Rating and evaluation of remaining life of bridges

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Rating and Evaluation of Remaining Life of Bridges

Classement et évaluation de la durée de vie restante de ponts

Bewertung und Berechnung der Restlebensdauer von Brücken

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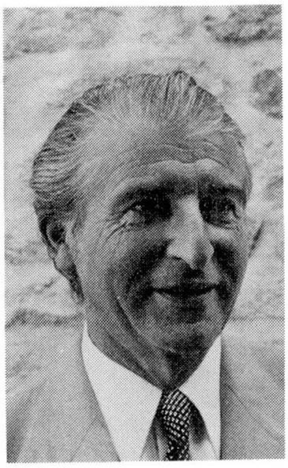

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SUMMARY
The remaining life of bridges depends on the condition of the structure, on its functional characteristics, and also on the foreseeable modifications. It depends mostly on the measures which are taken to extend it. It is generally more economical to repair and eventually to strengthen a bridge than to replace it. The decision must be taken in each particular case; this is sometimes difficult because of the remaining uncertainties. It is a complex domain which calls for a lot of research and international cooperation.

RESUME
La durée de vie restante des ponts dépend de l'état de l'ouvrage et de ses caractéristiques fonctionnelles, ainsi que des modifications à prévoir. Elle dépend surtout des mesures qui seront prises pour la prolonger. Il est généralement plus économique de réparer un pont et éventuellement de le renforcer que de le remplacer. La décision est à étudier dans chaque cas particulier; elle est quelquefois difficile à prendre à cause des incertitudes qui subsistent. C'est un domaine complexe qui nécessite de nombreuses recherches et une coopération internationale.

ZUSAMMENFASSUNG
Die verbleibende Lebensdauer von Brücken hängt vom Zustand des Bauwerks und seiner funktionellen Eigenschaft sowie von den vorzunehmenden Ausbesserungen ab. Vor allem hängt sie von den Massnahmen ab, die getroffen werden müssen, um die Lebensdauer zu verlängern. Es ist allgemein wirtschaftlicher, eine Brücke zu reparieren und eventuell zu verstärken als sie zu ersetzen. Die Entscheidung muss in jedem einzelnen Fall geprüft werden. Ein Entscheid ist oft nur schwer zu treffen wegen der bestehenden Unsicherheit. Dies ist ein komplexes Gebiet, das zahlreiche Untersuchungen und eine internationale Zusammenarbeit voraussetzt.

1. INTRODUCTION

It is widely believed in Europe that bridges have a very long life span. This opinion is based on the fact that several bridges and aqueducts built by the Romans 2 000 years ago are still surviving. In many European countries, a large part of the existing bridges are masonry bridges which appear to stand the test of time.

The other bridges, even if they are much lighter, generally produce an impression of strength and robustness which gives an illusion or long durability.

Another current idea is that the older a bridge is, the longer its remaining life, since it has resisted all aggressions. This may be partially true for stone bridges, but in most cases bridges, like other constructions and living beings, weaken and deteriorate with time.

Yet some spectacular accidents show that the safety of bridges is not absolute. The collapse of the Point Pleasant bridge in the United States in 1967, as that of the Reichsbrücke in Vienna in 1976, created a considerable stir in public opinion. In France, in 1978, the sudden collapse of several arches of a 18th century masonry bridge in Tours on the river Loire aroused a great emotion. By a miracle, there was no victim, but there could have been dozens of casualties if there had been many vehicles on the bridge when it collapsed.

Fortunately, bridge collapses are very unfrequent and their probability is very low, much lower than the probability of road accidents. But they are not admitted by the public opinion which considers them as unacceptable.

The engineers responsible for bridges are certainly aware that their life is far from being infinite. They know, which is most important, that their remaining life depends on their inspection and maintenance. It is sure that the reason why accidents of bridges are so rare is that those which appear dangerous are repaired or closed beforehand in order to avoid their collapse.

2. AVERAGE LIFE EXPECTATION

Is it possible to evaluate the expected life span of bridges ?

