Safety, building codes and human reality

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Safety, Building Codes and Human Reality

La sécurité, les codes de construction et la réalité humaine

Sicherheit, Baunormen und die menschliche Wirklichkeit

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SUMMARY
This paper presents a review of the present state of advancement of structural safety concepts in research and practice, as seen by a practising design engineer. It describes the three levels of strategies which seem to emerge for the control of structural safety in civil engineering, including tools such as code design rules, the checking for human errors and the design to limit the scope of failure, should it occur.

RESUME
Cet article présente l'état actuel des connaissances — dans la recherche et dans la pratique — concernant la sécurité des structures, vu par un ingénieur projeteur. Trois stratégies contribuent à la sécurité des constructions de génie civil et comprennent des outils tels que les codes de construction, le contrôle de possibles erreurs humaines ainsi que la conception de structures pour le cas d'un effondrement éventuel.

ZUSAMMENFASSUNG
Der Beitrag gibt eine Übersicht über den Stand der Forschung und der Praxis im Zusammenhang mit der Sicherheit der Tragwerke, vom Standpunkt eines praktizierenden Ingenieurs. Die drei Strategien, die für den Zweck Anwendung finden, werden kurz behandelt. Sie umfassen solche Hilfsmittel wie Baunormen, die Kontrolle von menschlichen Fehlern und das Konzept der Begrenzung des Versagens von Tragwerken.

1. INTRODUCTION

Safety from collapse is one of the basic essentials any structure must provide during all of its history, besides such other functions as serviceability, pleasing appearance etc. Structural safety has traditionally been the task of the design engineer although more recently it has found a place on the scientists' desk, to be analysed and understood. Substantial efforts, in particular during the past 20 years or so, have succeeded in resolving part of the problem while another part still evades our comprehension and direction.

In this account the author shall try to identify and describe that part of the problem of structural safety which sofar has largely escaped analysis, and remains full of questions unanswered. Although talked about rather frequently, some of these questions themselves are still rather fuzzy and, as we shall attempt to show, it is man himself who is at the root of the problem, and it is the knowledge about our own actions and their morphology which is still lacking, quite contrary to the principles of ancient philosophers like Socrates, who advised to begin with man himself in order to understand the world.

Other ages had their try at the problem of structural safety and mostly the means to control or improve matters have been on the plane of jurisdiction. The first systematic attempt to transpire into our day is contained in the laws of the Babylonians, as formulated in the writing on Hammurabi's Stone. It provides a rather explicite, as well as draconic schedule of restitution duty, or of bodily punishments should the individual identified as the builder fail to provide a safe structure. It is perhaps not the most significant aspect of this law that its severity is aimed at removing the unfortunate builder from the scene, should he be found wanting, by ruining him financially or physically, nor even the fact that the incentives provided are so exclusively and dramatically negative. The very essence of the law would seem to be that it is directed towards the human individual exclusively, indicative of the conviction of the legislators of the time that this is where the roots of structural safety are to be found; that the failings of humans in their duties are the real reason for things to go wrong. Long before any scientific leverage existed to analyse problems away from the realm of faith, religion, mores or customs, the sober conclusion of common sense was that the human builder is the element in the history of the structure where structural safety is decided and where it can be influenced by the ultimate recipient, namely the public.

This has not essentially changed in our times and the law still provides the means to reduce guilty individuals through restitution and loss of liberty. Incentives set are still purely negative although society has accepted a degree of redistribution of the financial burden deriving from failures throughout the community of builders, by means of insurance premiums. Even then, the engineer or builder found responsible for a structural failure will still be reduced to less than his former self, after the ordeal of lawsuits etc., morally and financially.

It would seem that a consensus still exists in our day's society to the effect that structural safety originates from humans, not from things or natural laws, although it could also be said that things do not respond to incentives, negative or not and cannot be made to suffer in compensation. Therefore the only possible satisfaction for a failure can be had from the human individual with its emotions like fear, or the modern expression of the need for security, the wallet. Be this as it may, the effects of the traditional attitude and approach are still generally accepted as satisfactory and indeed, the safety of structures against collapse compares quite favorably with other fields of safety, or of risk.

