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Contribution of knowledge of real properties of existing civil engineering structures in refining the structures reliability assessment

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Abstract: Within the framework of many consulting assignments about risk and lifecycle management of existing civil engineering infrastructures, OXAND's analyses relied on structures assessment taking into account the structure's state of deterioration, the quantitative estimate of its residual bearing capacity and the future progression of this capacity over time. The structure assessment can be carried out considering different methods. In a general manner, three main axes allow to characterize the method of assessment: behaviour modelling, origin of input data, uncertainties consideration. In this three dimensional basis, several assessment methods levels can be defined from purely regulatory calculation, using standard or design input data, to realistic and probabilistic approaches. According to the results of the first assessment levels, it is possible to refine the calculations by moving to higher levels. This methodology will be illustrated by an example which consists of networks of reinforced concrete beams subjected to a rapid increase in their mechanical stresses. The risk of a beam failure was brought under control by setting up a maintenance procedure, which unfortunately created a risk of unavailability of these infrastructures. Higher levels of assessment represent potential ways to reduce this risk of unavailability by taking full advantage of the real properties of the structures.

1 Introduction

The better the knowledge of the existing infrastructure is, the more precise the evaluation of its real performances can be. In addition, the management of the infrastructure may be refined all the more, with the aim of getting closer to the best balance between the control of the structure's performance (safety, reliability, etc.) and the constraints (unavailability, costs, etc) necessary for getting this control level.

At first, a structure is designed, and then built in order to reach a level of performance. However, the environment, the operating conditions, the materials' properties and what is expected from the infrastructure may evolve over time. Then, it is necessary to assess the reliability of a structure by considering, on one hand, the current state (ageing and/or more important loads) and on the other hand the required performances of the existing structure.

The consideration of the existing data representative of the current state of the structure helps to demonstrate the current reliability, in spite of ageing or operating change.

In this framework, developments, based on different techniques of infrastructure reliability assessment [1] [2] [3] [4] [5] [6] [7], have been carried out to consider the maximum of information about real properties of existing structures when they are being assessed.

The first part presents the general principles of infrastructures assessment and the different levels of assessment allowing to refine the calculations by moving to higher levels.

In the second part, this methodology will be illustrated by an example which consists of networks of reinforced concrete beams subjected to a rapid increase in their mechanical stresses leading to a risk of a beam rupture.

In order to manage this risk of rupture, the strategy which was implemented by the owner allows to completely manage the risk of beam rupture, however it generates a risk of unavailability for the concerned infrastructures. Indeed, it is necessary to temporarily stop operating in order to unload the structures.

Thus, in this example the study has highlighted some ways to improve the availability rate of the studied infrastructures, while preserving a good management of the risk of beam rupture. These ways are based on structure assessment methods enhancing the value of the real performances of the existing structure.

2 Infrastructure assessment: several approaches

2.1 General principles

Checking the infrastructure safety, during design or assessment phases, consists in making sure that the resistance (R) of a structure element is higher than the stresses (S) to which the element is subjected, and this with a prescribed safety margin. By considering the problem the opposite way, it is a question of making sure that the probability of having $R \leq S$ (or $R - S \leq 0$) is low enough to be considered acceptable. This probability represents the probability of failure of the structure (cf. Fig. 1).

The input variables, variables of resistance or variables of stresses can be considered as random variables. These ones can therefore be described using statistical distributions. Then, the probability of failure of the structure can be calculated by probabilistic calculations based on the statistical distributions of input data, and therefore allows estimating the safety level of the structure.

In practice, it is still quite rare to verify the safety of a structure with probabilistic calculations. In most design codes, in particular in Eurocodes [8], the verification of the safety of a structure is carried out by deterministic calculations, which take into account input data uncertainties and modelling approximations by using partial safety factors. These ones allow to increase the values of unfavorable stresses and to reduce the values of materials strength. These partial safety factors mainly result from experience feedback. They allow to take into account the variability of the input data and to design a safe infrastructure, according to the current regulatory prescriptions.

