

# Human involvement the unforeseen and robustness

Franz M. Knoll<sup>1\*</sup>

<sup>1</sup>*Vice-president, NCK Inc, Montreal, Qc, Canada*

\*Corresponding author: franz.knoll[at]nck.ca

## Abstract

Human error is present in all human endeavours and has proven to be quite intractable scientifically due to the great variety of causes and circumstances associated with it. To prevent it from taking effect altogether has turned out to be equally out of reach as checking and verification techniques are limited timewise and cost wise. Safety margins are intended to protect against expected variation of building parameters; they are tuned to probabilistic assessments of these variations, with no consideration of those caused by humans. An alternative strategy to mitigate the effect of human shortcomings in planning and execution of construction projects is proposed to be equipping structures to essentially resist unforeseen circumstances by resilience and reserves of strength and deformability, i.e. robustness. The art of robustness as required by modern building codes is not intended to compensate for the "unforeseen" caused by human error and shortcomings but in fact it does. Nevertheless, it should not be interpreted as a panacea compensating for sloppy work, or for a relaxation of checking and verification.

Keywords: Human error, Robustness

## 1 Introduction

Human made systems being what they are, infested with the shortcomings of human cognition, reliability and attitude, they can be seen as the product of an incomplete optimisation. Depending on the situation that optimisation varies from a well-thought out and long process such as the development of an airplane model, to the momentary snap decision made on a construction site where the progress of the work was stopped due to a "site" problem. In all such situations insight and devotion of the human participants is of decisive importance and the effective mobilisation of these is a primary task of management. It has been posited that every error that occurs and is allowed to persist, is also and always an error of management. Management implies the organization of the process, i.e to put appropriate human resources in the right positions.

Check lists and prescribed protocols have been put in place and work effectively in many contexts but not in others. When looking back on more than fifty years of practice as structural engineer, in commercial and institutional construction, this author has learned that much of the "hunting down" of errors happens in more or less informal ways where "well seasoned", i.e. experienced people view and review the production, communication and execution of the information that constitutes the construction process from conceptual design to physical expression.

We know for quite some time that this "filtering" reduces an initial rate of erroneous information and decisions by one or two orders of magnitude (1,3). If we wish to make it yet more effective, the conclusion seems to be that this can only be done by enhancing the circumspection, insight and commitment of the humans involved, and to increase the time and financial resources devoted to control and review. Limitations to both are often found among the main causes of something going wrong.

Codification, standardization and regulation were meant to help with this but have now become so all-encompassing, convoluted and voluminous as to be counterproductive. The response of industry and practice to this has been to delegate it all to computer processing which introduces an entirely new source of error that we are presently forced to recognize: The computer glitch. Once again, the only means to control this newly created problem, is to engage the insight of experienced humans.

In spite of all the progress of technology and codification the real rate of failure in construction does not seem to be abating, for reasons that cannot be discussed in this paper (increased complexity, sharpened pencils for economic gain, etc). It is clear however that it would be desirable to find other means to do something about the accidents and losses that still happen, complementing the "filtering" and optimization the construction process provides.

If little can be done about the frequency of errors, something may be possible to mitigate and control the consequences of those errors. Strategy doing this is the design for robustness, making the structures

more “resilient”. Its essence and limitations are discussed in section 3 hereafter.

## 2 The human mind, its strength and weakness

The cognitive processes involved in “error hunting” have not been researched in any depth to this author’s knowledge although their manifestations for example in the form of apprehension, are rather familiar. They frequently occur in sleepless early morning hours when, medically speaking, the blood temperature in our bodies is slightly lower than during the active daytime, making things appear more sombre or outright scary, leading the mind to “ruminate” on what is bothering. On numerous occasions this has led to better perception and to timely and pertinent correction of decisions and information. It’s pertinence is very much related to the emotional involvement one has with the professional activity. If those emotions are of a negative nature, or non-existent, for example because of personal conflicts at the work place, or personal problem situations, unease of body or mind, attention and cognitive digestion will suffer. On the other hand, an engineer too confident and sure of himself will tend to be less circumspect and attentive to potentially adverse situations than his worried colleague.