Comparative annual probability of death by accident *

	Hours exposure/ annum	Approx. annual risk/person
Mountaineering	100	1×10^{-2}
Air travel (crew)	1000	1×10^{-3}
Car travel	400	2×10^{-4}
Home accidents	5500	1×10^{-4}
STRUCTURAL FAILURE	5500	1×10^{-7}

Foremost of all individuals in question, two people are traditionally most exposed to the negative incentives of the law. They are the structural engineer and the structural contractor who shall be called "designer" and "builder" in this paper. The responsibility for structural safety is almost exclusively assigned to these two, with the sharing variable to a certain extent, from country to country, indicating that the two functions can not easily and clearly be separated. Indeed, in many circumstances it is one organization or individual who directs design and construction, concept and execution of a structure.

Before proceeding to discuss how the activities making up design and construction are interrelated and guided by tools, let us give one thought to the history of a structure in its entirety which, besides the concept and execution will include usage and the physical fact of existence during its lifetime, up to the eventual demolition, or loss, and including alterations, overbuilding, change of use etc. It becomes clear then that the engineer and builder are by no means the only individuals interacting with the structure's safety, as it will be exposed to other stages of existence than the concept or construction for a much longer time, with a much larger number and variety of humans related to it. Considerations of structural safety ought to include all of this since a substantial portion of failures do occur and are generated in the latter part of the structures lifetime.

Therefore, the discussion of man and the effect of his activity on structures should not be limited to their creation but must encompass the users, as well as other persons in contact with the structure and capable to endanger it. This for instance includes such humans as the owner or tenant who overloads or alters the structure, or the executive of a utility company who

* From: CIRIA Report 63. Rationalization of safety and serviceability factors in Structural Codes

decides to assign insufficient personnel to the checking of gas and water lines which may eventually cause accidents. It will even include people who are only accidentally or indirectly inter-relating with the structure, such as the truck driver ramming a column with his vehicle, or a Code Committee who leaves gaps or erroneous statements in the building regulations, or merely compiles a Code that cannot be used because it is too complicated or lacks clarity. In this context the owner or promoter with a tight budget or schedule must not be forgotten who forces designers and builders to deliver skimpy or shoddy work, with insufficient supervision or the like. Although these individuals cannot always be reached by the legal system, structural safety is related to them and if the frequency of accidents ought to be controlled or reduced, their contribution must be dealt with, which means: designed for.

2. STRUCTURAL SAFETY IN CODES

One of the traditional tools designers or builders are able to employ for the generation of safe structures is the Building Code. A few notes shall be devoted to this type of instruments and the way they treat the problem of structural safety.

Building Codes exist in a wide variety of presentation, specificity and even legal status. Some are set-up as guidelines or suggestions, whereas others are accomplished structural design handbooks and/or carry the weight of law. This is not the place to discuss the pro's and con's of these variations but to recapitulate the common elements which in recent time have undergone rather dramatic changes in the semantic and logistic sense, some of which is still under way or merely planned for.

The most conspicuous changes relate to the very problem of structural safety and the way it appears written down in the form of, mostly minimum, standards. Traditionally a safe structure used to be one in which stresses calculated according to some theory, did not exceed certain limits stated in the Code. These limits or allowable maximum stresses then formed the basic trade coin of safety, covering virtually all questions of structural adequacy, from safety against manifest collapse down to all types of serviceability conditions. Values were mostly set by consensus of the leaders of the profession, without much rational basis.

More recently, the trade coin of allowable stresses has been found wanting and gradually, they became replaced, at least as far as design rules for safety against collapse are concerned. The well known design expression of the general type

$$k_o \cdot \underset{i=1}{\overset{m}{R}} (k_i\ r_i) \geqslant l_o \cdot \underset{j=1}{\overset{n}{Q}} (l_j\ q_j)$$

was introduced, with r_i and q_j, R and Q representing nominal contributions (functions) of resistance (r_i, R) and loading (q_i, Q) and modifying factors (k, l) to all or some of the parameters. Many variations of the expression exist, differing with country, construction materials or type and function of structures. Variations from the general form are mostly achieved by omission of some factors (ki, l_j) or by splitting them up into products of subfactors. However, the general type of expression is always maintained which, to the user and reader, conveys two basic functions of the expression: One general and one specific.

What is described in principle is the situation at the time of design when a concept of the structure is being generated. In this context, the basic properties of structure and load are expressed by estimated or nominal functions of

$$R\ (r_1 .. r_i ... r_m) \quad \text{and} \quad Q\ (q_1 ... q_j ... q_n)$$

(nominal from latin: nomen = name) as more exact knowledge about real values is not or not yet available. What the expression, simplified

$$R \geq L$$

then states is that the resistance of the structure shall exceed the loads the future has in store for it.