This question was raised during the elaboration and development of the new principles of structural safety based on probabilistic concepts. The evaluation of the life time of a structure is an important element for the assessment of the probability of failure, as for the determination of the mean return period of the different actions. It has been agreed that for bridges the expected life to take into account was about 100 to 120 years. But this value is more a "*reference period*" to be used in calculations than a real expected life span. It applies only to new bridges to be built, i.e. to structures which are very different from the previous ones.

This question appears also for the elaboration of a programme of replacement of existing bridges, in order to anticipate the annual corresponding cost. Some studies have been made on that subject in different countries. For example, the O.E.C.D. report on "*bridge maintenance*" published in 1981 mentions a study carried out in Germany in the Rhineland-Palatinate Land which calculates the number of bridges to be replaced every year until the year 2037. This study is based on an average life of 60 years. The remaining life is estimated as the difference between the average life and the age of the bridge. This method can give a rough evaluation of the replacements to be made, but the results would be markedly different if the average life had been chosen longer or shorter. The problem is that the available data are not sufficient to evaluate precisely the average life of bridges.

2.1 Average age of existing bridges

A first approach consists in analysing the stock of existing bridges in order to determine their age. In Europe, it is obvious that this age varies very greatly from the Roman bridges to the most recent ones. It is therefore essential to make distinctions between the different types of structures. From some surveys it appears that in France the average age of existing bridges is about 100 to 200 years for masonry bridges which compose 75 % of the total stock, about 100 years for metallic bridges and about 40 years for reinforced concrete bridges. But these surveys are too restricted up to now and it is not possible to derive precise information from them.

Obviously, there is a fundamental distinction to make between the average age and the average life span of a type of bridge.

In the history of masonry bridges, it appears that a large number of Roman and Middle Ages bridges have been destroyed, sometimes few years after construction. The average life of masonry bridges is therefore noticeably shorter than the average age of the existing ones.

Conversely, the oldest prestressed concrete bridges are approximately 40 years, and many new ones are built every year. So the average age of this type of bridges is less than 20 years, and it is fortunately certain than their average life span will be much longer than their present average age.

There is no doubt that it will be very useful to know better the average age of the different types of bridges, but it is only a partial element which does not enable by itself to evaluate their remaining life.

2.2 Annual rate of replacement

Another approach consists in considering the annual rate of replacement of bridges, that is the ratio between the number of bridges replaced every year and the total number of existing bridges. An inquiry has been made on this question in the O.E.C.D. countries and its results are given in the report on "*bridge maintenance*". The national rates extend from 0,02 to 1,6 %, with a majority of values between 0,2 and 0,4 %. Theoretically, it could be concluded from these last values that the average life of bridges, which is the inverse of the rate of replacement, is situated between 500 and 250 years. Obviously this conclusion does not mean anything, because the population of bridges is not at all homogeneous. As the life span of most of the bridges is certainly shorter, it appears that the annual cost of replacements is not determined by the age of the bridges, but by other considerations. However, as more and more bridges will need replacement, it is very likely that this annual cost will have to be considerably increased in the future in order to avoid traffic limitations or accidents on the road network.

2.3 Causes and reasons of replacement

In order to try to evaluate more precisely the remaining life, it is very instructive to analyse the causes and reasons of the death of bridges. They may be classified in different categories :

- collapses of the structure, due to errors in the design or during construction, or to the deterioration of materials ;
- collapses due to traffic ;
- collapses due to natural actions, such as scour of foundations, wind action on some metallic bridges ;
- collapses due to accidental actions, earthquakes, impacts by vessels or vehicles, landslides, avalanches, etc .. ;
- intentional demolition for structural reasons in order to avoid collapse ;
- intentional demolition for functional reasons, because the bridge is too weak or too narrow, or too low above a road or a navigable river, etc ..

In many countries, including France, a great number of bridges have been destroyed during the wars. So the diagrams representing the population of bridges by age-groups are very different from those of the regions which have not suffered from the wars.

It can be noted in the history of bridges that collapses due to traffic are relatively rare. They occurred only when there was a serious defect in the structure, or when a heavy vehicle tried to cross the bridge despite the load limitation.

Fortunately, the intentional demolitions are much more numerous than the accidental collapses.

These various factors work differently according to the type of the bridge.

The *timber bridges*, which have been very numerous in the past and which have almost completely disappeared, except in certain regions, have been destroyed by floods, ice pressure or fire, or by physical, chemical and biological attacks, or have been replaced because of their too weak carrying capacity.

