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# Future issues for codes and standards

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ABSTRACT: Among the extensive array of codes and standards used by designers of structures, those that govern or control structural performance and safety are the focus of this discussion. Current legal codes are essential to structural design practice because without them, the designers would have to conduct extensive research for each project, they would compete over safety matters to the detriment of all, and the society would have even less understanding of what to expect for safety and serviceability than they currently do.

Several factors provide a basis for major changes to codes and standards and to the way they are used and developed. First, the computer has provided a means to have extensive databases of structural information so that there is no longer the need for the codes to specify loads and material properties. A properly sanctioned and standardized database can contain all the needed information in much more comprehensive fashion. Such databases could also encapsulate societal values, such as values of life, consequences of traffic delay, business interruption, and all the other values that the society places on individual structures. Second, society is ready to engage in discussions about its values, so that standards can have the potential of including the broader society in safety decision making. This readiness is due to developments such as the internet and a generally freer press in which broad discussions can and do take place, and it is partly triggered by the recent earthquakes, where the public at large has spoken out more vigorously about their expectations for safety.

The future holds the possibility that specific limits specified by codes can be dropped in favour of performing an extensive optimization that maximizes present expected value of the project. The optimization would be guided by the value system of the owner, and constrained by the value system of society through modern standard databases. Serviceability would be emphasized much more, while safety would be preserved through the social values in the standards. The various phases of design would be linked so that a real optimum, including effects of design of the concept and system, the detailed structure, its construction, and maintenance would all be accounted for.

## 1 INTRODUCTION

The past 40 years has seen a true revolution in the measurement and specification of structural safety. Codes and standards have adopted various versions of probability-based safety measures, and even practicing engineers have begun to understand and use probability concepts. However much remains to be done, and many questions have to be considered and resolved before we can claim to be at a mature stage of development in this field.

Virtually all of the literature on structural safety is devoted to determination of probability of reaching a limit state, usually the failure state, in a well-defined structure with assumed probability models for the design and load variables. This high degree of attention is based on the premise that safety is controlled by varying the strength (or sometimes controlling the load) of the already defined structure. This limited view of the scope of safety control needs to be expanded, as there are many stages in the development of a project in which safety can be affected. In fact the safety is influenced much more by the choice of structural system, the materials' behaviour, and the environment in which the design is carried out, than by the quantitative aspects of the analysis phase of design.

In addition to safety, design codes and standards generally deal with serviceability. In the classical limit states design format, serviceability limit states are treated similarly to strength limit states. This ignores the fact that real serviceability requirements are not absolute like safety limit states. There can be a wide range of serviceability responses, some more serious than others. Serviceability needs to be governed not by limit states design in the conventional sense, but by optimizing the value to the project, trading increased cost of construction against increased value of performance.

Maximum value of a project will be possible only when the project owner (representing users and society) takes a much more active part in a communication process that establishes value for performance. The values (including costs and consequences of negative performance) provide the basis for a process of optimization, with appropriate trade-offs between increased costs of enhancing safety and serviceability, and the value that such increases bring to the project. The values of society at large can enter this process readily in the form of constraints on the optimization process.

## 2 THE ROLE OF CODES AND STANDARDS

In a discussion of the future of codes and standards, it is useful to imagine first an ideal long-term vision, not only of the shape of codes and standards, but of the design process and the roles of the various parties in it.

Designers, including architects, planners, and engineers, will be better educated. All members of the design team will have good communication skills so that expertise is shared and understood as required for the development of the project. They will mutually have the expertise needed to optimize the project globally, trading values and costs among the various aspects of a project. They will have the ability to communicate with the owner to enable owners values to be integrated into the project value basis.

There will be extensive databases on all aspects of materials behaviour and loadings. These will replace the need for codes to specify strength and load combinations. The actual dependence and interactions of various loads will be readily accounted for in the structural analysis. The predictions of reliability of the model structure will account for all aspects of the material behaviour and loading. The well-educated designers will understand what they are doing. Black box engineering will not be acceptable.