The second statement is contained in the factors k_i, l_j. They are intended to express the degree of uncertainty, which for every assumed nominal value of a building parameter, must be accounted for: Parameters that are well known in advance will be qualified and multiplied by a factor close to unity, whereas in a case of great uncertainty, the factor will modify the parameter considerably from its "nominal" value. At the same time the modification factors introduce the compensation thought necessary for that uncertainty, in the design expression, and together they convey the picture of a "worst possible case" to be considered in a design where a structure with a resistance already impaired by some deficiencies is overloaded by a combination of loads exceeding the nominal values. This unfavorable case as described by the modified parameters

$$(k_i\, r_i\ ,\ l_j q_j)$$

and functions

$$k_o R\ ,\ l_o Q$$

shall then still result in a structure that does not fail.

The more modern design methods and recipes are all grouped around some version of this safety expression. Under such names as "ultimate strength design", "Traglastverfahren", "charges majorées" etc. they have been used for some time, giving recognition to the fact that what a structure is really asked to do in the first place, is to stand up, rather than to comply with some arbitrary stress limits.

Sofar on the face of it and qualitatively, everything is allright: The designer is given a tool evidently representative of the true nature of the problem, introducing and at the same time compensating for the various things that can reasonably go wrong in the history of a structure. Code writers are given the means to adjust the safety rules according to the requirements of the day, such as economics or values assigned to human life. The public receives construction to a generally accepted degree of safety, with the possibility of modification, should some class of construction become conspicuous through frequent failures or waste of construction materials due to overdesign.

However, two aspects of the problem of design for structural safety still remain unanswered by the algebraic expression now being generally used for design. Firstly the design expression does not allow for direct, quantitative introduction of data where and when it is becoming available on some building parameters. Much research effort has been devoted to the collection of such material and we shall review this research and what happened to it, as we shall see how the physical properties of a structure influence its safety.

The second aspect left unresolved by the design safety expression is the lack of relationship, even in the most general sense, to the real source of structural failure which remains with human individuals. It shall be discussed in a further chapter.

3. BLAMING THINGS. THE PROBABILISTIC CONCEPT.

Things lend themselves to be analysed and measured, interpreted and reproduced. Ostensibly, all construction is made up from things, like materials, elements and functional combinations of the two. All structures are also exposed to things like natural events, loading through wind, earthquake and the weight of materials, equipment etc.

The method of choice for the analysis and research which is and has been extensively used, is to gather statistical data on repeated similar or reproduceable events, and the use of such data as basis for a probabilistic approach to the safety problem. Thanks to the application of these methods a first definition of structural safety has been possible, it is the probability that a structure will not fail :

$$\text{Safety} = 1 - P_{failure}$$

as a specific case of the general notion of safety, which describes the probability that any unfavorable event will not occur. This probabilistic expression is now directly accessible to algebraic treatment in various ways. It can be related to a number of different possible modes of failure :

$$1 - P_{failure} = 1 - \Sigma P_i \text{ (different modes of failure)}$$

which allows to treat each possible failure mode separately. Probabilistic safety can be related to the design expression of the previous chapter

$$1 - P_{failure} = 1 - P\ (\overline{R} < \overline{Q})$$

by replacing nominal or design values for resistance and loading by true values, the probabilistic statistical properties of which can be gathered through research on building parameters.

Research efforts in the past twenty or so years have concentrated on the gathering of such statistical data, and its evaluation for use in adjusting the design safety expression. This has borne fruit and in many countries, such data is now being worked into the modification factors of the design expression, in an attempt to rationalize it, and to eliminate discrepancies that existed among different cases of structural design, with apparent overdesign on one side or excessive risk in other cases.

One step further, a relative adjustment of safety/risk has become possible which allows to reflect the value of losses related to prospective structural failure, for different conditions: Structures such as hospitals, or other buildings related to emergency services in case of disaster, are to be designed safer along with buildings likely to contain a great number of people, as opposed to structures intended for storage or other like purposes not endangering many persons in case of a collapse. Conveniently structural safety in the form of probability can be transformed into different expressions, assuming certain probabilistic or statistical relationships to apply such as the symmetrical (Gaussian normal) distribution function, although the validity of such assumptions can not always be verified, or in some cases, is known not to be true. However, some simplification is proposed to be acceptable considering the tendency of the distribution of a function of many statistical variables to approach a Gaussian normal form, independent of the particular types of the individual distributions. For comparison of safety levels in various design cases, the factor β has recently been favored; it can be demonstrated most easily on the figure of a Gaussian normal distribution :

