Zeitschrift: IABSE surveys = Revue AIPC = IVBH Berichte

Band: 9 (1985)

Heft: S-33: Hazard scenarios and structural design

Artikel: Hazard scenarios and structural design

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DOI: https://doi.org/10.5169/seals-49374

Hazard Scenarios and Structural Design

Gefährdungsbilder und Tragwerksbemessung

Scénarios de danger et dimensionnement de structures

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SUMMARY

The survey represents a fairly consistent compilation of the rather scarce literature on the Hazard Scenario Concept. It also contains some additional considerations regarding the development of a conceptual framework for Design-Value-Format codes for structural design. The survey was prepared in order to promote the discussions within the General Task Group 13 of the CEB.

ZUSAMMENFASSUNG

Der Bericht gibt eine zusammenfassende Darstellung dessen, was in der eher spärlichen Literatur über den Begriff «Gefährdungsbild» zu finden ist. Er enthält zusätzliche Überlegungen zum begrifflichen Hintergrund von Vorschriften für die Bemessung von Tragwerken. Der Bericht wurde für die Arbeitsgruppe 13 des CEB erarbeitet und wird dort weiter diskutiert.

RÉSUMÉ

La revue donne un aperçu détaillé du nombre restreint d'articles publiés sur le concept de «scénarios de danger». Des considérations sont faites en vue du développement d'un cadre général pour l'établissement de Règles techniques pour le dimensionnement de structures. La revue a été préparée en vue de discussions au sein du Groupe de travail 13 du CEB.

1. THE NOTION OF "SCENARIO"

The notion of "scenario" was probably first used in [1] in the sense that is allocated to it in this context. There it stands for a "methodological device for the study and evaluation of the interaction of complex and/or uncertain factors". Scenarios are defined in [1] as "hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision-points" and are supposed to answer "two kinds of questions: (i) Precisely how might some hypothetical situation come about, step by step? and (ii) What alternatives exist, for each actor, at each step, for preventing, diverting, or facilitating the process". The authors state that "with a set of alternative futures and scenarios that lead to them by alternative routes, one may see better what is to be avoided or facilitated, and one may also gain a useful perspective on the kinds of decisions that may be necessary....". In fact, scenario thinking was first performed by military analysts, economists, futurologists and political advisers.

The notion of "scenario" actually is found in many recent papers from quite different fields but all are concerned with forecasting problems, predictions for the future and the like. The notion is introduced in order to make clear that what follows is concerned with models and that any results presented, do not pretend to describe the future but may be elements of future situations. The use of the notion emphasises a fact that is often overlooked: we are working with models, we explore models and not reality, and everything we conclude is based on the results obtained from model thinking.

Models consist of well defined basic variables and clearly described patterns and rules of interaction. A distinct set of assumptions concerning basic variables and interaction rules defines a scenario. Exploring the scenario by introducing this set of assumptions into the model yields results that clearly are conditional. Considering different scenarios brings forward additional information which may lead to reliable statements on the problem under consideration.

Scenario thinking is in considerable contrast to conventional thinking in natural sciences, where the researcher is trying to reflect nature in models. As nature is quite complex, simplifications are to be introduced into the models. These unavoidable simplifications then are to be seen as the reasons that results obtained are not "true". A "scenario thinker" is not so concerned that results are "true", provided the results derive from a consistent logic. He clearly sees results as being conditional, conditioned through the complexity of the model used and the set of assumptions introduced. He is aware of results necessitating interpretation and the application of judgement. And, of course, he is aware that scenarios must reflect reality, otherwise any implications to be drawn from them might be meaningless.

What is important in this context is the imaginative freedom introduced through the notion "scenario". Applying imagination can help to open up attitudes which may be very rigid. Some engineers tend to think that they really are forecasting reality. Deficiencies are simply considered to be a result of insufficient knowledge and data. They are not fully aware of the model character of most methods and tools applied and of the scenario character of most basic data they are handling. Thus, the notion "scenario" leads to a more thorough exploration of problems with the result that the solutions are better. This is why future structural codes, for instance, should clearly introduce the notion and handle information given in an appropriate manner.