There will also be extensive databases on the values encountered in the projects. These will become a basis for thorough communication between owner, society, and designers (including all designers on a project). Values will include the negative values (costs) of consequences of failure or non-performance, including life safety, structural failure, deterioration, and transient serviceability aspects. They also include life cycle costs and construction costs. The values of health and safety would be arrived at through a process of social consensus and social monitoring. This will ensure that the values of society are embedded in the standards of design.

The design process would begin with a complete definition of the project and the appropriate values, with owner and designers involved as a single team. The separation of parties into potential adversaries, as is common today, would not occur. Project insurance would cover all parties together. Insurance companies would have an incentive to foster good standards to minimize total liabilities.

A major aspect of this ideal scenario is that owners and designers would have to communicate in detail to define the project. In contrast, today most owners simply assume that design will proceed in accordance with codes that they do not know much about. They expect great performance, but every application of cost control pushes designers into a tendency to reduce safety and quality. This forces us into the narrow vision of safety that we generally have at present.

In the context of current design practice, this vision of future design means that we focus on standards, and envision a time when codes as legal documents enforced by building officials will become obsolete. This is similar to how the medical system operates. There are protocols and professional standards, but we trust our health and safety to a system in which doctors guide decisions using the value system that is derived from patient consultation within societal constraints.

## 3 OPTIMIZATION

There are many forms of optimization. The one that appears most useful for codes and standards to adopt as a decision tool is to maximize present expected net benefit (or minimize present expected net cost).

Construction or initial costs are taken at face value. Future benefits are reduced to present expected value by appropriate discounting and accounting for possible randomness. Future consequences (of failure or damage, for example) are also taken at their present expected value.

In many cases, a monetary value scale may be used. Where human life or serious environmental damages are involved, account must be made of risk aversion.

Standards that represent societal values can represent the appropriate optimization process for the many and varied situations that arise. The most obvious difference that will occur with such methodology is that structures with high consequences, or great importance as to future benefits, will have higher safety and higher initial costs, while structures of low value or low consequences will have lower safety levels and lower initial costs. Further, the amount of life or significant environmental risk will influence the required safety levels. It would be difficult to defend the current system, in which high consequence structures have the same safety prescribed for individual elements as do low consequence structures.

A brief result of a simple optimization example is mentioned in Section 7 (see fig 1).

## 4 STRUCTURAL ANALYSIS PHASE

This phase of design is not the first, but it is the one given almost exclusive attention by the design codes and by researchers in structural safety. We consider it first in this discussion only because it is the most familiar.

This is the stage in design in which an idealized model of the structure is developed and analyzed for a variety of loads and effects. It's elements are proportioned to meet the code requirements, which are generally based on finding, for each load combination, the proportions that meet or exceed target safety levels.

It is surprising that after about 40 years of development of probability-based structural engineering, our codes and standards take a very limited role. While most codes claim to adhere to principles of limit states design, they tend to focus on safety or ultimate limit states, with few provisions addressed at serviceability limit states. They generally deal with a well-defined structural model or, commonly, with individual members of the structure, and they specify a target reliability index $\beta$ that is, with few exceptions, a constant for a particular code, and is the same for each of a set of specified load combinations. They do not tend to cover the various types of redundancy or load path, or the variety of construction risks that may or may not apply to specific system choices. They do not deal with value, as in cost or consequence differentiation.

In the actual design process, designers cope with all of these and a myriad more, constantly aware of safety, cost, and value implications. This is done subjectively and requires a great deal of experience. Good designers or design teams manage to balance the competing issues and develop successful projects with only a minor amount of help from the mathematical and probability aspects in the codes and standards. The ideal database referred to in Section 2 will contain the information needed for this broader coverage of real structural design.

