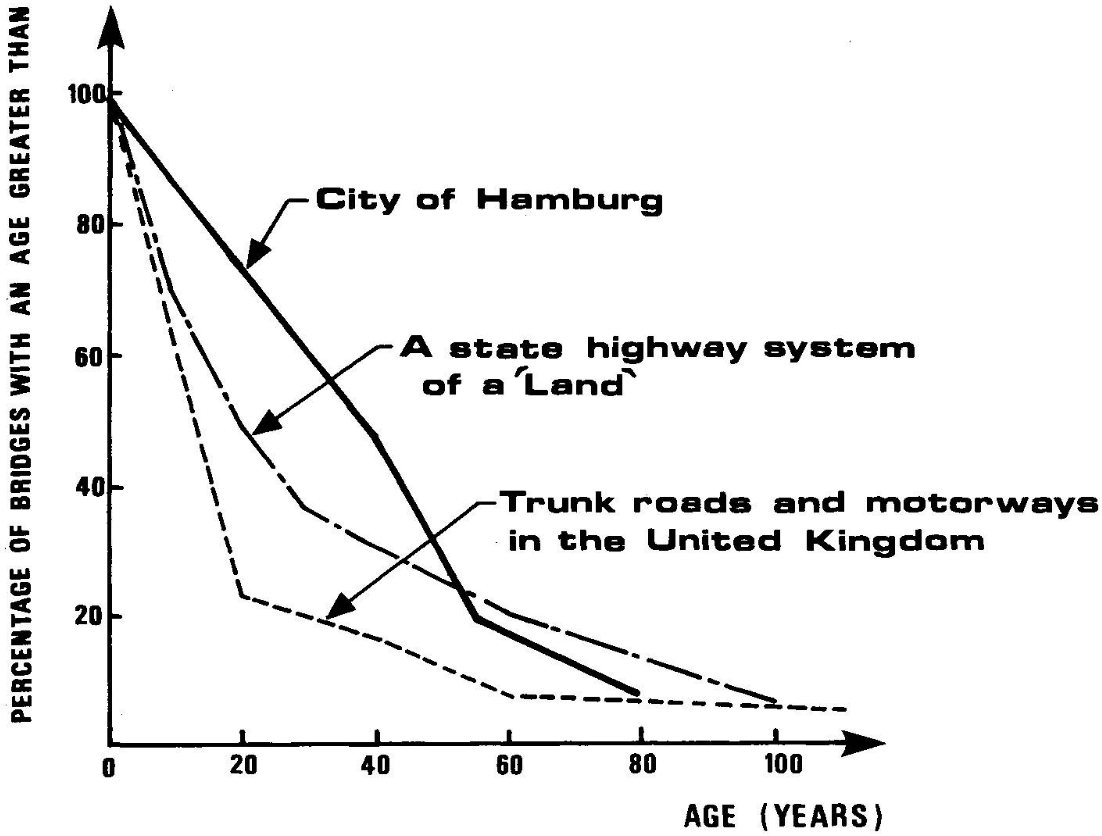

Fig. 1 : Example of age distribution

How it is possible to take into account the age distribution is well illustrated by a study of the German Land of Rhine Palatinate concerning bridge construction planning. The "bridge generation cycle" is assumed to be 60 years, and is shown in the form of a spiral in Figure 2.

Starting from the total number of bridges existing in 1918, this graph shows the number built each year between 1918 and 1947, then between 1947 and 1977. During the period 1977-2007 the bridge building programme will consist on the one hand of new structures (over 1,000), corresponding to the extension of the existing stock, and on the other hand in the replacement of bridges built between 1918 and 1947, when they reach the age of 60 years, the total number of the latter being greater than the former. Then, after 2007, the bridges built between 1947 and 1977 will progressively need replacement.

The method is interesting, although a life expectancy of 60 years seems to be a little short. Moreover, it neglects two factors : first, the deck area to be rebuilt would perhaps be a better parameter than the number of structures, as the latter includes large and small structures. Then, bridges of various ages were built with different techniques, and there is no reason to assume that different techniques lead to the same expected life.