Turning now to Structural Engineering: the engineer aims to plan, design and construct structures which are fit for use, safe for people and economical for the owner. It clearly involves forecasting, taking account of a large number of basic variables and interaction patterns. Thus, scenario thinking can be applied. In order to prepare or to check decisions of engineers and others, hazard scenarios relating to the safety of people in the wake of structural failure [3], [9] should be considered.

The following clauses of this report concentrate on design of structures for safety. Most of what is discussed, however, is equally valid for design with respect to serviceability and utilization scenarios respectively.

2. OBSERVATIONS FROM FAILURE INVESTIGATIONS

In actual fact, structural safety and serviceability failures do occur quite often. Investigations of such failures [2] show that in almost all cases gross human errors are to blame. Approximately one half of all failures are due to gross errors during construction whereas one third can be traced back to gross errors in design. It is obvious that such errors can only be partly coped with during the design and detailing phase. In addition, it is necessary to improve the conditions for error-free human activity and to closely supervise constructions. This is pursued under the label Quality Assurance [9] [14].

Looking more closely into gross human errors in design reveals that misinterpretations and misuse of complicated or dubious design rules occasionally occur. In order to minimize this portion of errors, design rules should be as simple, comprehensive and clear as possible. This is in fact the main requirement structural engineers state in relation to the formulation of design codes. Simpler design rules are preferred even if this is somewhat detrimental to economy, since the cost of the load bearing structure is seldom a dominant factor compared to the cost of the total construction.

However, gross design errors result principally from an underestimation or even the neglect of important facts or influences when performing design calculations e.g. ignoring loads or other stress inducing effects. Errors also occur in the preparation of drawings or due to inadequate consideration of the construction process.

Therefore, ensuring completeness of the design and the feasibility of the construction process is more important than checking for numerical and computational errors which are only very rarely the cause of structural failures.

In dealing with problems of completeness of design, hazard scenario thinking is certainly beneficial, this mainly because it demands that the designer adopts a more open attitude than perhaps operates today.

3. HAZARDS, HAZARD SCENARIO AND SAFETY PLAN

3.1 Hazards affecting safety

In order to ensure the safety of people affected by possible failures of bridges, buildings and other structures (in the following addressed as "constructions", see Nomenclature), two broad classes of hazards threatening the design and the construction should be considered [3] [5] [10]:

- Man made hazards:
  - errors, negligence and ignorance in planning, design and construction procedures,
  - overload by loss of control on service loads, accidents in service, fire, vehicular impact on structural or nonstructural elements,

  - fatigue and chemical or physical deterioration in conjunction with deficiencies in maintenance procedures,
  - man-made geotechnical hazards and other hazards from the man-made environment
- Natural hazards:
  - wind, water (including wave), snow, ice...,
  - earthquakes, avalanches, landslides, rockfalls...,
  - temperature effects,
  - geotechnical hazards from the natural environment,
  - other chemical and physical influences.

It is obvious that these hazards should be considered for the useful design life of the construction which begins with the first design decision and ends, when the construction is adapted to a new purpose or demolished.

Obviously, it is not sufficient to consider single hazards that at a given moment affect the construction. Different hazards can act simultaneously affecting it more seriously than any single hazard acting alone in its most adverse capacity. It is necessary to imagine and analyse the simultaneous action of hazards, for instance in the form of hazard scenarios.

3.2 Hazard Scenarios

In the sense of a definition, one of the hazards contained in a hazard scenario is assumed to act in its most adverse capacity and is labelled "predominant hazard". All other possible influences and all other hazards acting simultaneously are labelled "accompanying" hazards and are assumed to be in some "average" or "random-point-in-time" state, influenced possibly by some characteristics of the predominant hazard.