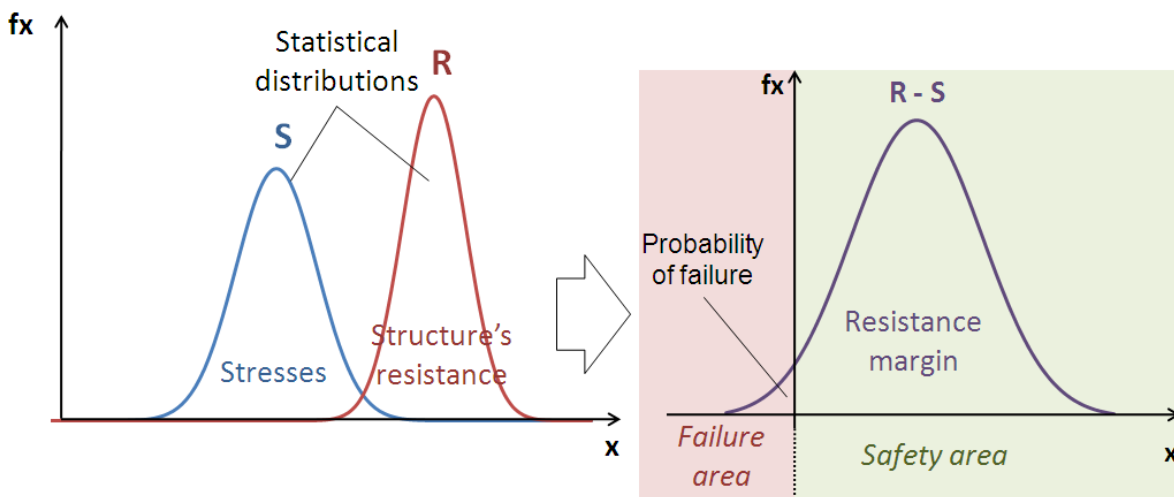


Fig. 1: Probability of failure of a structure [1]

Beyond the classical regulatory verification, and even by staying within the framework of the regulatory verification, the structure assessment can be carried out considering a lot of possible methods. They vary according to the context, the available input data, the wished precision, the wished approach, etc.

2.2 Three main axes to characterize assessment

In a general manner, three main axes allow to characterize the method of assessment. Then, it is possible to describe the various assessment methods by their location on these three main axes:

2.2.1 Axe 1: Behaviour modelling

There are a lot of possibility for behaviour modelling (structure mechanical behaviour models, loads models, etc.) from calculations said as "regulatory" to calculations said as "realistic" (cf. Fig. 2).

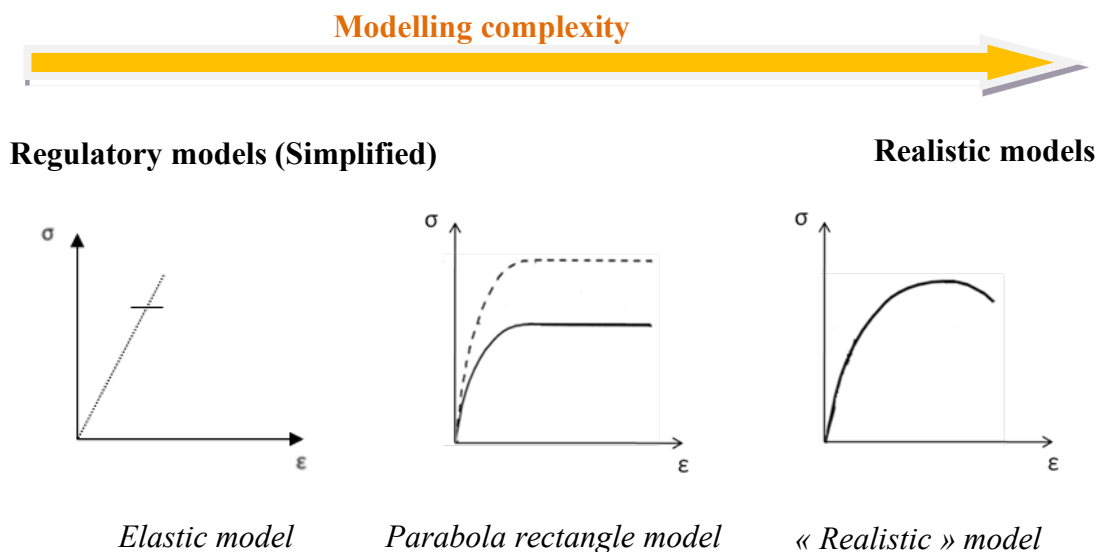


Fig. 2: Modelling complexity (Example Concrete behaviour law [8])