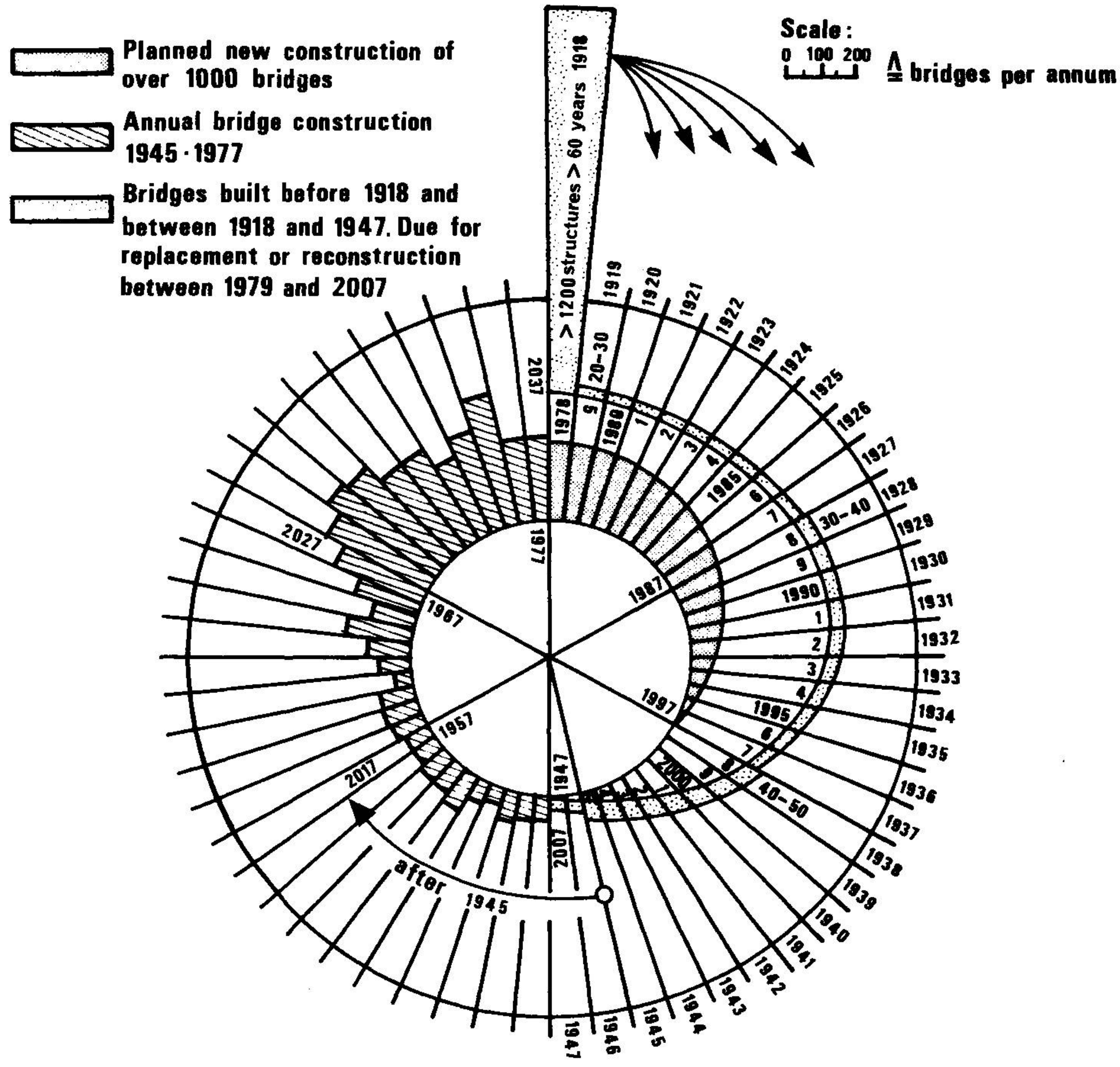

Fig. 2 : Bridge generation cycle of Rhine Palatinate Land

In France, for example, there are no detailed statistics concerning the materials of bridges and their state of maintenance, but a survey of the repair files established for financing purposes as well as the experience of local Départements make it possible to give an idea of the durability differences between techniques.

Many bridges, especially small and medium-sized in the local networks, are still masonry arches. They often have suffered from lack of maintenance, but because of their strength they often present sufficient serviceability, sometimes after some repairs. It also appeared that the foundations of the old masonry bridges on large rivers frequently were not deep enough to escape undermining, as a consequence of the technical limits imposed when they were built. But a foundation strengthening is possible, and if done, puts them in excellent serviceability.

As far as the old steel bridges are concerned, they generally support fairly well their growing old, if the painting has been renewed with sufficient frequency.

They were indeed fairly liberally dimensioned, because of the lack of knowledge in the calculation of structures, and fatigue does not seem yet to affect them. An exception, however, is to be mentioned concerning all steel bridges the deck of which is made out of little masonry arches : the latter are not waterproof and the corrosion has often strongly attacked the steel pieces supporting the deck.

