Structural Engineering Documents

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Franz Knoll
Thomas Vogel

Design for Robustness

International Association for Bridge and Structural Engineering IABSE
Association Internationale des Ponts et Charpentes AIPC
Internationale Vereinigung für Brückenbau und Hochbau IVBH

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Preface

Robustness is a property, the description of which varies so much with context that it is difficult to put order into its manifold aspects, relationships and ramifications, let alone to pronounce a consistent and general theory.

This text is an attempt to provide at least a practical review of the important elements of robustness in the context of structural systems, and to collect ideas or ways and means to deal with some typical circumstances in terms of structural design, in order to enhance survival, or to mitigate the consequences of unforeseen events to structural systems.

The text is divided into two parts:

- A review of the elements of robustness and strategies for its establishment by design (Chapters 1–8). Hopefully, this part will be found to be sufficiently short and concise for the reader not to become overly and prematurely bored.
- A review of specific scenarios intended to illustrate some typical or notorious situations where robustness must be established beyond the schoolbook structural design procedures (Chapters 9 and 10).

Writing a book is a lonely business. It's all the more important that other people have an attentive look to the outcome before it is printed. The authors wish to express their gratitude to the IABSE Structural Engineering Documents Editorial Board with its chairmen Geoff Taplin and Mikael W. Braestrup and their assigned reviewer Loring A. Wyllie, Jr who spent their valuable time in reading the manuscript and helped with their feedback to improve the present document. Finally, special thanks go to IABSE and its headquarter who made it possible to disseminate our experiences and ideas to such a distinguished audience.

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Chapter

1

Introduction

1.1 What is robustness?

Robustness is the property of systems that enables them to survive unforeseen or unusual circumstances.

The design of a system, be it a natural or an artificial one, is typically oriented towards normal use, i.e. circumstances which must or can be anticipated to exist during the intended working life of the system. Limiting the design to this may however leave it vulnerable to the effects of events that were not included in the set of anticipated circumstances. These effects can be of very diverse character and may be related to the features that were anticipated in the design but for an unanticipated intensity, or they may be of a description altogether foreign to the design premises.

The first case can be exemplified by a structure, which, although it was designed to resist a set of physical conditions (e.g. climatic or seismic effects), succumbed to some of these because they turned out to be of greater magnitude than foreseen.

An example for the second case could be seen in the fate of natural systems, for instance certain species that are perishing because of exposure to anthropogenic adversity in the form of destruction of habitat or such. Nature will, of course, always survive and mostly this will happen through expansion of the system: Where one species as a system is lost, others will take its place as part of a larger system—nature can expand *the system* up to a planetary scope and beyond—“Nature will survive humanity”. The question for us is of course whether humanity will survive, and how, with humanity’s power to expand itself and the systems it creates being limited.

In order to say something rational and consistent on the property of robustness, some basic concepts must be described and clarified as far as possible—although a strict definition in the sense of a reduction onto other, well-known concepts may just be out of reach. The two concepts foremost in need of clarification relate to two terms used in the brief introduction above: *System* and *Survival*.

1.2 System

In the case of *system*, it is easy to see that this term can mean anything in a very wide range of variations. From natural ecosystems of different scope to the digestive apparatus of a living individual, and from the political system of a state to a tool such as a computer or a kitchen appliance to a mental construct such as philosophy, or the instructions for the use of that kitchen appliance. In view of this diversity, it would appear that limiting the scope of application would provide the only hope for finding a manageable description of *system*. So here goes: Since the goal of this report is to find ways to make structures more robust, the concept of system shall be limited to what can reasonably be called a structural system. The term still includes a considerable variety of things, from the cast-in-place concrete frame of a building to a method of supporting formwork for the same, to an individual structural element such as a bridge girder or welded steel connections. All of these constitute subsystems to an overall structural system and their robustness will be instrumental for the survival of the latter.

Unlike in nature, all structural systems are limited in time, space and purpose. While in natural systems the passing of an individual is of no great importance, this is not the case for human artefacts, which are created and purchased for a distinct function. If the roof of my house collapses under the weight of the 50-year snow during a blizzard, its replacement is not an acceptable recourse since it was built to shelter me from snow and cold and wind, i.e. for a distinct and limited purpose.