A large number of hazard scenarios may be defined by considering each of the other hazards alternately as predominant hazards and by looking at further relevant time intervals. Obviously, not all hazard scenarios that can be identified will be relevant to the structure under consideration. Normally, only a quite small portion will be retained for further investigation and for the planning of adequate counteractive safety measures. Generally, the most important hazard scenarios are predominantly man-made, initiated by errors, negligence, ignorance and loss of control in all phases of the building process from the first steps of planning through to the demolition of constructions.

As already stated above, completeness is essential for planning and design with respect to safety. It therefore makes sense to use formal, so-called morphological methods [18] for identification of hazard scenarios. A simple form is a two-dimensional matrix, listing vertically in chronological order all relevant states a construction passes through from the beginning of the execution (since at this point errors in planning may manifest themselves for the first time) followed by its use and ending up with its demolition. Horizontally, all relevant man-made and natural hazards are listed [5],[10].

Each state-hazard-intersection in this matrix identifies one possible hazard scenario described on the respective horizontal line by all possible accompanying hazards. Again, not every intersection will apply but going through such thinking can reveal hazard scenarios which otherwise might have been overlooked.

A warning at this place, however, is appropriate as well: Engineering thinking clearly cannot be replaced by, even sophisticated, paper work. It is creative imagination that is the essential ingredient of our work.

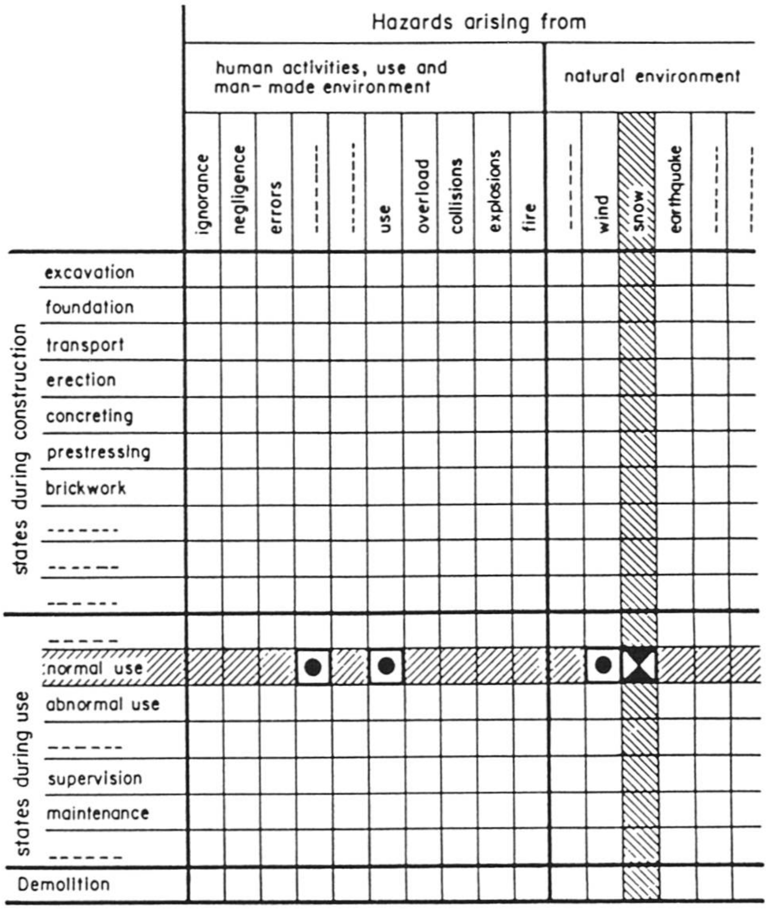

Fig. 1: Hazard Matrix
Example "Snow during normal use", see 3.5

predominant hazard

accompanying hazard

Hazard scenarios are quite often related to a failure (german: Ausfall) of components of processes or systems [12], e.g. a communication failure in a communication system or a failure of a column in a structure, respectively (whatever the reason may be). In this way concepts such as progressive collapse are introduced. In fact, such "failure of component"-thinking is a good starting point for safety considerations and obviously linked to other formal techniques as for example event-tree- or fault-tree-analysis.