- Calculations said as "regulatory" consist of the elements of the structure (section of reinforced concrete, etc) with which the resistant capacity (resistant efforts) is calculated to justify the section according to the models of resistance presented in codes. For example, bending moment capacity, shear capacity, etc.
- Calculations said as "realistic" consist of calculations carried out with more accurate and refined models. They allow the implementation of more complex models, to take into account in a more realistic way the combination concrete-reinforcement of the reinforced concrete, non linear behaviour of materials, evolution of the behaviour of materials over time, etc.

2.2.2 Axe 2 : Origin of input data

The origin of input data is diverse (cf. Fig. 3):

- Standard or design values: The values of input data are taken identical to the values which have been used for design (calculation notes, etc), or they are determined as standard values from guidelines or from design codes.
- Estimated values: The values of input data can be updated, from feedback or estimations which take into account available information about the structure. It can be, for example, a feedback about compressive strength of concrete after a given lifetime and given environmental conditions. It can also be simulations which allow to estimate the residual section of steel reinforcements. Live loads can be estimated from updated hypotheses of operation, etc.
- Measured in situ values: To reach a maximum of precision, the values of input data can be measured on the existing structure. It consists for example of geometrical measures on the structure or of experimental, destructive or non-destructive, testing on materials. Live loads can also be measured in situ (measure of road traffic, etc).

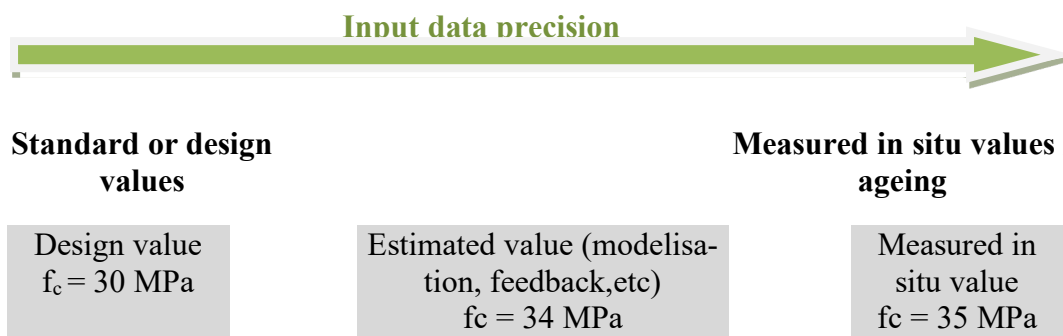


Fig. 3: Input data precision (Example Compressive strength of concrete)

2.2.3 Axe 3 : Uncertainties consideration

The level of uncertainties consideration can vary from deterministic approaches to probabilistic approaches (cf. Fig. 4):

- Deterministic calculation: All variables are represented by deterministic values.

- Probabilistic calculation: Among all the variables, at least one is random and represented by its statistical characteristics (statistical distribution).