1.3 Survival

The other concept essential for the discussion of robustness is *survival*. Survival is not an absolute and its description may vary, depending on the context. Normally it means *survival of function*, i.e. through its robustness, the structural system must continue to provide the function for which it was created, modified or preserved, and it must do this *whatever happens*, i.e. independent of circumstances. These circumstances may include limited damage to the structural system, perhaps a reduction or interruption of the full function limited in time, but essentially the function must be maintained through the intended working life of the structural system. A building, which comes through an earthquake with some cracks, broken glass or the like but can be repaired in reasonable time and at acceptable cost, has survived even if some of its occupants must be evacuated or inconvenienced for a while. Not so for another building, which, although it is still standing up, must be condemned and demolished because it would take too long, be too costly or too dangerous to repair it.

For the discussion ahead, the term *structural* then needs to be substantiated also. Structural functions normally include: Resistance to load effects or chemical attack, shelter from climatic phenomena, containment of substances, and sometimes more specialized purposes such as providing visual aspects, fortification, security, shade, etc.

1.4 Robustness in structural codes

Although some building codes require that structures should be robust, only the newest ones define robustness in a prominent place. The Eurocodes for instance that should replace the National building codes of all countries of the European Community and some others such as Norway, Switzerland, Iceland, Cyprus require robustness in their Basis of Design only implicitly ([3] Clause 2.1 Basic requirements):

“[3] A structure shall be designed and executed in such a way that it will not be damaged by events such as:

- explosion,
- impact, and
- the consequences of human errors.

to an extent disproportional to the original cause.

[4] Potential damage shall be avoided or limited by appropriate choice of one or more of the following:

- avoiding, eliminating or reducing hazards to which a structure can be subjected;
- selecting a structural form which has a low sensitivity to the hazards considered;
- selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localised damage;
- avoiding as far as possible structural systems that can collapse without warning;
- tying the structural members together.”

In Eurocode 1–7 on accidental actions, finally, robustness is defined as: “the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause” ([4], Clause 1.5.14).

It is of course easy for a committee to write such sweeping requirements into the code. It leaves the engineer in a rather uncomfortable situation, however, if help is not provided along with the demand. No code is presently doing this in any useful way, leaving the engineers to themselves with the task. This little book is intended to provide some of that help.

Chapter

2

The Foreseeable Unforeseen

2.1 Ordinary structural design

Today, the design of structural systems is most often based on *mathematical models*, which are substituted for the future *real structure*, for purposes of analysis. Modelled are, besides the physical description of the structure (geometry, topology, stiffness, mass, weight, etc.), the circumstances to which the structure is thought to become exposed during its lifetime (loading effects, chemical deterioration, abrasion, etc.). Sometimes, physical models such as scaled down reproductions, full-scale prototypes or the final structure itself are used to justify its design, through proof loading or other representative testing.

The fact that the proof of aptness of the structural system must be brought about using substitutes of some form and can only rarely be demonstrated on the final product[1],has been recognized and rationalized by the *règles de l'art* (i.e. *the art of engineering*), and expressed in building codes and handbooks in the form of modelling rules and stipulated minimum safety margins. Safety margins are intended to compensate for differences which are anticipated to exist between the idealized models used for the analysis, and the physical equivalent, the real structure and its circumstances. Where the maximum snow load expected to occur in 50 years is quoted to 2.5 kPa in the building code, a satisfactory design must provide a structure which will resist a higher load (e.g. 1.5 times). At the same time, the modelled resistance of the structure is put into question and somewhat lower resistance values are presumed in the design, recognizing that the creation of the real structure may leave something to be desired and may result in a somewhat less resistant system than specified on paper.

These safety margins have been developed, mainly through a vast amount of experience with real structures but also through much research in laboratories, and their values are usually established as a consensus in committees appointed for the purpose. They are periodically adjusted, reflecting new information concerning the aptness of their values and also their format. However, for the great majority of applications, no substantial adjustments (greater than, e.g. 10%) have been introduced recently, reflecting a general impression that all is as it should be.

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[1] Often structural systems are, unlike industrial products, "one of a kind", so that no prototype or serial testing is possible, especially when it is destructive.

Chapter

3

Survival through Robustness

For a structural system to survive unforeseen events or circumstances, with its intended function intact, it must possess sufficient reserve capacity to stand up to conditions during and after the event. A robust structural system has therefore:

$$\text{Residual capacity} \geq \text{Residual demand} \tag{3.1}$$

Most often, *capacity* will relate to resistance to forces (i.e. strength), but it may also mean deformability, ductility, stability, weight, mass or stiffness as any of these properties may be critical, depending on the context. The term *residual* or *after the event* may not always be temporal in the literary sense but, as in the case of a hidden flaw or weakness, may rather mean: In the situation where the event (the flaw taking effect) has taken place.