There are cases where the predominant hazard is some sort of a complex made up of different hazardous components. Examples for such hazard complexes are "poor workmanship", "bad management" or "meteorological depression", the latter for example composed of strong winds, temperature drop and rainfall resulting finally in ice deposits on structures exposed to heavy wind forces.

In such cases, one of the components of the hazards complex is taken in turn as the predominant hazard, the other components put to values that may be expected "in the average" under the condition that the predominant hazard is effective. This makes evident the need for adequate tools or methods to handle such hazard complex segregation problems.

Finally, a study of observed structural failures reveals that hazard scenarios should envisage human error in its various forms as a predominant or at least as an accompanying hazard.

3.3 Safety Measures

Hazard scenarios identified as relevant and important to the safety of people must be counteracted by appropriate safety measures. Five categories of measures can be identified. It is possible to

- eliminate hazards at their source,
- avoid hazards by changing intentions or structural concepts,
- control hazards by safety devices, warning systems as well as by checking, supervision and inspection followed by adequate corrective measures,

- design against hazards by dimensioning the structure using sufficient safety provisions
- accept hazards because they either cannot or can only be counteracted at great cost by one or more of the above measures.

In most cases, the best policy is a well balanced combination of the above measures, for example to counteract a hazard scenario acting on a structure partly by control, partly by dimensioning structural parts and to some small amount by accepting hazards as unavoidable or acceptable.

It should be noted that design against hazards (for example dimensioning of the load bearing structure) is just one of the possible measures and in many cases clearly not the most economic one. It should also be noted that at this stage safety measures should be seen applied to all relevant parts of the construction and not only to the load bearing structure of the construction.

3.4 The Safety Plan

The development, the setting down on paper and the management of the resulting set of coordinated actions in various areas are important planning tasks. What is thus set down may be labelled the "Safety Plan". The safety plan allocates the different hazard scenarios to the various counteractive measures. In its simplest form it may be just a list. For large and sensitive systems with large consequences of failure it will certainly be a set of documents consisting of different parts, e.g. control plan, maintenance plan, structural design brief, users' instructions, etc. [3].

While it is clear that the structural designer will play an important part in the compilation of the safety plan, it is just as clear that its success will depend mainly on proper communication with others: managers for design and execution, specialists in other disciplines, supervisors, building authorities, and the client. A properly established safety plan contributes a great deal to overcoming these difficulties [5].

Calling for a safety plan is probably pedantic for the simpler types of construction work. Current codes and regulations contain (or at least should contain) many directives which, seen together, form some sort of a consistent safety plan which is probably adequate for simple structures. The notion "safety plan" in such everyday problems just serves as a reminder that communication and coordination in the planning, design and execution process is essential. If this need is neglected, safety or serviceability or economy or all three will be impaired [5],

3.5 An Example [10]

Let us look to the roof covering a platform of a railway station high up in the Alps of Switzerland (see Fig. 2).

Some of the hazards which can be identified and should be covered by adequate safety measures are snow loads, wind forces, unreliability of the designer in performing correct calculations, unreliability of the contractor in placing reinforcing bars of the correct size in the correct place and finally lack of proper inspection and maintenance during use. It is obvious that this complicated but quite likely hazard scenario cannot be covered just by dimensioning the loadbearing structure. Other categories from the list of safety measures have to be applied in some effective combination.