Fig. 3 : Old steel bridge

Another exception, the suspension bridges : there are a little more than 200 of them in France, the major part of them being built a fairly long time ago and located in the secondary networks. Their load carrying capacity is frequently insufficient, and their maintenance condition rather poor. The collapse of one of them during the particularly cold winter of 1985 pointed out the vulnerability of the suspension bars of most of them, under low temperatures, due to the steel quality used at the time.

Fig.4 : The Sully suspension bridge

Further, the reinforced concrete bridges fall into another category. Some of those built in the first decades of reinforced concrete construction are beginning to need replacement. At that time indeed, no means of correct vibration were available, and the concrete density was insufficient. Modern concrete bridges seem to have a good behaviour, but will this last for a long time, particularly with salt aggression : we simply do not know. Many countries have suddenly encountered rather serious corrosion problems with the use of salt on roads during the winter. In France fairly high percentages of cement in the concrete used to be employed, and this

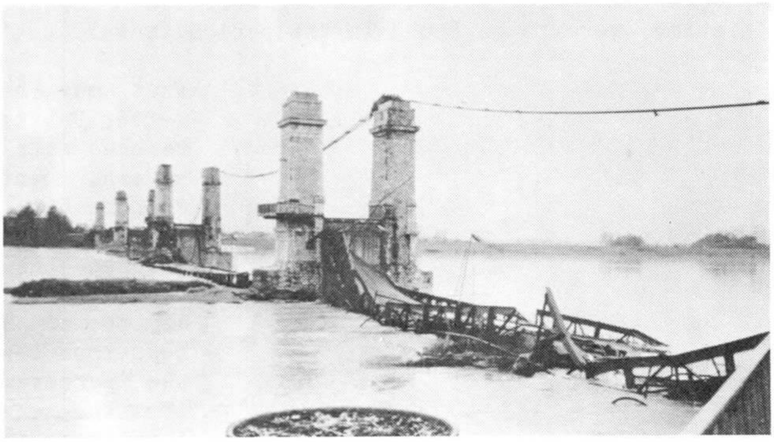

Fig. 5 : The same after collapse on Jan.16. 1985

explains perhaps the now prevailing good condition of the relatively recent concrete bridges. Nevertheless the appearance of some cases of alkali-aggregate reaction in the North of France points out a danger which up to now had not yet appeared in this country, and nobody knows whether this problem will remain limited or not in the future.

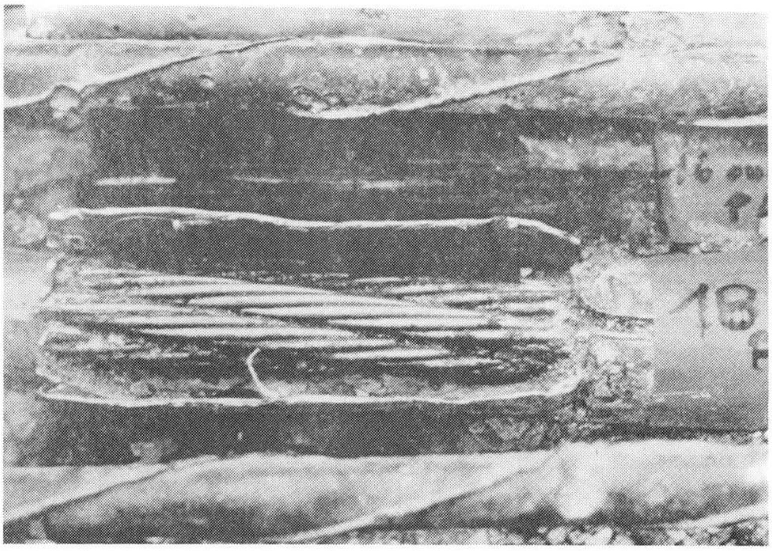

Fig. 6 : Attack of the tendons by corrosion

Finally, the last technique of primary importance to appear in the field of bridge construction is, of course, prestressed concrete. The first structures built in the 1950's were made out of precast in-situ prestressed beams. Many structures of this decade present lack of grouting and insufficient waterproofing, so that the tendons have been severely attacked by corrosion. It has been necessary to replace several structures of this type.

Another defect, which appeared in prestressed box-girders of the 1960's and the beginning of the 1970's is the lack of prestressing, due to some effects now well known. This lead to repairs by additional prestressing, which do not seem to have a noticeable effect on the life expectancy of these bridges.