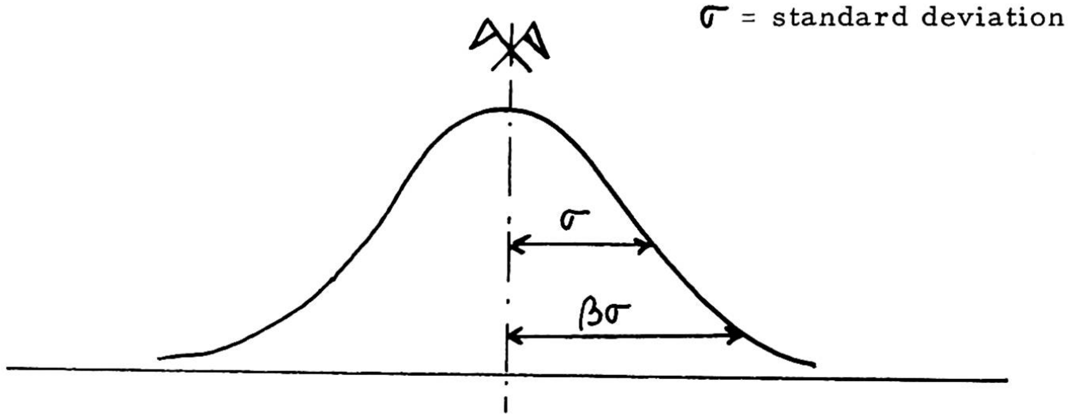

FIGURE 1.

On this basis a comprehensive and consistent logical concept is being created presently to reflect the behaviour of "things" (essentially nonhuman quantities), as they work in or onto real structures, influencing safety. Rules are being derived from the theory and worked into the factors making up the design expression, which are being adjusted to reflect new findings. New general concepts such as "limit states design" are being introduced in building Codes, allowing the unification of structural design with different materials, or for different types of structures.

In spite of this evident success the probabilistic concept of safety which is essentially based on the "blaming of things", still fails to answer two salient questions which an ultimately successful concept of structural safety must resolve.

The theories built around statistical properties of building parameters have yet to be measured against the real frequency and make-up of structural failure. No algebraic relationship has been established between the population of structural failures and the statistical properties found for building parameters. Failures are, fortunately, rare events and - unfortunately - they are not always altogether and most of the time not clearly reported, a fact which relates quite closely to the practicalities of restitution an d the working of the legal system which in most cases sets the incentives against comprehensive and public reporting. This has made it very difficult sofar to analyse failures in a systematic manner and therefore, the final word cannot be spoken yet on the validity of the limit state theorems. This expresses itself in the fact that although the modification factors in the safety expression can and have been varied singly or in groups, no absolute calibration has been found possible, based on rational scientific fact and the overall magnitude of the combined modification factors is still entirely a matter of the consolidated judgement of the code committee.

The second weakness of the probabilistic concept, and hypothetically the same as the first one in essence, is that it still fails to include the human source of structural failure. Where human errors find mention at all they are notoriously attributed to the realm of "what must not happen, can not happen", with the excusing corollary that sufficient control and supervision would have prevented the human error to take effect.

But would it ? Or is it so that sufficient, or acceptable efforts are already being spent on control and supervision, checking and verification, with the manifest result that structural failure is, although rarely, still taking place ?

4. HUMAN REALITY

Is it not that humans direct most of the things contributing to a structure ? A designer determines structural system, material specifications, dimensions etc., the builder introduces construction sequence, organizes the labor to do the job, selects suppliers and materials, building elements and equipment. The user directs the exploitation of the structure as a load carrying device. The neighbour influences snow, wind, foundations of the structure through his own adjacent object. Dissatisfied workers or irresponsible people of all descriptions, including terrorists, expend their malevolence by sabotage or in other destructive ways. Eventually even accidents unrelated to the structural system must be considered, such as fire, collisions, explosions, the effects of war or events related to a future technology presently unknown.

All these possible causes of failure have a common origin, man. The action of individuals, or the inaction at a critical time and place, will always be the cause of the vast majority of structural failures. With the exception of such purely natural events as wind, rain, snow and earthquake, all "things" entering the building process will be selected, fabricated, or put together by humans. Humans will verify the activities of other humans, rectifying errors or omissions, or they will not, in a number of cases, and some of these will eventually develop into failures.

Human activity has sofar eluded attempts to statistical analysis, and research efforts in this direction have been discouragingly few and far between although the facts recited above have been exposed rather clearly for quite some time.