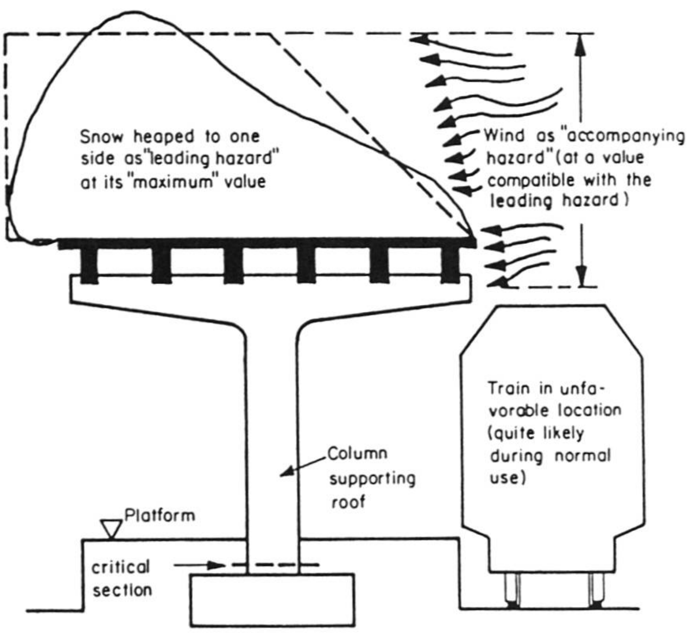

Fig. 2: Roof covering a platform of Railway station

Restricting the hazard scenarios to states during normal use of the structure and labelling for instance "snow" as the predominant hazard we can consider the five categories of safety measures: snow loads cannot be eliminated at their source nor can snow be avoided by changing structural concepts in this case (roofs, however, in other cases can be steep enough to shed the snow). Snow could be controlled by specifying snow clearance when the load exceeds a predefined value; this, however, is not practical as during heavy snowfall railway personnel is otherwise occupied. Thus, snow loads have to be overcome by adequate dimensioning of the structure.

The next problem is to fix the design snow load and the geometric profile to be assumed. It is quite clear that this is a question of specifying an acceptable probability of exceeding the design snow load. This problem must be solved in the loading codes.

Having fixed snow loads and profile at some reasonable value, the accompanying wind action is to be examined. This is a question of estimating probable values of wind action under the condition that snow loads are at their defined maximum. This is Turkstra's rule [17]. Again, this is a task of the loading code. Regarding the use of the structure, a train in an adverse position with respect to wind must be assumed.

This is the hazard scenario "snow" in a very simple form and shown also in the "Hazard Matrix" given in Figure 1. Human error in some "accompanying" sense, however, must be discussed also:

One might be tempted to say that design errors are almost excluded because the structure is quite simple and the designer (by the way appointed by a railway company that is aware of the problems) should have the capability to perform such simple work. This supposes that the right man has been put on the job which may also be looked upon as an act of adequate "dimensioning". For more complicated structures a design check would nevertheless be desirable. Some small risk of errors being missed during such a check must of course be accepted, even when multiple steps of control are introduced.

Measures to reduce the possibility of incorrect placing of reinforcing bars include using a more limited range of different sizes maintaining a large visual difference between adjacent sizes, along with the proper execution of the usual site checks on tolerances.

It is obvious that during this process of thinking through hazard scenarios the necessary safety measures are conceived. Keeping a record of related decisions forms finally what is called the safety plan.

The above example is taken from a serious structural failure. In 1970 the roof covering a platform of the railway station of Einsiedeln, Switzerland, failed during severe snowfall and wind. Fortunately, no one was injured or killed, because the roof fell onto a favourably placed train thus probably saving the lives of many people occupying the platform.

The causes of this failure provides an important lesson: The actual swiss codes give the snow loads only and no indication on snow densities and profiles; Swiss codes also give values for wind forces, but only for the net roof profile without any indication of snow possibly increasing the area of attack. So, as usual, the designer assumed some unsymmetric snow loading, calculated the respective load effects, added to these the effects of wind acting on the net roof profile and proceeded with dimensioning. This error slipped through the informal control exercised by the personnel of the client. It took several years, however, to reveal the error in a heavy snow storm. Most probably other roof constructions in Switzerland and in other countries of the world hide secrets of a similar kind. And certainly there are similar examples for other codes and lots of other examples showing oversights of a similar kind in our present professional environment.