Nearly all collapses of *masonry bridges* are due to failure of foundations, mainly because of scour, especially when they were supported by timber piles, as in the case of the Tours bridge. Many of them have been replaced because they were much too narrow or too low above a navigable river.

A large number of other bridges, some of them still young, have been destroyed because of defective *foundations*. Such accidents, which do not depend on the material of the superstructure but only on the type of foundations, still happen nowadays, as a result of scour and erosion during floods, or changes in the soil bearing capacity.

In certain regions, *earthquakes* have caused the collapse of many bridges.

The average life of the first *metallic bridges* which were built in cast iron has been rather short. They collapsed or have been replaced because of the brittleness of the metal. Many fractures appeared in the structure due to vibrations and temperature variations. In Paris, in 1939, a cast iron arch bridge on the river Seine was struck by a boat and collapsed instantaneously. After that, several other bridges of the same type have been replaced in order to avoid a similar accident.

In other types of bridges too, total or partial collapses were due to *impacts* by vessels or vehicles either against the supports or against the superstructure when these components were not robust enough.

Many accidents have occurred in the 19th century in *suspension bridges* because of corrosion and wind effects. It has been necessary to replace a number of those which had remained for it was not possible to strengthen them. Even in the 20th century, some accidents have been caused by wind. Every bridge engineer knows the adventure of the Tacoma bridge which collapsed in 1940 after a particularly short service life.

In *iron and steel bridges* built since the 19th century, the main cause of the disorders has been corrosion. The effects of corrosion have been very different depending on the various elements, on the detailing and on the possibility and quality of maintenance of the structure. It has been generally possible to repair or replace deteriorated elements and to avoid accidents. On the contrary, fatigue phenomena have caused some collapses without any warning.

Reinforced concrete bridges have suffered from the cracking of concrete and the corrosion of steel, especially those of the beginning of the century because of the shallow depth of concrete cover. When the deterioration was very serious, the bridge had to be replaced. In some cases, the concrete was greatly weakened, or was decayed due to chemical phenomena, when the bridge was situated in very aggressive weathering, or when the cement or aggregates were of bad quality. Some disorders came also from freezing and thawing and more rarely from alkali-reaction between the cement and certain types of aggregates.

Among the first *welded steel bridges*, some have collapsed because of phenomena of brittle fracture which are now overcome and can be avoided with some well known precautions concerning the quality of steel and the methods of welding.

It is too soon to analyse the reasons of the demolition of *prestressed concrete bridges*, and consequently it is not possible to predict their remaining life. In France, the first bridges built by Freyssinet over the river Marne from 1946 to 1950 are still in service and in good condition after some partial repairs. The very few bridges which have been demolished were more recent. Their defects came either from unsatisfactory design and a bad evaluation of the action-effects, or from the fact that the necessary precautions had not been taken during construction. Sometimes the quality of the concrete was not sufficient, or the position of the tendons and their protection against corrosion and especially against stress corrosion had not been carefully controlled.

It appears that water is one of the worst enemies of bridges. In many cases, whatever the material of the bridge, disorders were due to the seepage of water into the structure. That is why in most countries of Europe decks are protected by waterproofing layers. This precaution is considered as very important and necessary. The fact of the matter is that the observed degradations are much more serious when the waterproofing layer is of poor quality or deteriorated. On the contrary, when this layer operates correctly, the structure remains in a much better condition.

It would certainly be very useful and instructive to analyse in detail and quantitatively the reasons of the demolition of bridges in the past. Some studies have been made in this field, for example that of D.W. Smith quoted in the O.E.C.D. report "*evaluation of load carrying capacity of bridges*" in which are examined the causes of 143 collapses between 1847 and 1975. It appears that 60 % of the collapses are due to natural phenomena. A more complete inventory, including the intentional demolitions, would require long historic research for which much information would be lacking. But it is certainly possible and desirable to keep up to date in every country lists of annual replacements of bridges, with the precise reasons of each decision.