### 4.1 *Future issues for the analysis-based phase*

Much remains to be done with load combinations and with the unquestioned idea that each load combination should be tested against the same $\beta$ value. We require advanced load models that represent the appropriate dependence and interactions among the many loads. Instead of a set of load combinations, it may be better to devise the set of failure modes or limit states, and then establish the load models that trigger them. In the ideal of the future, all loads would be part of one overall model, and instead of a target reliability index the value system for the project would lead to an optimum design. The optimization procedure would include both safety and serviceability.

Current codes, while espousing "limit states design", tend to focus on strength limit states, and do much less for serviceability. In fact serviceability is much more likely to be noticed by the users, and it does not generally make sense to refer to serviceability limit states. Most serviceability conditions do not present sudden thresholds; rather they are gradual increases in some characteristic that may be undesirable, such as deflection or increased vibration. This is the ideal situation for optimization, in which a penalty is established for the offending behaviour, and a cost is determined for its mitigation. A balance is found at minimum total penalty plus cost. This is an area that can be greatly improved, because it is at the heart of the increased communication that would have to occur with the owners and users of structures.

We are currently at the stage where optimum $\beta$ is being determined in some specific structures. Codes and standards should proceed to develop an environment in which this is sanctioned as a normal part of design. Designers need to develop databases on costs so that marginal costs are readily available as functions of changes in safety. Also needed is consequence cost data, which must come from open consultation with user groups, insurance companies and representatives of the larger society, which is affected by "unsafety".

When we accept a form of simple optimization, where consequences and initial costs are minimized, we can more readily account for unusual situations such as temporary structures like falsework which may be exposed for only a short time, or for unusual consequences, where failure of some small element may have disproportionate consequences. Both of these factors are important in construction falsework, where conventional practice leads to quite risky situations (Sexsmith and Reid 2003). See fig 1.

Most codes and standards apply to new structures, and different documents have been developed for special applications to existing structures. An example is seismic retrofit, where upgrades to existing structures are often needed, but compliance with the applicable codes is difficult impossible, or too expensive. A recent survey (Hirata et al 2005) showed that marginal retrofit cost to reduce present expected value of future earthquake damage was much higher than the reduction of damage cost (for some common structural types in Vancouver Canada). This would generally indicate that retrofit to new standards would not be reasonable. However, a rational optimization procedure that accounts for all consequences would lead to reasonable retrofit strategies for individual structures. The key in this case is that individual costs and consequences have to be determined, and a strategy for the particular structure has to be developed, based on the costs unique to that situation. Our codes and standards would be much more sensible if they could accommodate such individual situations, rather than the overall “one size fits all” approach that they currently promote.

The structural analysis phase of design would be based on standards that would encapsulate the values of society for safety and serviceability, and the loading and materials behaviour that would be required for detailed analysis. The values of the owner would also be incorporated through much enhanced communication (compared with current practices). The process would be much more like that of medical practice.

## 5 DESIGN AND ARCHITECTURE

The first stage of any project, after needs have been identified and financing is secured, is the initial conceptual design and architecture - the choice of form and materials. The mathematical probabilistic models used in conventional structural safety assessments are not likely to be much help in this phase of design. Yet the initial choices of concept, form, and materials can have a major effect on the resulting safety of the structure.

Nowadays architects or engineers have to satisfy functional safety requirements, longer and maintenance-free lifetimes, and environmental conservation. They need principles of optimization to make appropriate trade-offs among competing requirements. Codes and standards need to foster a more quantitative, yet individualized approach to such design decisions.

### 5.1 *Effect of form on safety*

In 1968, a gas explosion in an apartment at Ronan Point in London’s Docklands knocked out a single column at the 18$^{th}$ floor supporting a corner balcony. This triggered the progressive failure of all the columns directly above and below, causing a major disaster that was disproportionate to the initial failure. Since then, codes in the UK and elsewhere began to introduce the idea of prevention of progressive collapse. The National Building Code of Canada introduced clauses that were intended to prevent or minimize the likelihood of collapse of a magnitude disproportionate to the cause (NBCC 1977). This was accomplished by introducing rules regarding perimeter ties and investigations into ultimate behavior when key structural elements were removed from the structure. Since 2001 September 11, there has been intensified interest in this area , exemplified by several conferences on extreme events, blast protection, etc. (for example, the Elsevier sponsored conference “Response of Structures to Extreme Loading” held in Toronto in 2003).