4. DESIGN AND DIMENSIONING

4.1 Derivation of Design Situations

What from a hazard scenario is considered to be covered by dimensioning the loadbearing structure may be called "Design situation" [11]. Each design situation is characterized by a predominant hazard (in some modified form) and contains generally only a part of the respective accompanying hazards. The specification and especially the numerical values allocated to the hazards may be cut back as a benefit of safety measures in other areas e.g. from checking of completed reinforcement work for proper placing and, if necessary, remedial action or for example from accepting some risks from environmental loads.

Each design situation is specified by a design equation stating the safe domain and containing a number of design variables. This is the basis for further treatment by second moment reliability theory and other related methodological features.

It may be noted that the so-called "Turkstra's principle" in handling time-dependent stochastic processes reflects the methodology used here to derive design situations from hazard scenarios: failure is most probable when the predominant hazard takes on its maximum, accompanying hazards having just random-point-in-time-values. The principle, however, also works in the case of ordinary random variables as for example geometric or material properties.

More details on mathematical handling of hazard scenarios or design situations can be drawn from chapter 3.4 of [5].

4.2 Design Variables and Design Values

Problems associated with design variables and the derivation of distinct design values for simple safety checks are not the subject of this paper. Difficulties are well known and some methods of coping with them are ready for use, for example Turkstra's principle [17] and the Hasofer/Lind-scheme [16].

It is believed, however, that giving more thought to obvious differences between different kinds of design variables could help to overcome some further difficulties in deriving consistent Design-Value-Format Codes.

It is useful to distinguish between three categories of design variables that are completely different in origin [13]:

- environmental variables
- structural variables
- utilization variables.

Variables of the first kind come from the natural environment, mainly in the form of wind, snow, temperature, earthquake etc. In most cases they can be handled as stochastic stationary processes in time. They cannot or can only to a minor extent be controlled by man. Fixing design values for such variables leads to fixing the probability of exceeding them and thus to an accepted risk (see 3.3), provided no other appropriate measures have been taken in this respect.

Also, some influences from the man-made environment, e.g. fire, explosion, corrosion and man-made geotechnical hazards may fall into this first category.

Structural variables on the other hand are planned and man-made, in the form of geometrical properties of sections, material properties etc. Variables of this kind are in the hand or under control of the designer or contractor or both. They can be checked for defects and if necessary sorted out if defective. The design values for such variables must take account of tolerances laid down in other parts of codes and standards.

In fact, structural variables are not really variables during the life of the construction but are discrete values of the structural properties at a given point and time. Only the forecast of these values during design is difficult, in most cases impossible, because results of processes always differ more or less from intentions. Formally, forecasting errors can be introduced in describing structural properties in the form of random variables, but account should be taken of the truncation which will arise from proper site control.

Structural properties may be affected by time dependent influences such as corrosion or time hardening. They may also depend on the stress or strain history, but these are additional difficulties which should not be confused with the above argument.

The third category of design variables originates from the foreseen utilization of the construction, for example live loads in buildings, loads from cranes and other equipment etc. Fixing design values for utilization variables relates to the intended use of the construction and necessitates foresight. The fixing of design values also should consider the possibilities of control and supervision during the utilization of the construction. More stringent control of loads - for instance in railways - justifies lower ratios of design load versus nominal load than less controlled road traffic. In some cases loads are truncated automatically to values which would be close to respective design values. The risk of failure of automatic control, however, must be restricted to some acceptable level. The same holds for the supervision of utilization which may also fail due to human error, negligence and the like.

It is obvious that also the above arguments are direct derivates from the hazard scenario concept.