Is it that the secrecy of human activity should be protected in this manner, or is it merely that researchers are being deterred by the difficulty of the problem? Is it that success in research on "things" that cannot evade analysis is won more safely and easily than with the elusive working of the human mind which directs the "things" ? Let us not forget that structural failures are almost never caused by one element alone but by combinations of a number of them : Even if it was the wind that blew down that roof, it was the designer who specified an insufficient number of nails, the builder who provided inferior quality or quantity, or the worker who cheated with the spacing in order to finish the day early. And again it was the foreman or superintendent who failed to check the worker, or the design, and let the deficiency slip through.

It is the checking function which is consistently cited as the only means in our power to control structural failure caused by human error or omission. Let us therefore devote some moments to the morphology of that checking function as it turns out, by elimination, to be the central element in the prevention of structural failure and, therefore, the principal tool for the achievement of structural safety.

Logically, the objective of supervision and checking is to eliminate in a second round what went wrong in the first one. This sounds rather simple but in practice, it is a very complex endeavour. In many cases, corrections can be made quite easily when an error has been recognized. Sometimes the time for recognition and correction is limited as for example in the case of concrete reinforcing faultily placed: As soon as the concrete has been placed, the error will be hidden from sight and corrections become very difficult and costly. The target of the checking (control, supervision) function is then, in trivial words :

For the right person to be there at the right time and paying sufficient attention.

Errors occur in an infinite variety of ways but they all have their history of development into conditions deleterious to the structure, during part of which they can be recognized and rectified. Eventually, real structural safety will therefore principally depend on the effectiveness of checking and supervision.

Let us consider how it is presently being performed, in order to understand how it works and why, in certain cases, it does not. Recapitulation of two facts appears to be justified at this point, in order to prepare the stage for the further discussion :

1. Structural failures are rare events and the number and variety of building parameters contributing is virtually infinite.

2. The amount of effort presently spent on checking and supervision is by and large what is considered adequate in today's social and economic conditions. It is not likely to change dramatically.

Various organizational mechanisms exist, varying from country to country and from case to case, to implement checking, review and supervision design, construction and sometimes the usage of structures. From state imposed institutions, like "Prüfingenieure" or "bureaux de contrôle", to the North American practice of leaving it more or less to the parties directly involved with the structure to decide on the intensity of control, many different systems are considered acceptable. No one has been proven to be superior to others, where the only ultimate proof of course would be a relatively lower frequency of failures within the domain of a particular system, or inversely, by making possible higher economy by lowering safety margins (reduction in expenditure for building materials) without an increase in the frequency of failure. Therefore no "perfect" or "best" version has been found sofar.

In practice, checking is usually left to one or more individuals with not much more at their command than their personal experience, commonsense and inclination, and some furtive and unsystematic knowledge about what has gone wrong elsewhere. More or less systematic guides are rare to be found in the field of structural engineering, and they usually extend only over certain limited portions of the problem such as design calculations, consistency of shop drawings with plans and specifications, or quality of certain construction materials.

If one compares checking and supervision with a network set to catch errors of all kinds, then apparently, no particular type among a wide variety has been found to outcatch the others. With the average size of mesh sensibly invariable, as we have seen, improvements can be found only in one way, namely by finding and removing gaps and leaks in the mesh where errors still slip through, large enough to cause structures to fail. As good fisherman, we should go about mending our nets as we shall not be able to buy new or better ones. Gaps are not located in the same positions in all versions of the nets but one common property can be seen: They all need mending.

If the amount of thread available represents the total effort available then the best possible network is certainly the one with uniform mesh size throughout, and containing no gaps. This has always been implicitely recognized by the profession of engineers at large, the consequence having been that whenever a certain type of failure became conspicuous enough to cause concern, design methods and rules were adjusted and checking for the particular condition was intensified. Network mending is therefore a continuing process but, as experience shows, it normally takes place only after gaps have become evident through massive leakage, i.e. frequent accidents of a specific type. Earlier in history gaps in the net existed that could be filled by new developments in the theory of structures which subsequently were acquired such as the theory of stability, whose development and dissemination followed a number of large scale accidents due to instability of steel members or assemblies. Not much hope exists today that new theories will help us much further in controlling structural safety. Building Codes are in the process of fine adjustment and dramatic improvements in our knowledge about building parameters do not seem to be waiting around the corner.

What is it then that can be done in the sense of improving the consistency of the network, in order to prevent large fish from slipping through ?