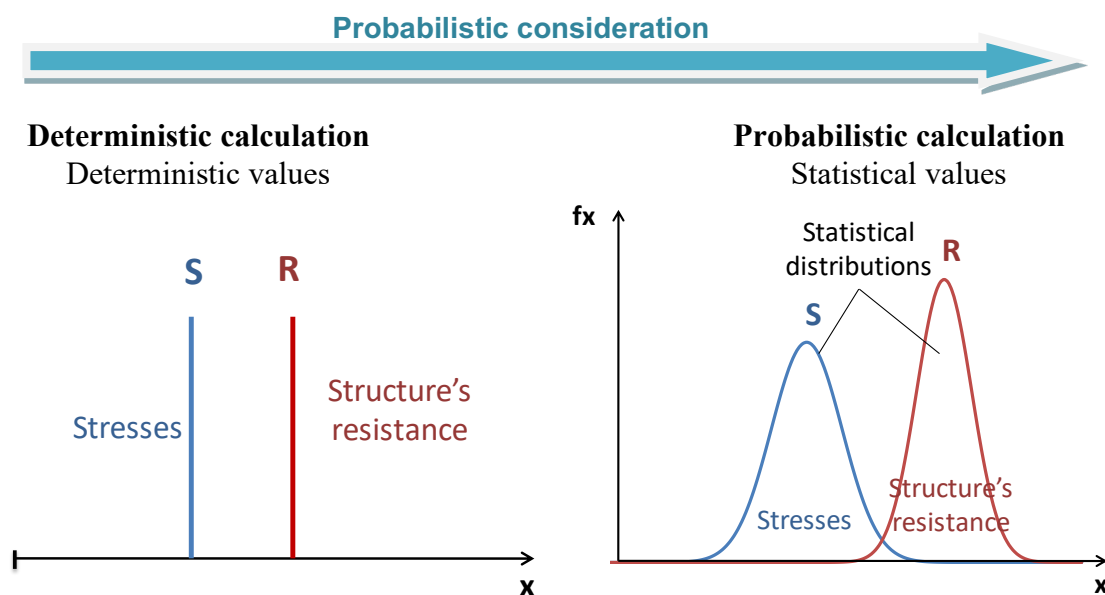


Fig. 4: Probabilistic consideration (Example Verification R-S)

For each of these three axes, the more we tend towards the right position, the more precise and realistic the assessment will be. Indeed, the more simplified the assessment is, the more important margins it has to integrate in order to be able to cover the uncertainties regarding adopted simplifications and so the more conservative the results will be. On the other hand, when we are able to reduce these uncertainties, with regards to the same safety margins, results can thus be less conservative.

The more precise the knowledge and the assessment of the structure is, the more refined the structure management can be.

2.3 Different levels of assessment

When positioning methods of assessment on axes which have been presented previously, there is a multitude of different combinations, which provide a large number of possible methods of assessment. They can be defined by their location in the three dimensional basis made of the three main axes (cf. Fig. 5).

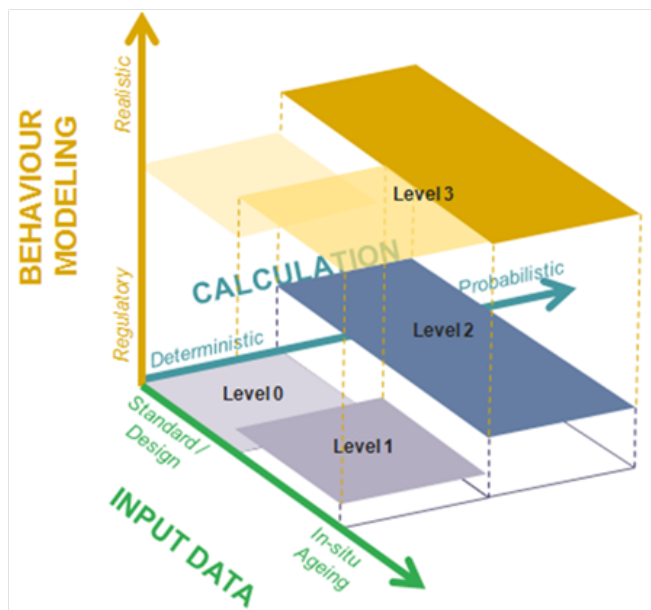


Fig. 5: Different levels of assessment

Among this set, four main levels of assessment have been defined, as described below:

- **Level 0:** The calculation is purely regulatory, by using standard or design input data. It may eventually be necessary to adjust design input data, in case of a change of code between design and current assessment.

Context: The calculation is purely regulatory and allows to take into account (1) operating modifications (change of nature or value of loads), or (2) regulation modifications (new standards).

Objective: Verify that the structure « such as designed » and with the current operating conditions complies with the standards' prescriptions.