5. A HAZARD-SCENARIO-FORMAT FOR DESIGN CODES?

The following outlines some extensions of the hazard scenario concept which are put forward as proposals for discussion.

A possible proposal is to fix for each design variable at least two distinct values. The first value would be introduced if the respective variable is dominating the design situation (corresponding to the predominant hazard of the respective hazard scenario). The other value would be introduced when the respective variable has some accompanying character (corresponding to the accompanying hazard of the hazard scenario). Fixing the two values would be in line with what was said in 4.2.

Checking for safety would then imply the calculation of the n outcomes of the design equation containing n design variables using in turn just one dominant value, all others fixed to accompanying values. Even the worst outcome should then fulfil the corresponding safety condition. This algorithm would replace the iterative procedure of the Hasofer/Lind-scheme to calculate the most probable set of values of the design variables at failure.

It may be argued that running n times through the design equation is rather time-consuming and that, in general, shortcutting of this procedure by experience or guessing is not reliable. In addition, it is well known that what is proposed here is slightly on the unsafe side.

On the other hand, the application of the Hasofer/Lind-scheme is also laborious and the necessary fixing of alpha-values (for instance in codes) might be unsafe as well.

In reply to the two above arguments it is proposed to split the design equation into a stress constituent and a resistance constituent and to apply hazard scenario thinking separately to each of the two constituents.

The stress scenario would contain the stress related design variables and is to be checked for the worst outcome by, in turn, setting one stress variable to its dominant value and keeping all others at accompanying values. As the number of stress variables is quite small, this procedure is easy.

The same idea is applied to the resistance scenario setting, in turn, one of the resistance variables to its dominant value and keeping all others at accompanying values. The worst outcome should be compared with the worst stress scenario outcome in order to check for safety. This seems to be a comprehensive concept, is easy to understand for practitioners and would certainly lead to simple codes. Refinements are possible, for example, by specifying more than two values for specific loads to be applied under specific circumstances (as has been done in the draft of the new Swiss Loading Code [15]).

This splitting of the design equation has the added advantage that it allows for separate material oriented design codes mainly dealing with the respective resistance constituents of the design equation and one loading code valid for all materials dealing with the stress constituent.

It may be added, that the resistance scenario reflects what is to be built. And what has been built, most probably, will change in time monotonically towards the unfavourable and should overcome in any time interval the stress scenario, which in most cases is really a time-dependent stochastic process.

Obviously, even in following this line of thinking, difficulties will arise. Some of them are already recognized and to some extent even solved. Others certainly can be tackled successfully. I think that this line of thinking is the more "strategic" way towards a new set of mutually dependent and consistent codes wherein the structural design codes are just an important part.

It may be argued that the proposed method is not "true" since it presents a starkly contrasted black-and-white image which cannot represent the actual shadowy grey of reality. But no other method is true either. And nobody is asking for true codes. Codes should be simple, comprehensive, consistent, clear and obviously safe enough, providing a firm basis for fair competition.

6. FINAL REMARKS

The text above essentially gives indications about the possible format of future Design Codes. But design to the codes is just part of our professional work. It must not be forgotten that we need in addition extensive and powerful measures against errors not only in the design but throughout the whole planning, construction and utilisation process. This leads on to the notion "Quality Assurance" which is not considered further here except to say that also in this field Hazard Scenario Thinking can be of great assistance.

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NOMENCLATURE

construction = bridges, buildings and other structures	ouvrage	Bauwerk
structure	structure porteuse	Tragwerk
hazard scenario	scénario de danger	Gefährdungsbild
predominant hazard	danger prépondérant	Leitgefahr
accompanying hazard	danger concommitant	Begleitgefahr
safety plan	plan de sécurité	Sicherheitsplan
dimensioning	dimensionnement	Bemessung
design situation	situation de projet	Bemessungssituation
design value	valeur de dimensionnement	Bemessungswert
stress	sollicitation	Beanspruchung
resistance	résistance	Widerstand