The conclusion of this short review is that it is not possible to take into account only the age of a bridge and an average life span in order to evaluate its remaining life. An overall assessment, like that which was made in Rhineland-Palatinate may be useful for drafting future programmes, but it would be quite unreasonable to order the retirement of a bridge when it reaches 60 or 100 years. It is absolutely necessary to examine the problem in each case.

2.4 Forecasts for the future

In order to anticipate the remaining life of bridges, it is not enough to analyse the experiences of the past. It must be considered that the aggressions they are exposed to will certainly get worse in the future.

The number of vehicles and the weight of freight vehicles have considerably increased in recent years. More and more permits for very heavy vehicles and exceptional transports are requested. It is possible to a certain extent to check the loading capacity and to evaluate the risks of fatigue deterioration of existing bridges under the present level of traffic. But it is not possible to predict the future. If the number and weight of vehicles still increase in the coming years, if new routes have to be adjusted to the transport of more heavy exceptional loads, it will be necessary to replace a lot of bridges which are now in good condition and the potential remaining life of which will be reduced. On that subject, one of the conclusions of the I.A.B.S.E. Symposium which took place in Cambridge in 1975 was that the authorities responsible for bridges had to warn the governments about the consequences of the increasing weight of very heavy vehicles as regards the safety and cost of strengthening of the structures.

It will be also necessary, if the traffic increases, to widen a certain number of bridges. In certain cases, it may be possible to widen the deck and to maintain and strengthen the bearing elements. Sometimes, a second bridge will have to be built along the existing one. But in other cases, the only solution will be to demolish and to replace it by a wider bridge. In this case too the remaining life will be voluntarily shortened.

As regards the other variable actions, especially wind actions, their effects are much better known than in the past. A great progress has been made when it has been recognized that they have a probabilistic and not a deterministic character. But the discussions which take place in the Joint Committee on Structural Safety and in the International Standardization Organization about the fixation of their characteristic values, and the discrepancies between the national codes, prove that our knowledge is still very insufficient on that subject.

The danger of some accidental actions, such as collisions, will increase with the traffic. It can be reduced by protective measures, which are never absolutely efficient and which cannot practically be implemented in all structures.

The chemical aggressions have increased in recent years, because of the weathering pollution and mainly of the generalized use of de-icing salts in order to ensure free traffic in winter time. These aggressions will probably still increase in the future, so that the deterioration of materials will be accelerated. Obviously their consequences will depend on the material and the location of the bridge.

Other new dangers already appear. For example, for some time past, extractions of materials from the river beds for the needs of construction and agriculture have considerably increased. If the volume of these extractions is not limited, the foundations of bridges can be severely attacked due to the lowering of the river bed and collapses may occur.

Conversely, it is possible that new protections and remedies are found against these dangers, thanks to the means of maintenance, repair and strengthening which can be improved, and to the protective measures which can be taken by the authorities.

Finally, it appears that the remaining life of a bridge is not at all fixedly determined : it depends essentially on what will be done intentionally or not to make it longer or shorter.

3. INDIVIDUAL DECISIONS

In practice the decisions are to be taken in each particular case, taking into account the present condition of the bridge and the foreseeable changes in the future.

3.1 Results of inspections

In most countries, bridges are systematically inspected. Generally, there are different levels of inspections : superficial inspections carried out permanently by the ordinary maintenance personnel, in order to detect the defects which may appear ; principal inspections carried out by trained personnel, at intervals of one or two years for general inspections, and of three to five years for major inspections ; special inspections made in unusual circumstances in view of a reassessment of the structure.

In recent years, these inspections have been carried out more regularly and carefully, as the engineers in charge of bridges became more aware of the dangerous condition of certain structures, when they heard of dramatic accidents which occurred in their country or abroad. On the other hand, the increase of requests for exceptional permits for heavy vehicles obliged them to check the load carrying capacity of many bridges. Moreover improvements in inspection methods have led to detect many defects which had not been discovered previously. For example, in France, underwater inspections by divers have been prescribed systematically over the past 25 years. These inspections of the lower parts of the supports are made regularly, sometimes with the aid of TV cameras, and have detected disorders which would have possibly caused the collapse of the bridge if they had not been discovered and repaired in time. As for the superstructure, thanks to the improvements of the means of access, and especially to the use of mobile inspection equipment operating from the bridge deck, it has been possible to inspect in detail those parts of the bridge which were previously very difficult to visit. So many visible deteriorations have been discovered, and more detailed inspections have been considered as necessary. And modern techniques of inspection have discovered other hidden deteriorations and obliged to take maintenance and safety measures.