- **Level 1:** The calculation is regulatory and uses updated input data which take into account the real state of existing structures (structural abnormality, ageing, etc).

Context: The calculation is regulatory and allows to take into account structural problems (difference between « such as designed » / « such as built ») or/and structure ageing. The input data (loads, section of steel reinforcement, compressive strength of concrete, etc) can be updated from :

- Inspections, in-situ measures and testing on the existing structure ;
- Estimations and numerical simulations with data on the existing structure.

Objective: Verify that the existing structure « such as built and aged » complies with the standards' prescriptions.

- **Level 2:** The calculation is probabilistic, « out of classical regulations » and is based on the knowledge of statistical characteristics of few input data.

Context: If the classical regulatory calculations conclude to a nonconformity of the structure, it is possible to use more precise methods which are « out of classical regulations », allowing to assess the importance of the difference between the current struc-

ture and standards, and thus to assess the level of urgency for scheduling compliance actions.

Objective: Assess the safety level of the structure with a probabilistic approach in order to assess the level of urgency for scheduling actions.

- **Level 3:** Calculations are carried out through a realistic approach and modeling, for which input data could be considered as deterministic or as probabilistic.

Context : The realistic approach allows in one hand to assess structure's resistance margins (residual strength capacity) in a more realistic way and to provide arguments to owners in order to decide if it is necessary to do something immediately or if it is possible to delay actions in time. On the other hand, it allows to model the structure behaviour in specific conditions and in the most realistic way possible.

Objective 1 : If the results from the first levels are not satisfactory, calculations can be refined again with a realistic approach (and eventually probabilistic too) in order to bring additional precisions regarding the level of urgency of the intervention.

Objective 2 : The realistic approach can provide answers to specific questions about the structure behaviour in specific conditions (plane crash, etc) or by modeling future ageing (level of prestressing after 30 year, etc).

The choice of the assessment method can be made according to the context and the expected objective. According to the results of the first assessment levels, it is possible to refine the calculations by moving to higher levels. For the structure which doesn't satisfy the regulatory verification, a more precise assessment can allow, for example, to estimate the urgency of compliance actions, with the aim to assist the owner in scheduling and prioritizing actions.

Beyond the consideration of the ageing of the structure, assessments which are based on knowledge of the real state of existing structures, allow to consider the real performance of the built structure. In certain cases, the actual existing structure can demonstrate performance which is higher than the performance of the designed structure.

2.4 Potential margins between the structure « such as designed » and « such as built »

Although structure design is more and more precise, with the aim of being safe enough without excessively overdesigning the structure, hypotheses of design are generally conservative with regard to the real properties of the built structure.

On one hand, dimensions and minimal resistances imposed by design are generally slightly increased during the construction: strength of set up materials can be sometimes slightly higher than those expected, and dimensions are often increased for construction needs (we choose for example steel reinforcement of reinforced concrete according to the available diameters superior to the theoretical design diameters).

On the other hand, the uncertainties which exist during the design phase are taken into account by increasing the unfavourable structure loads, and by reducing the materials strength. However, a part of these uncertainties (for example the variability of input data)

can be precised by investigations on the existing structure. Then, input data can be taken into account in a less conservative way.

Therefore, it is possible that the structure “such as built” presents a resistance margin higher than the resistance margin wished for structure “such as designed”.

The consideration of a maximum of data about the properties of the actual existing structure can allow in certain cases the structure to still demonstrate sufficient reliability, in spite of ageing or operating change.

The interest of the various levels of assessment presented in the previous chapter is to be able to take into account the various levels of information on the existing structure, and so to be able to get closer to the "real" reliability of the structure.

3 Application case: structure subjected to an increase of its mechanical stresses

3.1 Context

The study which is presented through the next paragraphs represents a good example of an infrastructure assessment taking into account the real properties measured on the existing structure in order to improve risks infrastructure management.

Some nuclear civil engineering structures consist of networks of reinforced concrete beams which are subjected to a rapid increase of their loadings due to operational conditions.

The objective was to establish an overall diagnosis of the state of the beam networks and of their exploitation, and to identify the main risks associated with the current exploitation of these infrastructures.