A generalization of this idea is to consider the load path as the key to a safety measurement. Redundant load paths affect safety in a variety of ways, depending on the ductility of the elements and their arrangement.

In same cases an interrupted load path contributes to safety by isolating the effect of accidental loads such as ship collision, ice load, or blast. An example is the Confederation Bridge in Canada, the world’s longest high level highway bridge crossing 13 km to Prince Edward Island, Canada. In this case, the design specifications required that collapse (in the event of massive ice or ship collision) must be limited to immediate spans only. This was accomplished by ensuring that the removal of a pier or any one span would occur with an easy breakaway that could not pull down adjacent spans.

Redundancy in a structure is difficult to model, yet it has a dramatic effect on safety, especially as affected by structural element strengths. Codes and standards need to develop means to reward and credit redundancy, and designers need then to learn how to design the form and arrangement taking into account the benefits or penalties associated with various forms.

Structural irregularity is often at the root of earthquake-induced failures. The loading is so unpredictable that the best defense is a regular, simple structure that can be modeled realistically. Seismic codes now deal with structural irregularity, with a variety of prohibitions or safety factor modifications for changes in lateral or vertical stiffness, changes in regular load paths, and many other irregularities. These were introduced in the United States and have recently been introduced in the Canadian seismic provisions (NBCC 2005).

Redundancy, isolation, and irregularity are now controlled in a few building codes in a qualitative way. It is time to develop probability-based structural safety concepts to be applied in these areas for development of the architecture or form and load path arrangement of the structure. Codes and standards may be able to exert a degree of control on the concept /architectural phase by providing incentives to good practice.

As a first step in this direction, comprehensive studies are needed to determine the effect on safety of various forms of redundancy, isolation, and irregularity. For many generic structural forms, adjustments to calculated safety measures could be derived. This could be in the form of qualitative changes to calculated reliability indices. The adjustments would be developed through calibration studies on structures with various redundant systems using higher-level non-linear analysis methods that account for system effects. The adjustments would be subjective, hence should be subject to review by a concept review entity in the design team.

### 5.2 *Design of the form and materials of the structure*

In the architectural or form development stage, it is likely that fuzzy logic or other similar types of heuristic models will be applied, with some type of rating system to arrive at the best safety level that should be achievable under whatever architectural constraints exist. The safety in this stage should not be a prescribed single level, as structures will vary widely in form, arrangement, materials, and connectivity. Rather, it is likely that the structural safety requirements in the subsequent structural calculations could be made to depend on the type of form and arrangement safety that this first stage produces.

Current codes have some simple elements of this idea: The Canadian Bridge Design Code (CAN/CSA S6 2000) provisions for steel design provide different requirements for fatigue of steel for different combinations of redundancy and failure mode (brittle or ductile).

### 5.3 *Value*

The value and cost of safety in this phase of the design would be determined by studies of existing examples. The designer would have measures on the cost of using the various alternative types of system, and would also have measures on the savings or benefits accrued by them.

We need extensive studies on the cost changes that take place as functions of the changes in safety, and on the cost changes as affected by changes in architectural arrangement or system. With this information the designer can isolate and value the particular choice of architecture.

The project has to include a detailed definition of the decision maker, with appropriate means to share the risks and benefits of the various decisions. Developers cannot expect designers to make decisions in the best interest of the project if some of the costs accrue to the designer without adequate compensation. The best way to incorporate the values fairly is to carry overall insurance covering all parties for all events. This frees the designer to make decisions to optimize the project, while maintaining professional responsibility.

The codes and standards that regulate or guide this process need to find ways to include input from the society at large, through some forms of consultation accompanied by education in order to foster intelligent decision making.