This is the reason why the number of disorders has apparently increased rapidly during the recent years. In fact, many of these disorders existed already for a long time, but they had not been detected, and after all the bridges have been inspected, the number of disorders discovered every year will probably decrease.

Depending on the results of these inspections, the responsible authorities have to take decisions about the fate of the bridge. When there are no disorders and if no functional improvement is necessary, the only thing to do is to carry out regular maintenance of the bridge. When disorders are detected, there is a choice to make between repairs, eventually with a weight limit, and replacement of the bridge. When the disorders are serious, immediate measures are to be taken, traffic limitation or closure of the bridge, and possibly precautions against falling lumps under the bridge.

When functional improvements are necessary, the possibilities of strengthening or widening the bridge have to be examined.

In France, there are two annual programmes concerning existing bridges. The first one applies to the rehabilitation of those which need repairs, the second one to the improvement of functional characteristics of those located on special routes. In many cases bridges need both structural repairs and functional betterments.

When the condition of the bridge is evidently so bad that no rehabilitation is feasible, the decision of replacement is imperative. But generally the choice between repair, strengthening and replacement is not evident and comparative studies must be undertaken.

3.2 Data and information

At first, the problem is to gather and assemble all data concerning the bridge, to find the original design and the documents about the repairs and modifications carried out since it was built. The archives are often lacking, or they are very incomplete and the drawings must be done again using the exterior dimensions of the accessible elements of the structure. Even when the existing documents seem to be accurate, they must be examined with caution, because it happens that the actual dimensions are different from those of the old drawings, and it is advisable to compare them as closely as possible.

All the disorders detected during the inspections, such as deformations, corrosion, cracks, etc .. must be analysed in order to obtain a first assessment of the condition of the bridge.

3.3 Evaluation of load-carrying capacity

If it appears possible to keep the bridge, its load-carrying capacity has to be evaluated. Except for recent bridges, the design specifications have changed since its construction. The loadings fixed in the codes have increased with the number and weight of vehicles. The permissible stresses have also increased, but generally the result of the calculation appears more unfavourable than the original one. So the safety level seems to be insufficient compared to that of new bridges. On that subject, it must be pointed out that there are considerable and unjustified differences between national codes, as well in the systems of traffic loadings as in the safety elements to be taken into account in the design.

Before taking the decision of strengthening or replacement, it is advisable to analyse the problem more completely. It is particularly useful in this field to resort to the new principles of safety. It has been shown that the concept of "*safety level*" is very complex and cannot be expressed quantitatively in a simple manner.

Firstly, a distinction must be made between ultimate and serviceability limit states. Thanks to this distinction which did not exist in the previous specifications it is possible to treat differently the effects of the actions which are really dangerous, and those which would have only minor consequences.

Secondly, it is also useful to refer to probabilistic concepts in order to evaluate the random elements to be taken into account, which are not the same as in a structure to be built. As the bridge exists, the permanent loads are known more precisely, provided that the real dimensions have been checked, and only the remaining uncertainties are to be taken into account. For the variable actions, it can be considered that the remaining life of the existing bridge will be shorter than the life time of a new bridge, hence the reference period and consequently the characteristic values of the actions may be reduced. But the evaluation of these life spans is not sure enough to arrive at precise conclusions. For the combinations of actions, the probability of simultaneous occurrence of unfavourable values of several independent actions is reduced, so that the values of some of the variable actions may be reduced, in accordance with J.C.S.S. and ISO documents. For instance, it would be unreasonable to combine the heaviest loading with the strongest wind action.

Concerning action-effects and resistances, it is important to know the actual condition of the structure. Strengths of materials can be measured by some removals of samples for laboratory tests. The mechanical behaviour can be appraised by the exterior condition and deflections of the load-carrying elements and also by close examination of the bearings and expansion joints. It may be necessary at this stage to carry out more complete investigations in order to determine the internal condition and the behaviour of the structure. Several non-destructive methods can give useful information : sclerometer (rebound-hammer), pachometer (magnetic detector), ultra-sonic devices, fissurometry, extensometry, gammagraphy, bearing pressure weighing devices, etc .. In certain cases, with recent techniques, it is possible to measure the total stresses of steel and concrete and not only the variations of stresses under loading.