In order to consider the potential ageing of reinforced concrete over time, in particular because of the mechanisms of the corrosion of steel reinforcement, concrete carbonation simulations were carried out with the software SimeoTM Consulting developed by OXAND. The simulations were carried out by taking into account environmental properties of these structures (temperatures, relative humidity, carbon exposure), materials properties (compressive strength of concrete, porosity of concrete, etc.) and the age of these structures.

The properties of materials were defined from the building characteristics of concrete formulation, and were completed by the results of concrete compressive strength testing, carried out a few years before the study.

Considering all these characteristics, the results of the simulations highlighted a very low current level and a slow evolution of the carbonation depth of central parts for the years to come.

As a conclusion, the diagnosis highlighted the absence of ageing and the good general state of the beams. Nevertheless, the continued increase of mechanical stresses, linked to the increase of live loads, represents a danger for the structures' resistance (cf. Fig. 6).

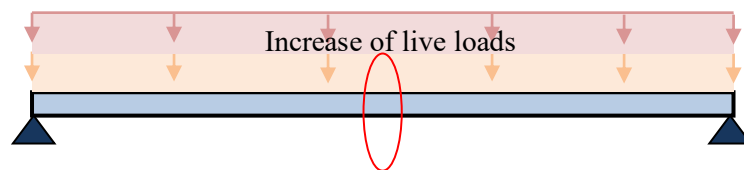


Fig. 6: Bending beam subjected to an increase in mechanical stresses

In order to manage this risk of failure, the strategy which was implemented by the structure owner consists in regularly measuring the level of overloads and in relieving the structure before the overloads reach a limit criterion, based on ultimate limit state calculations with design data.

This practice allows to completely manage the risk of beam rupture, however it generates a risk of unavailability for the concerned infrastructures. Indeed, once the limit criterion is reached, it is necessary to temporarily stop operating in order to be able to unload the structures.

Thus, the study has highlighted some ways to improve the availability rate of the studied infrastructures, while preserving a good management of the risk of beam rupture. These procedures are based on structure assessment methods enhancing the value of the real performances of the existing structure.

3.2 Refine the structure assessment

In the implemented strategy, the limit criterion, beyond the one the infrastructure operation is interrupted in order to carry out actions to relieve the structure, was defined from ultimate limit state calculations by considering design data for the beam elements (compressive strength of concrete, yield strength of steel reinforcement). That represents a level 0 of assessment (cf. Figure 2). However, data can be refined by considering the actual built structures (level 1 of assessment). It is a question of taking into account differences between the structure "such as designed" and the structure "such as built and aged", and to take into account the fact that the uncertainties existing at the time of design can be partially precised by investigations on the existing structure.

While complying with standards' requirements and with the conditions of an ultimate limit state calculation, several ways lead to believe that it may be possible to obtain a refined limit higher than the currently used limit:

- The ageing of the beams is very not important and even non-existing;
- Bending test which had been carried out on several beams some years before the study had highlighted a real bending resistant capacity higher than the expected one;
- It seems possible to be able to reduce the partial safety factors used in the ultimate limit state calculation, considering the knowledge of real statistical properties of materials strength.

Bending test was carried out on several beams. The results show real bending resistant capacity, around 10 to 20 % higher than those estimated in calculations using design data.

This difference is linked to a real materials strength which is higher than design limits. In this particular case, it would be the yield strength of steel reinforcement of reinforced concrete.

Besides, testing compressive strength of concrete highlighted a strength mean value very slightly higher than the design one and a coefficient of variation of this strength lower than 10 %. According to the Eurocode [8] recommendations, this low variability of compressive strength of concrete allows to be able to reduce its associated partial safety factor (a little more than 10 %).

By taking into account this information about the real properties of the existing structure, the bending resistance margin of existing beams is higher than the one of designed beams. Therefore, by keeping a fundamental ultimate limit state calculation in compliance with standards, the refined limit criterion could be higher than the initial limit criterion, by at least 15 % according to our estimations (cf. Fig 7).