Another indication concerning the life expectancy of bridges is given by following little statistics concerning 501 bridges replaced in France between 1978 and 1983. 13 of these only, all masonry bridges, were more than 200 years old and in the period from 150 to 200 years 15 were masonry bridges and 3 metal bridges. The highest densities of replaced bridges, according to their actual lifetime, were to be found in the period from 75 to 100 years.

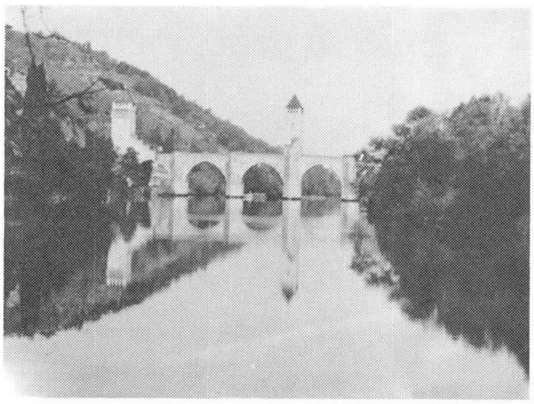

Fig. 7 : Masonry technique reached its maturity through centuries

What may be concluded from this brief survey ? The old technique of masonry reached its level of maturity through several centuries and it left some comfortable capacity margins for live load. Modern techniques have highly reduced the costs of construction, but they are developing faster and faster and a lot of bridges are built before their behaviour can be tested by time. Moreover, the increase of heavy traffic, the attacks from the environment, the use of salt spreading in winter, the growing strains allowed by codes are factors affecting durability.

Nevertheless most of the initial defects of a new technique are later overcome. Moreover, modern structures do not necessarily require complete reconstruction, because the foundations, piers and abutments can usually be retained. Thus, while some existing bridges may need replacement after 40-60 years, a design life of the order of 100 years is generally considered to be attainable by modern structures.

2. THE CHALLENGE OF THE DESIGN

New techniques and innovation tend surely to lower construction costs in high proportions, and make it possible to have more ambitious construction programmes, with a fixed possible expenditure. But the audacity of the innovator must be accompanied by an equal prudence. As an example the five bridges built on the Marne River by Freyssinet in 1949, which were among the very first prestressed bridges, are nowadays in good condition, while some other prestressed bridges built later required rather substantial repairs, as we just have seen.

The experience from many repairs shows that some additional but limited expense during the building period would have later saved heavy expenses. Moreover, repairs are not always able to restore to the structure its normal life expectancy. One might say, as a figure of speech, that one dollar wrongly saved in the design generates ten dollars needlessly spent on site, and that ten dollars wrongly saved during construction generates hundred dollars of extra repairs during the lifetime of the structure.

So the challenge to the designer consists in avoiding false economies, while saving all what is possible through technical progress and skilled design. Intelligent design indeed is quite different from blind application of technical prescriptions or rules. It is fairly difficult because the designer has to think of many things : general design, detailing, possibilities of future disorders, accessibility for inspection and repair, etc. In the case of a somewhat innovative structure, he must imagine how this one will be working and find appropriate calculation models.

Usually the owner of a future structure chooses a particular designer, consultant or official, according to proficiency criteria, which he cannot always appreciate with a certain accuracy, or he even selects him according to quite other criteria, for example the amount of the required fee or the geographical proximity. In our opinion, this way of acting ought to change somewhat. The importance of good design for the bridge durability does not suffer to emphasize other criteria without sufficient regard to professional skill.

For some years now in France, and for fairly large structures, of course, we usually choose two or even more designers who will work together, splitting the whole task between themselves under the direction of one of them. This makes it possible to benefit from the specific experience and proficiency of several designers. It also allows one to make two and even several complete designs for a given bridge. So it is possible to test by the competition between contractors which is the better structure from the economical point of view, and to promote progress with all the required care. Design fees indeed are very small, compared with the benefits to expect from better designs.

Another solution equally used is for the owner choosing another consultant than the one in charge of the design in order to advise him, i.e. in fact to propose to the designer improvements to the design. We are convinced that the greater technical difficulty of large modern bridges is a valid reason to give greater care to obtaining a better design, as much in its main features as in all its details. Durability is at this price.

3. THE CONTRACTS

For contracts the same balance as for design is to be kept between security, which is a condition of durability, and risk, which is the counterpart of technical progress. A source of progress consists in allowing the contractor to present some alternate features to the design, in order to adapt it to his own equipment and building methods, or even in some cases to propose an alternative. The alternate features permitted by the competition rule may be more or less extended, but in our opinion it is desirable to leave a margin to the contractor, considering the importance of building methods in modern bridge design.