A structural system may change its character during or due to *the event*, in particular concerning the description of *load paths*. This term can be defined as the integral of all elements of the system affected by internal and external forces. It is described by stresses, internal forces, reactions, etc., which occur in those elements and can be traced by calculating or measuring those quantities from the point of application of the load to the boundaries of the system. A simple example is provided by the chain with a weight hanging from it: The load path goes from the hook through all the chain links to the point of suspension (and beyond if elements beyond are to be included in the system).

The example of the guardrail along the roadway is quite illustrative for the change in load path: When the impact of a collision is light, the rail will resist it in bending, without being deformed much. Heavier impacts will be resisted in membrane fashion, the guardrail being bent out of position and acting now mainly in a hammock-like manner. This second load path represents a *second line of defence*, one of the principal strategies for robustness.

As indicated above, the structural system may also change its function as the result of the event, as in the example of the car in an accident, or a building after an extreme earthquake. This is not always the case, however, and structures may have to be designed to survive with their primary function intact, or with a similar one assigned to them after the event. Important examples for this are – aside from military facilities – hospitals, schools or similar spaces intended to serve as shelters for people who were displaced by the event. Likewise, roadways, bridges and airports needed for access to distressed areas, must serve with their original function preserved following the event. If they do not, considerable loss of life is often the consequence.

Chapter

4

The Hazard Scenario

Circumstances which require robustness are those where critical physical conditions exceed the limits of resistance which the structure was equipped with, in terms of strength, deformability, durability, etc., or where the real resistance of the structure is lower than anticipated, or a combination of both.

The essence of a *hazard scenario* is that the resistance of the structure has been overcome, leaving it in an impaired, damaged or altered state. Examples for this are very diverse and include rupture of certain elements in a system, yielding, instability, displacement, reduction in cross section, etc. Large deformations often accompany the event, which must be considered when analysing the altered structure.

It is perhaps useful to classify the events in a very general sense since different *families* of scenarios require different approaches to robustness. We shall call one family the *interior flaws* or simply *flaws* where the origin of the event is located within the structural system. The second family will then be *exterior causes*. Forensic investigation of accidents often finds that a combination of causes relating to both classes is responsible for the mishap, i.e. a weakened structure was subjected to loads that exceeded the design loads. It may be that one of two or several events would not have been sufficient to cause distress and only their cumulation did.

4.1 Interior flaws and the like

Structural properties such as strength, stability, stiffness, durability, etc. are variable quantities. For the design and analysis of a structure, one substitutes hypothetical values for the real ones, which can be determined only when the structure exists (this may be difficult even then, involving complicated or indirect testing procedures). A variation will therefore exist between the hypothetical and real values. This variation has been the subject of much research and a large amount of probabilistic as well as forensic data exist comparing *specified* (or *expected*) values with tests or reality. These data were used for the establishment of safety factors (among other considerations) and a certain amount of variation is considered *normal, usual* or *legitimate*, i.e. not much can reasonably be done to reduce it. The variation follows more or less a Gaussian distribution for random data, with some special considerations for extreme deviations–which one tries to eliminate through testing, inspection or quality control procedures, recognizing that large variations are less *legitimate*, even though probabilistic theory permits them to exist.

Chapter

5

Considerations on Hierarchies

5.1 The hierarchy of failure modes, targeting quality control

Most structures can fail in different ways with each mode of failure answering a description of the course of events, as well as of the consequences for the system; two common examples will illustrate this:

- The failure in compression of a column in a building is usually sudden, with little advance warning, and in most cases will be of catastrophic consequences, especially if it supports several floor plates.
- The failure of a beam in bending will often be paramount to yielding of steel only, which will cause permanent deformations, and redistribution of loads but not much else. Beams usually carry only one section of a floor so that the scope of a beam failure is limited to that particular section.

Robust structures are those that develop less catastrophic failure modes first which very often leads to a subsequent limitation of forces associated with the event (see Section 6.7: *Capacity Design and the Fuse Element*) or to remedial action. It is possible in design and analysis to rank the failure modes of a structure in terms of a hierarchy in such a way that the less harmful ones are generated at lower loading levels. This must be done without load and resistance factors, with realistic values representing the physical conditions and on a probabilistic basis. Usually one introduces sufficiently high ratios between the load intensities belonging to different failure modes; typically they will amount to factors of 1.3 or so, in order to ascertain that uncertainties of modelling or material properties (e.g. overstrength), etc. cannot upset the assumed hierarchy in the real structure.