These supplementary investigations are rather costly and must be used only for precise purposes, in close collaboration with the design office.

The structural analysis should apply to the bridge in its actual condition and eventually in its condition after repair or strengthening. As far as possible, the calculation should be carried out taking into account the real behaviour of the structure, including the influences of cracking, frictional forces, redistribution of stresses, etc .. With the present methods, the results of this calculation will be more accurate than the original ones.

According to its conclusions, an evaluation is then made of the load-carrying capacity. It must be recognized that this notion is not so simple as it may appear. It is not sure that the posting of a weight limit for one vehicle can prevent from dangerous stresses in certain elements due to random distributions of loads.

The results of the calculation can be confirmed by static full-scale loading tests which allow a comparison between theoretical deformations and those observed experimentally. A comparison may also be made between calculated and measured stresses in certain sections.

Dynamic tests, as those which are made in Belgium, will perhaps be able to give supplementary information on the condition and evolution of the structure.

These tests are useful to check the behaviour of the bridge as a whole and to detect the defects which have not been taken into account in the theoretical study. But they cannot allow to determine the maximum load-carrying capacity of the bridge, for the test loads are necessarily below the ultimate load, nor its resistance to a combination of several different actions. And of course they cannot say anything about the fatigue behaviour of the structure.

One of the problems encountered in this field is the fixation of permissible stresses or partial safety factors, which are not necessarily the same as for new structures. When the data concerning an existing bridge are sufficient to reduce the uncertainties, it may be considered that its "*level of safety*" is the same as if it was a new one, even if the numerical values of the safety factors used in the calculation are lower.

Up to now there is no international recommendation on that subject which deserves very useful research.

3.4 Disorders, repairs and modifications

When the conclusion of these studies is favourable, the design is completed for repairing and if necessary strengthening or modifying the bridge.

It is very important not to repair only the visible defects, but to find their causes in order to remedy them and avoid further deteriorations. It must be determined whether the degradations are due to the material itself, or to the detailing of the structure, or to movements of foundations, whether the cracks are normal or not, etc ..

It is also necessary to examine all the consequences of the planned rehabilitation work, some of which may be unfavourable or even dangerous. For example, when additional prestressing tendons are necessary, it must be checked not only that tensile stresses will be suppressed in certain sections, but also that dangerous stresses will not appear elsewhere.

The possible repairs and modifications are appreciably different according to the type of structure.

Masonry bridges are essentially exposed to disorders in their foundations. The vaults are generally very robust and able to carry very heavy loadings. It is often possible to place a reinforced concrete slab on the vault in order to widen the carriageway, provided that the foundations are strong enough. The remaining life of these bridges may be very long if their foundations are properly maintained and if necessary repaired and strengthened. In some cases, vibrating effects of traffic have caused cracks and loosening of stones, which are generally not worrying and can be easily repaired if the piers and abutments are sound.

Disorders in the *foundations* are dangerous for all types of bridges. They can be detected only in an indirect manner, through deformations in the supports and in the structure. It is often difficult to determine their cause and the corresponding repairs are generally very expensive. But they must be made without hesitation in order to avoid a possible collapse of the bridge. When the superstructure must be replaced for structural or functional reasons, it is sometimes suggested to re-utilize the supports which appear in good condition. This could be accepted only if it is ascertained that the existing foundations are strong and durable enough, for it would be unreasonable to build a new superstructure on defective foundations.

In *steel bridges*, the components which mainly suffer from corrosion can be quite often repaired and strengthened. It is possible to strengthen too weak elements with the aid of welded plates, or to replace them when they are too deeply deteriorated. So the remaining life of steel bridges can generally be extended and made very long. However some difficulties appear when some parts of the structure are not accessible or when metallic pieces are embedded in masonry or concrete. It is advisable in this case to demolish and rebuild those parts of the bridge which may be dangerous. Other serious problems arise from fatigue and corrosion fatigue phenomena and it is always necessary to strengthen or replace the elements subject to this menace.