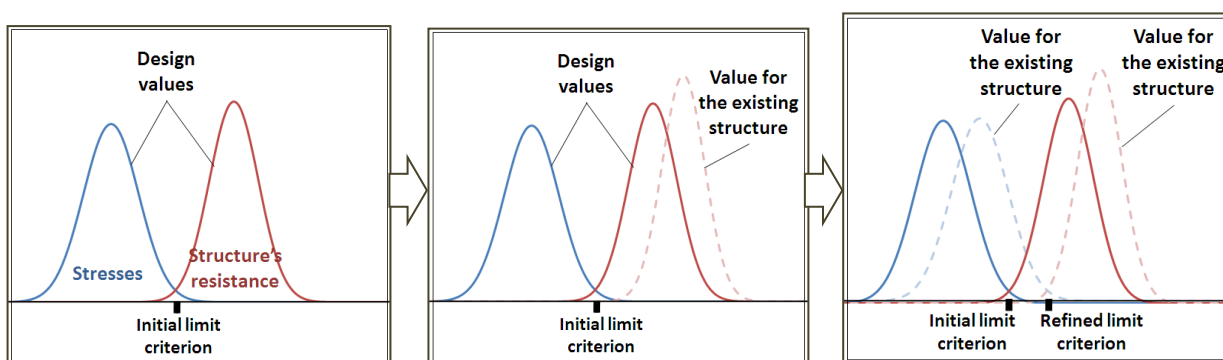


Fig. 7: Refined calculation of the limit criterion

At this upper level of load, the risk of failure still complies with calculation standards' requirements. On the other hand, the use of the refined load criterion would allow to reduce the risk of unavailability of the infrastructure. Indeed, the refined criterion brings both a gain in acceptable overload which is associated with a gain in time before being forced to interrupt operation in order to relieve the structure (cf. Fig 8).

Thus, the gain in time increases the chances of reaching a scheduled outage before being forced to relieve the structures. It decreases the risk of having a fortuitous unavailability between two scheduled outages. The risk of unavailability during cycles is reduced, while preserving the control of the risk of beam rupture.

This gain must be more precisely determined by investigating the various ways allowing to refine the input data of the calculations. The studies may be based on the analysis of construction notes, on the measures and testing already carried out on the beams' elements and on additional testing.

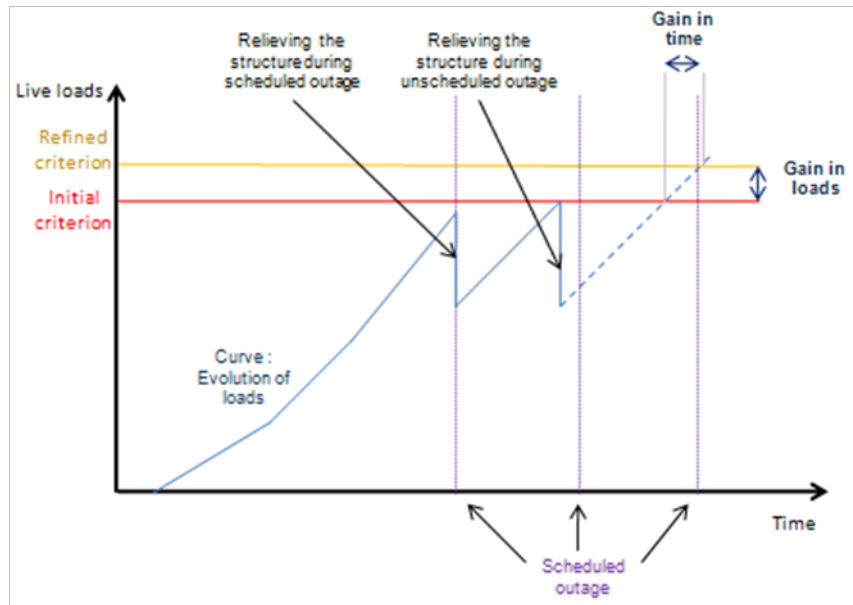


Fig. 8: Gain provided by the refined limit criterion

In the framework of the study, this approach to reduce the risks of unavailability was compared with other more traditional possible approaches:

- Replacement or reinforcement of all beams presenting the lower resistance margins. However, the increase of load limit would be relatively low because the resistance margins of the residual beams are only slightly higher.
- Total redesign and refurbishment, which would assure to have a very low risk of unscheduled unavailability.