## 6 STRUCTURAL CHECKING PHASE

Actual failures of structures occur far too often, even though the failure rate or frequency is rather low. The tremendous consequences of a failure require us to target extremely low probabilities, a rate much lower than observed. It follows that almost all observed failures are not the result of random (unlucky) events involving the limit state as modeled in a reliability analysis. Instead, they are due to an error, often a computation or conceptual error.

It is not conceivable that we eliminate all such errors. Therefore a part of the structural safety aspect for codes and standards has to be a rigorous screening process that will detect such errors, with a failure rate for checking just as well controlled as the familiar reliability index.

Codes and standards would benefit from some research-based standards on checking. Required is a logical sequence of check phases that provide assurance that errors of calculation and judgment have not occurred.

## 7 CONSTRUCTION PHASE

During the construction phase, the partially built structure takes on many forms, and is exposed to many unusual loading conditions, yet the typical codes and standards devote little to the control of safety during this phase. The costs of mitigation, and the consequences of failure, vary more widely during the construction phase than they do for the completed structure. Safety may be better controlled by individual attention to the specific case, rather than by codes and standards. However, the codes and standards must provide the environment for the individual considerations to take place.

Fig. 1 (Sexsmith and Reid 2003) illustrates the widely divergent safety results when consequences and costs vary for temporary construction stages. In the figure, B is the slope of a line representing cost of construction as a function of safety factor (marginal cost of construction for an increase in safety), $C_f$ is the assumed cost of failure. The horizontal scale T is the exposure time, or reference period for the structure, ie the time over which the costs should be optimized, and the vertical scale F is the load factor on the 100 year return period wind force at which the structure should be proportioned to reach the failure limit state. Interest rate of 5% is assumed. The curves near the top of the figure represent very high cost of failure relative to construction cost ($C_f$ /B = 150), while the lowest curve represents $C_f$ /B = 10.

Note that in this example the required safety, represented by F, can be quite low when the reference time is low and when the consequences are low relative to construction cost ($C_f$ / B small), but for higher consequences, even with low T, the load factor is in the more familiar range of about 1.4. This result should be of concern in the many bridge erection projects that use a 10 year wind value and conventional load factors, because failure consequences in such cases are often very high relative to construction marginal cost.

## 8 INPUT FROM SOCIETY

The long-term future should include standards that provide a basis for true optimization. An important part of the value system for such a process is the values of the society. This will require some type of forum in which social objectives are recognized and converted to a form that can be combined with the values of the owners of future structures.

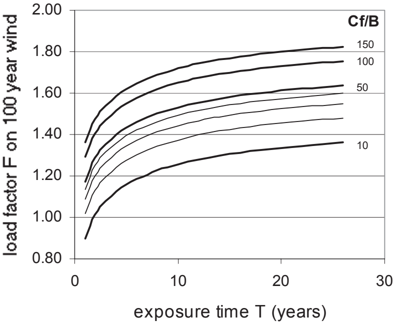


Fig. 1 Safety factor F vs reference time T

A major difficulty with this idea is that the broader society does not usually show interest is the safety of structures. They assume that it is “100 percent safe”. When we experience a rare structural failure they are shocked and surprised. Earthquakes are the one fairly visible event in which there may be many structural failures. When these occur the level of shock and surprise depends on the extent of the damage, and the level of seismic shaking. It is hoped that after such events there is more willingness to discuss the values of society, and an opportunity to incorporate these into design standards.

## 9 SUMMARY

We envision a more well educated and prepared design profession, with extensive databases for structural systems, effects of redundancy, loadings, construction, maintenance and failure costs, and values. The values provide the basis for establishment of cost of failure and other less severe performance costs (floor vibration, for example).

The owner representing users of the structure, will become more highly involved by providing a value system for performance that can be integrated with the values of society. This would realize “performance-based design”

With value defined, optimization can become the heart of the design process. Maximum present expected value, with constraints by society for basic health and safety, is the target.


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