In earthquake engineering this has for example led to the *weak beam/strong column* concept where one designs the columns to resist higher load intensities than the beams which can be designed for ductile behaviour much easier and more effectively.

A very important corollary of structural hierarchy concerns the quality control. Usually the means available for the detection of flaws and errors in terms of time, money and logistics are not sufficient to exercise exhaustive control and verification of each and every element of a structure being planned, fabricated and erected. The question then becomes: Where do

Chapter

6

Elements of Robustness

The menu includes a number of strategies and considerations, some of which may not be mutually exclusive but can or must be combined or belong to more than one course in the menu:

- Strength
- Structural integrity and solidarization
- Second line of defence
- Multiple load path or redundancy
- Ductility versus brittle failure
- Progressive failure versus the zipper stopper
- Capacity design and the fuse element
- Sacrificial and protective devices
- The knock-out scenario
- Stiffness considerations
- The benefits of strain hardening
- Post-buckling resistance
- Warning, active intervention and rescue
- Testing
- Monitoring, quality control, correction and prevention
- Mechanical devices

Each of them may be applicable in certain circumstances but not in others. In particular, the type of event and the type of structural response will decide about the strategy of choice:

- Is the event load controlled or deformation controlled?
- Is it repetitive?
- What are its physical limits in terms of forces, impact, energy, deformation, movement, duration, etc.?
- What will be the conditions following the event? Structural function, further events?

Chapter 7

Maintaining Robustness

Older structures have usually seen a history of alteration, modification, remodelling, redecoration, etc., which leaves them in a state that may be quite different from the original and may no longer conform to the hypotheses, assumptions, specifications and plans which formed the basis of the design and construction. Often, these alterations (holes, notches, cuts, transfers, etc.) are of a minor nature when seen individually and have been introduced at different times, for variable reasons and by different agents. Their sum, however, may be quite significant, and usually of a negative nature, i.e. reducing such desirable structural properties as strength, resistance, stiffness and robustness. Finishes, hiding the messy character as well as the weakening represented from view, usually cover much of the modification. It is a good idea to consider this *fact of life* and if one wishes to depend on certain structural elements and their resistance, to verify if they can really be counted on, or if the safety margins their original design included, has been eaten away even where no signs of distress are detectable.

The popular argument that a structure that has stood the test of time, having survived for a century, will do so for another 100 years is entirely fallacious unless supported by sufficient evidence that the original state of the system is still intact. There is no reason to assume that a building will respond differently to use and abuse than a motorcar that, after it has travelled a certain distance, needs to be repaired, nursed, rebuilt or replaced. There is no reason to believe either that our ancestors built more solidly, with more attention to quality and robustness than we do today. The *good old times* never were, and the plague of giving all work to the low bidder has been with us since the beginning of time, as witnessed for instance by the famous letter Vauban[6] wrote to his superior Louvois[7] on July 17, 1685, concerning work done by the low bidder and by contractors forced to provide rebates (*Figure 7.1*).

Since the document shown in *Figure 7.1* is written in French, a free translation by the first author follows:

“A number of works are waiting which are not completed and never will be. All this is due to the confusion which is caused by the frequent rebates which are made on our works, for it is certain that all these broken contracts and promises, re-adjudications are only attracting

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[6] Sébastien le Prestre de Vauban (1633–1707) was General Inspector of fortifications and Field Marshal to King Louis XIV of France in numerous wars. He is also the author of scientific work on taxes and statistics.

[7] François Michel Le Tellier, Marquis de Louvois (1641–1691). War Minister to King Louis XIV of France.

Chapter

8

Conclusion

The toolbox for dealing with the problem of robustness is endowed with numerous strategies, which in many circumstances leaves several options open to choice. This of course constitutes a classical optimization problem: Where do I put my money and effort so it produces a maximum effect. Because quite often, numerical assessment of these effects, in terms of probabilistic or deterministic quantification, is out of reach because of the high rates of uncertainty inherent in the scenarios affecting robustness, and evaluation will remain qualitative and subjective. This may not be such a bad thing as it permits to bring fuzzy-type information and subjective experience to bear, which does not depend on scientific "rules of the game" and availability of significant data, to be considered valid.