These three approaches were compared, according to the coupled “cost of intervention” and “importance of the reduction of the risk of unscheduled unavailability” (cf. Fig. 9).

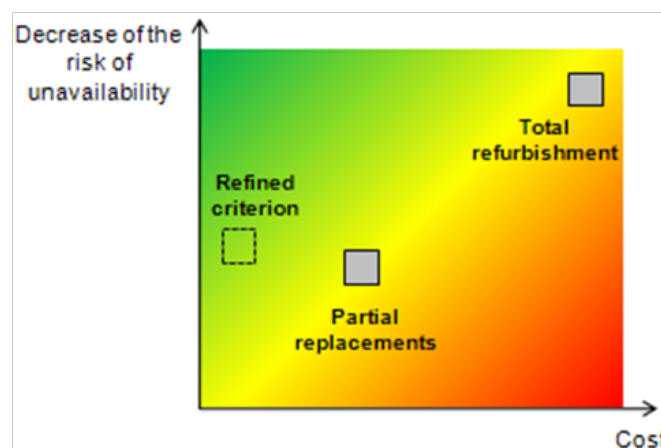


Fig. 9: Comparison of the three approaches

The method of calculation of the refined criterion seems very promising. Indeed, the costs required for such a study are relatively low, nevertheless considering current information and estimations, the reduction of the risk of unavailability would not be negligible. The recommendations of the study have highlighted the need to study the method of calculation

of the refined criterion in order to assess precisely its benefit in terms of reduction of risk of unavailability before being able to conclude regarding the best strategy to be adopted. The choice of the solution to be adopted may be only made with the knowledge of coupled "costs / benefit" for each solution.

4 Conclusion

Developments of structure assessment techniques allow more and more the integration of the real state of the existing structure by enhancing the value of measures and investigations carried out on structures. On one hand, this information allows to take into account the structure's ageing and therefore estimate the residual resistance and reliability. On the other hand, by investigating the real properties of the structure and of its operation, refined calculations can sometimes highlight a resistance margin of the structure "such as built" higher than the one considered during design. The precision on the "real" reliability of the structure allows to refine risks management of the infrastructure.

Developments of assessment methods are increasingly oriented toward probabilistic approaches. Although they go out of the "classical regulatory" framework, they bring precision on the "real" reliability of the structure.

Using higher assessment levels needs to have more important and precise input data, what can lead to the need to carry out more detailed investigations. However, these methods offer interesting ways, which can provide, in certain cases, useful additional information for the decision-making of actions to be engaged.

References

- [1] Goy R., Gaine C., Thillard G., Cornish-Bowden I., Auge L., Capra B., *Potential contribution of materials investigations in reducing the risks of unavailability of nuclear civil engineering*, Fontevraud 7 Contribution of Materials Investigations to Improve the Safety and Performance of LWRs, 2010.
- [2] Tanner P., *Reliability-based Evaluation Concept for Everyday*, Saving Buildings in Central and Eastern Europe - IABSE Colloquium, 1998.
- [3] Calgaro J.A., *Introduction aux eurocodes, Sécurité des constructions et bases de la théorie de la fiabilité*, Presses des Ponts et Chaussées, 1996.
- [4] Crémona C., *Applications des notions de fiabilité à la gestion des ouvrages existants*, AFGC, Presses des Ponts et Chaussées, 2003.
- [5] Schneider J., *Introduction to Safety and Reliability of Structures*, Structural Engineering Documents 5, IABSE ed., 1997.
- [6] Breyse D., *Maîtrise des risques en génie civil*, Hermès – Lavoisier, 2009.
- [7] Cremona C., *Approche probabiliste de la performance des structures*, Hermès – Lavoisier, 2010.
- [8] Eurocode 2, EN 1992-2– Calcul des structures en béton – Ponts en béton – 2005 ; EN 1992-1-1– Calcul des structures en béton – règles générales, 2004.