Concerning *suspension bridges*, in spite of the improvements in the inductive-magnetic techniques and more recently in acoustic spying, it is not possible to evaluate accurately the amount of corrosion and of breakage of wires in the cables.

If it appears that the strength of the cable is too weak, the only solution is to replace it, which is difficult and expensive, or to replace the bridge by a new one. Similar problems are likely to appear in cable stayed bridges, that is why it is preferable to separate the cables in harp, in order to be able to replace them individually if necessary.

Reinforced concrete beams and girders can now be repaired rather easily and efficiently as a result of new techniques and various products created by modern chemistry. It is generally possible to rehabilitate the structure when the disorders are not too severe, but it is very difficult to strengthen and practically impossible to widen it. Recently in France a reinforced concrete bridge which it was not possible to close has been strengthened by prestressing cables, and the cost has been nearly the same as that of a new superstructure.

Some examples of repair and strengthening of *prestressed concrete bridges* exist already. In each case, the method must be designed in detail by specialists.

It is not possible to forecast the remaining life of these bridges, but it is certainly desirable to find new techniques of inspection and repair in order to extend it.

In all cases, in order to avoid new disorders, it is necessary to prevent seepage of water into the deck and for this purpose to protect the deck by an efficient and durable waterproofing layer.

3.5 Financial and safety criteria

When the design is completed and the cost of the works approximately known, the problem is either to repair or to replace the bridge.

The answer is immediate when the main elements of the structure are in good condition and when only partial repairs or strengthenings are necessary. In most cases, the proper solution is to increase the remaining life of the bridge by replacing or stengthening some deteriorated elements. Sometimes the load-carrying capacity can be notably raised by reducing the permanent load, for example by replacing a heavy deck slab by a lighter one, using such materials as lightweight concrete or aluminium.

The decision is more difficult when the cost of the works is very high. This cost must then be compared to that of a new bridge, to which are of course to be added the cost of demolition and all supplementary expenses due to disturbance of traffic. These supplementary expenses are sometimes so important that the total cost of reconstruction is much higher than the cost of the new bridge.

For this financial comparison, the concept of "*discounting*" is employed, which expresses the fact that future costs are of lower present value than present costs. Some economic studies have been made in this direction. For example, a calculation made in the O.E.C.D. report on maintenance shows that if the reconstruction of a bridge is postponed for 15 to 20 years, it is more economical to make repair works reaching 40 % of the replacement cost if the discount rate is higher than 3 %. Generally the discount rate is effectively higher than 3 %, and the remaining life due to so expensive works must be longer than 20 years. The conclusion is that from the economic point of view it is better to extend the remaining life of a bridge than to replace it, even if the corresponding cost is high.

But this point of view is secondary compared to the most important one which is to ensure safety. The main difficulty often encountered for the decision is that the results of investigations and calculations are not completely sure and that some uncertainties subsist. In fact, these studies can prove that the structure is unsafe, but they cannot totally ensure that it is safe, or will be safe after repair. Every engineer knows that absolute safety cannot be achieved.

It is then necessary to imagine danger scenarios and strategies against potential risks, and to look for the main determining factors and the major weaknesses which could threaten the bridge.

The main uncertainties concern those parts which cannot be inspected and are checked only by indirect ways. The principal danger is situated in the bearing elements the failure of which may lead to sudden collapse without any warning, for example :

- condition of foundations which cannot be assessed but very partially and indirectly ;
- condition of internal wires of suspension bridge cables and of their anchorages ;
- condition of elements subject to fatigue phenomena ;
- corrosion or rupture of prestressing tendons.

Methods and techniques of investigation have been very much improved in recent years. Yet further research is required and new improvements must be made in order to reduce the remaining uncertainties and to arrive at reliable qualitative and as much as possible quantitative data.

It is not enough to utilize at spaced intervals advanced instruments and methods. It is desirable to find more rapid and economical measures, such as acoustic spying or gammascopy for cables and tendons, which could allow a more complete and frequent inspection.

In spite of the improvements which may be awaited in this field, uncertainties will remain for a long time and a balance has to be achieved between the acceptable residual risks and the financial considerations which lead to extend the life of the bridge.