Chapter

9

General Applications

9.1 Punching failure of flat plates (strength, ductility, second line of defence)

This is a type of failure which, in spite of being well known, even notorious, still occurs with frightening frequency. A number of reasons can be cited for this to happen, not least the mere volume and complexity of current building codes[8] which have become an important source of errors themselves as design engineers are forced to delegate their task to the *black box* of the computer.

The mechanism of punching shear failure is well known and does not need to be discussed here. One feature however is important to note in the context of design for robustness: The real shear resistance of a concrete slab around a column head is a function of the tensile strength of "real life" (not laboratory prepared) concrete, among other effects such as cracking, eccentricities, etc. It is therefore highly variable. This fact puts the problem into the class of situations that are highly infested with uncertainty, this time affecting the resistance side of the expression for structural safety.

Three different approaches have been proposed and used to provide sufficient robustness in this case, and certain building codes are addressing some or all of them:

- Increase slab thickness and/or provide stronger concrete over the columns.
- Provide shear reinforcing in the critical zone.
- Provide bottom reinforcing through the column.

In this discussion, it is exemplarily easy and clean-cut to assign each approach to a certain *strategy for robustness*, with the different connotations and consequences of each one.

The first method is obviously to provide sufficient *strength*. Building codes provide criteria for it, which persist being the subject of never-ending discussions in the code committees about precisely how thick is thick enough. In some instances, regulations have been made stricter than in the past which raises the notorious problem of the existing construction, which was designed to less restrictive requirements that are presently considered insufficient. Does this construction now need to be condemned or rehabilitated?

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[8] The International Building Code, published in 2003, has XII + 660 pages and weighs 1.7 kg. For the design of a concrete slab one also needs to study the ACI Code with 369 p., weighing 1.0 kg.

Chapter

10

Examples

10.1 Structural integrity of a historic building

This case concerns a complex of nineteenth century buildings located in a zone of moderate earthquake risk (Montreal, Canada). These buildings were constructed in the years 1860 to 1880 for the Sœurs de Miséricorde with the materials available at the time, namely stone for the walls and timber for the horizontal elements and columns. Most materials are reported to have been donated, which fact does not reflect well on the quality of the original construction.

In the course of their history, the buildings have gone through a number of major and minor modifications, mostly in connection with the installation of several generations of mechanical and electrical systems. Some of these modifications were less than thoughtful and left the structure in a state of severe degradation, with the telltales common to this style of construction: Walls bulging, beginning to buckle and disintegrate, floors sagging, floor joists broken and having to be shored up and portions of buildings evacuated and condemned because their condition had become too worrisome.

Robustness, or what part of it may once have existed, had obviously been lost. As well, structural integrity in its basic sense had never been provided, with the floor construction connected to the walls by contact friction only. In numerous places joists and floor beams were found to be sliding gradually off their supports, leaving the walls effectively freestanding for a height of two or several storeys (see *Figure 10.1*).

The buildings being of some heritage value, their demolition was deferred and studies undertaken to determine potential cost and circumstances of rehabilitation and new utility.

Rehabilitation will concentrate on re-establishing structural integrity, stability and robustness, as well as upgrading seismic resistance. Besides the repair of broken, damaged or degraded elements, it will include the installation of ties with some ductility anchoring the floor structure into the walls (see *Figure 10.2*) and some additional shear walls in the form of elevator and stair enclosures in reinforced concrete where the existing walls are found to be lacking sufficient strength to resist earthquake loads.

The floor finish can be used to create a diaphragm with some nominal reinforcing. The additional weight may have to be compensated through composite action or reduction of live loads. Surely, the structural integrity in terms of consistent and reliable coherence is the central

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Design for Robustness

Robustness is the ability to survive unforeseen circumstances without undue damage or loss of function. It has become a requirement expressed in modern building codes, mostly without much advice as to how it can be achieved. Engineering has developed some approaches based on traditional practice as well as recent insight. However, knowledge about robustness remains scattered and ambiguous, making it difficult to apply to many specific cases.

The authors' attempt to collect and review elements, methods and strategies toward structural robustness, using a holistic, almost philosophical approach. This leads to a set of considerations to guide selection and implementation of measures in specific cases, followed by a collection of applications and examples from the authors practice.

The world, engineering and construction are imperfect and not entirely predictable. Robustness provides a measure of structural safety beyond traditional codified design rules.