Other fields of human endeavour have to deal with similar problems where the consequences of human failure to act appropriately at the right time is at the source of most of what goes wrong. Examples like the handling of airplanes or other complex technical equipment come to mind. All of them have in common that many elements or parameters work together for the final result, such as a safe trip, faultless fabrication of industrial products, or in the case of structures, a fail safe history. One frequently used method of ensuring a gapless control or supervision has been the checklist to be performed before the start of the real run.

A great number of errors leading to failure, have been traced to a mere lack of attention of the right people at the right time. A few seconds of looking would have been needed to recognize the hazard of the missing bolt or the instable condition of a support: A gap in the mesh that was quite easy to see but still not noticed, because no one was looking in the right direction. With this in mind, a tool like the checklist appears to be quite promising as it forces the performer to focus his attention for a minimum of time onto each and every item. Of course, the performer will have to be equipped with the necessary knowledge and authority to correct errors which will make him the most highly qualified individual among the designers and builders: in airplanes it is the pilot himself who attends to the performance of the checklist.

As a tool for the verification that everything necessary for the success of the operation (or design) has been considered, the checklist is the simplest form of systematic prevention of errors of random character. If set up properly it can make any effort spent on checking decisively more consistent and efficient. In its simplicity, it lends itself to easy adjustment and completion whenever needed.

Perhaps it is time to equip the engineering profession with something more systematic than today's rather random methods of supervision in design and construction.

5. LIMITING THE INEVITABLE, CONCLUSION

On the 1978 joint Conference of the ASCE, ICE and CSCE, the subject of design against hazards was formulated, with one half of the conference devoted to the problem of human hazards. It is the engineers after all, or designers, who are in a position or ought to be, to influence the resistance of structures under the assault of hazards, or of the unforeseen.

Human errors, as they were named for convenience in this paper, do of course include human hazards in the narrower sense and strategies aimed at the prevention of errors or their consequences will have to extend to all adverse conditions the structure will meet during its history, no matter what their particular nature or classification may be. In Hammurabi's time a structure had to resist failure without any ifs or questions asked. This is still essentially the case despite all probabilistics and the "blaming of things", as it were.

To achieve this, different approaches have been found to provide part of the answer: A first and classic strategy has been seen to be the application of the design expression which includes safety margins to cover "reasonable" deviations of the building parameters from their assumed nominal values.

A second strategy was found to consist in an improvement not so much of the intensity as of the consistency of checking and supervision. It is quite obvious that this activity is limited practically to the duration of design and construction, unless certain controlling functions are extended beyond those stages, as is the case for certain types of structures such as railway bridges, power dams or structures of similar scope. The majority of structures however, will be left to itself and its users after the construction crew has left.

Other strategies will therefore have to be found to compensate for errors and hazards occurring after construction, as well as those that escaped the first two approaches to structural safety. In recent years, the beginnings of such strategies has been recognizable, with earthquake resistant design leading the field. Notions like design against progressive collapse, toughness or ductility of structures have made their appearance, triggered for example by the famous partial collapse of the Ronan's Point apartment building. They are what this author would like to call strategies of the third line of defense and they all have a common aim, to design a structure in such a way that failure, where it inevitably occurs, will be limited in scope, geometrically, in terms of value or danger to life.

In conclusion then, three types of strategy are presently being applied for the control of structural safety; by their state of advancement, they can be ordered:

1. Design safety margins, as represented by the typical expression

   $$\text{minimum Resistance} \geq \text{maximum Loading}$$

   This method is established and included in building codes and is being generally used in structural design and construction. Its development is very advanced and fine adjustments are presently being implemented. It is based on statistical recognition of the variation of building parameters, not considering random influence of human (or gross) errors.

2. Checking and supervision during design and construction. This strategy is generally applied in practice, with substantial effort but little consistency from case to case. A greater intensity not seeming to be probable in the near future, improvement will have to be found in the direction of making it more systematic and by directing the available effort onto where it counts. Research efforts in this field have been hesitant and much is left to be improved. The second strategy is mainly aimed at the elimination of human errors which are recognized to cause the majority of structural failures. The use of checklists for guidance seems indicated.

3. The beginnings of a third line defense strategy have been recognized in certain fields. It is aimed at equipping the structure with reserves for the case of accident or where the first and second lines of defense have failed to prevent structural failure. Specifically, types of initial failures possible or probable are established and limited in their scope through the choice of appropriate structural systems. Notions like earthquake resistant design, design against progressive collapse, ductility or toughness of structures, failure mechanics belong to this general approach. To make it into an effective and systematically used tool will be one of the tasks of the future.