As the available funds are very generally limited, the responsible authorities have to make difficult choices when establishing programmes and priorities.

Some decisions are compulsory :

- The protection of the national heritage of bridges obliges to preserve as long as possible all the bridges with a historical or aesthetical character, even when the cost of their maintenance and rehabilitation is very high. Such is the case for almost all bridges prior to the 19^{th} century, and for several more recent ones which possess an architectural value or have represented a new step in the technical evolution.
- Conversely, those which are functionally insufficient and which cannot be modified, or are structurally in so bad a condition that they cannot be repaired, are to be replaced, as well as those which would necessitate very expensive repairs followed by permanent surveillance and maintenance expenses.

Between these two groups, there are a lot of bridges the remaining life of which must be extended for economic reasons. The necessary repairs or improvements must be carried out in order to ensure safety as much as possible, to avoid new disorders and to reduce further maintenance costs. In some cases, the loadings have to be limited.

Before the repairs are done, or when some doubts remain about their efficiency, supplementary inspection and warning measures are to be taken, in order to allow immediate emergency decisions concerning safety, including load limitations or even closure of the bridge if necessary.

4 CONCLUSIONS

In the present state of knowledge, it is not possible to evaluate precisely the remaining life of bridges. It is just a matter of very approximate engineering judgment.

For recent bridges, it is generally considered that their life time will be of about 100 years, but this prediction is obviously more subjective than rational. For the others, the remaining life depends essentially on the type and the basic material of each bridge, on its age and condition, and above all on the possibilities of repairs and improvements which can extend its service life.

Therefore it would be very useful to gather in each country inventories of existing bridges classified along their type and date of construction. It is also desirable to continue inquiries on the annual rate of replacement of bridges, indicating the reasons of each replacement and as far as possible to look for information on this subject in the past.

With the aid of various documentation systems using cards, registers, databanks, catalogues of defects, which allow to analyse the behaviour of the different types of bridges, it may be possible to prepare in a more precise manner the overall programmes of replacements for the years to come.

But the decision must be taken in each particular case either to extend the remaining life of the bridge or to demolish and replace it. This decision must take into account the actual condition of the structure and its foreseeable evolution as well as its functional capacities and the necessary improvements to be made for the needs of traffic.

The choice is sometimes difficult to make because, in spite of the new techniques developed in recent years, many uncertainties subsist in the appraisal of existing bridges.

Improvements are very desirable in this respect :

- in the techniques of inspection and investigations, especially in order to find out rapid and economical non destructive methods, allowing to check the internal condition of cables of suspension bridges and of tendons of prestressed concrete bridges, and the soundness of foundations ;
- in the design rules to be applied to existing bridges, which need special specifications ;
- in the techniques of repair, strengthening and widening.

Generally it is more economical to repair and modify the bridge than to replace it, and anyway the available funds are not sufficient to demolish and rebuild all defective ones. When the structural or functional condition is too bad, the reconstruction is unavoidable. But in many cases a balance is to be achieved between safety and economic considerations. Sometimes, when the bridge is kept in service, safety measures such as traffic limitations and increased surveillance must be taken.

It results from this policy that it is desirable to extend as much as possible the life expectation of new bridges, by different means : attention paid to durability aspects and eventually overdesigning of certain elements, protection devices especially for drainage and waterproofing, easy access for inspection and maintenance and possibilities of strengthening the structure if necessary.

It is much more economical to do so, because these precautions in the design can avoid expensive repairs in the future and substantially postpone the replacement of the bridge without appreciably increasing initial costs. In this field, prevention is certainly better than cure.

For new bridges as well as for existing ones, it is of the utmost importance that all relevant data information such as records of construction, inspections, repairs and alterations, as-built drawings, calculations, etc .. are collected and filed with continuous up-dating.

In every case, the remaining life depends obviously on the quality of inspection, maintenance and repairs, and on the future changes in traffic and environment of the bridge ; so it depends essentially on decisions the effect of which will make it longer or shorter.

These decisions involve a wide range of technical knowledge and a good engineering judgment, they call for much experience supplemented by advice from specialists of laboratories and design offices.

It is a very difficult problem which deserves a lot of studies and research in different fields in order to fill some serious gaps in our present knowledge and for which an active international cooperation is very desirable.

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