The counterpart of this intervention of the contractor must *not* be a reason to reduce the requirement of proficiency and skill concerning the main designer. On the contrary, it is necessary to have the detailed design proposed by the contractor entirely verified and recalculated by the consultant. Quality and durability require this care in the perfecting of the design.

We have concentrated on the quality of the design, but a similar effort is to be made to use the quality assurance methods in the whole building process. The professions of construction are not yet aware enough of the necessity of improving their working methods, as it is now being done in industry. This ought to be even more obvious for bridges, the life expectancy of which is much longer than for industrial products.

4. SMALL BRIDGES

Each small structure cannot be designed with the same luxury of care as with large structures. Nevertheless small bridges are much more numerous than the large ones, and the asset they constitute is higher. Therefore, the problem of their durability is as important as for the latter. Moreover, the contractors who build small structures generally are less skilled than those who build the large bridges.

So the major point concerning small bridges is simplicity : simplicity of design, simplicity of building. This is the best guarantee of their durability. A good solution to obtain this simplicity consists in standardizing them. Prefabrication may accompany this standardization. This last solution is used for example in Belgium, and in the cold countries, for obvious reasons of climate.

In France both the economical conditions and the climate make it possible to build small structures with cast in-situ concrete. So the major part of the standardized small bridges is composed of slab decks. Their design is quite simple and fast, due to the fact that the calculation of the standard slabs is made at low price in a special public office using specific computer programs.

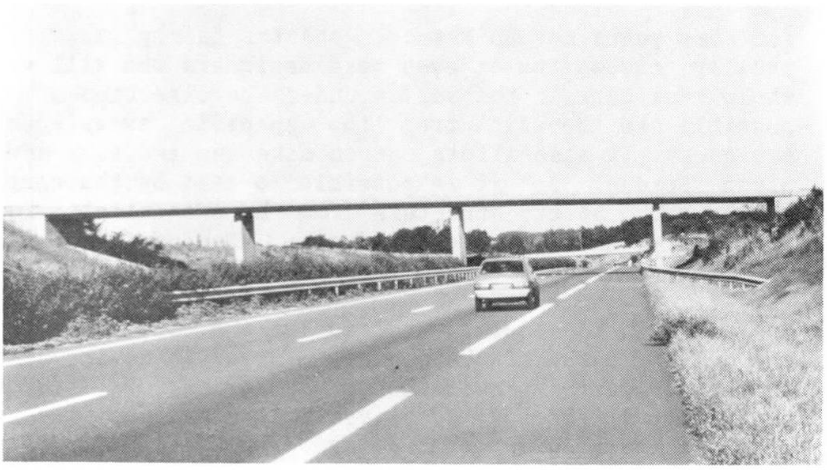

Fig. 8 : Simplicity of the slab deck for common bridges

These slabs are very strong structures, since in more than twenty years thousands of this type of bridge have been built, and their durability appears to be excellent.

5. BRIDGE MANAGEMENT

The different countries are now more aware of the necessity of promoting bridge inspection and maintenance policies, in order to obtain sufficient durability of this considerable asset. Prevention is more efficient and less expensive than subsequent repairs. Bridge inspection rules and bridge inspection manuals have been developed in several countries. Another step will consist in developing a bridge management system in order to obtain the best efficiency of public repair expenditures.

But an important aspect of maintenance concerns the inspection equipment. Large progress has been done in this field, but much more still remains to be done. For example, testing the load carrying capacity of reinforced concrete bridges by calculation would require further progress, in order to be able to detect the diameter and the location of all reinforcing bars. Devices exist nowadays, which can detect some details of the reinforcement, but not all the desirable ones.

6. CONCLUSION

It is now the moment to conclude this brief survey of some general aspects concerning bridge durability. The latter is an essential requirement for bridges perhaps even more for them than for other products of human activity, because the considerable asset they represent cannot be replaced very quickly, due to limitations of public budgets.

Now it seems that the main efforts of technical progress up to the present have tended to reduce the cost of construction. Without renouncing this purpose, it will be necessary in the future to bring an equal care to quality, which is an essential factor of durability. Taking into account the greater complexity and boldness of modern bridges, this may imply some change in enginering practice concerning design and contracting procedures. Finally, the better care now brought to maintenance certainly must be more developed.

Examining all these points is the object of the present Symposium. I hope it will come up to the participants' expectations.