Between the formalized protocol and the informal review by experienced professionals every variation can be found for the activity of error control, all of them depending for their effect on the emotional involvement of the humans doing it. It will be difficult to produce research that stands up to the rigours of modern science when it comes to emotional involvement of the human organism with the work it is doing. It is this author’s experience however with observing colleagues in the engineering enterprise I have worked for more than fifty years, that individuals who made their work a part of their life rather than just an exercise to “make a living” have been much more successful in producing satisfactory and reliable results. People whose priorities lie elsewhere tended to quit the company sooner, leaving often a “mess” behind that needed to be cleaned up, meaning to get rid of erroneous information such as “bad details”, ill thought through decisions, contradictions etc.

It is a tempting conclusion to believe that the power of “lateral thinking”, i.e. imagination, insight and circumspection, are directly related to how completely the mind is attending to the task. “What I like doing I am doing well and what I am doing well I like doing”. It may be that all this is having to do with our need for a sense of accomplishment, as basic as the daily bread, one might say.

Some types of potential sources of errors are better dealt with formally such as inconsistencies of data and communication – is the intent of the conceptual engineering drawings truly reflected on the manufacturers shop drawings? Others such as modifications along the process, must be reviewed for all their ramifications on other elements, something that involves the contribution of people familiar with those. Conceptual and fundamental decisions must be revisited for all their consequences which may reverberate throughout the entire destiny of a building project, including use and, eventually, deconstruction: why was the penny-wise decision made for the more “economic” construction method which causes future modifications to the structure to become so much more onerous, complicated or risky?

There are fundamental differences between large and complex endeavours such as offshore oil platforms, nuclear power stations on one hand, and everyday simple projects like high rise residential constructions, road bridges, warehouses, parking garages etc., on the other.

In the first case, vast amounts of regulation and protocols are installed and extensive studies conducted in order to detect potentially dangerous scenarios – with mixed success as we now know, following such recent accidents as Fukushima or BP’s platform in the Gulf of Mexico. On the commercial construction site time pressure reigns and things must be decided, adjusted, corrected or adapted quickly which does not permit any lengthy testing, study or reflection.

Experience shows that the accumulation of several harmless looking circumstances can cause great and unanticipated damage. The anticipation of such scenarios may sometimes resemble clairvoyance and is the product of experience, imagination and dedication; it is often treated in brainstorming sessions, involving participants from several disciplines, with some success. However, this still resembles a “shot gun” approach where a good portion of the issues is reviewed in what may be called “guided random” manner, depending on what crosses the mind of the participants, i.e. their power of imagination. To make the review process more exhaustive, a more systematic approach will be needed. It has been proposed that this should be given to Artificial Intelligence, and it certainly looks as though this will come - we are not there yet.

In any case, the human input will be needed for a while to come, and the role of random style lateral thinking will always exist, including its emotional basis.

### 3 The unforeseen, safety margins and robustness

Every building process and its product are carrying a certain measure of uncertainty that can traditionally be represented by some probabilistic concept such as a “bell curve”. This uncertainty has numerous sources, to begin with variations of material properties, imprecisions of geometry, underestimated exposure, etc.

Codified safety margins are intended to compensate for this. They are limited to what the Code Committee was able and willing to recognize as “legitimate” or “expected” variations. It has been customary since the time design rules became based on probabilistic concepts to calculate numerical values of the safety margins from “ $\beta$ ” factors of 3.5 or so, meaning that variations from “nominal” values up to 3.5 standard deviations should be compensated by factors reflecting pessimistic expectation about reality:

$$\text{Prob (real resistance} > \text{exposure)} \geq 1 - (10^{-5} \text{ to } 10^{-6})$$

and

$$\text{factor } x \text{ nominal resistance} \geq \text{factor } x \text{ expected exposure}$$

Theoretically then, a probability of ( $10^{-5}$  to  $10^{-6}$ ) would be the result, far away from reality which is  $10^{-2}$  to  $10^{-3}$  or so depending on the circumstances and how one counts. These probabilities, real or theoretical, correspond to a sort of consensus in society that this is by and large as it should be since the cost of increased margins to produce a lower probability of failure, would not be acceptable. Of course, this does not prevent society from hunting down and finding a guilty party if something goes wrong.

As a consequence, safety margins are and have been essentially unchanged for several decades and the quest for better safety has recently taken a different tack; it focusses on the description of the failure and the goal has become to mitigate its consequences, excluding catastrophic events and limiting the cost associated to what one did not succeed to catch and correct in time. This can be summarized with the term “robustness”. A precise and all-inclusive definition of this concept has been elusive but the intent is clearly to deal with the shortcoming of probabilistic theory at the tail end of the “bell curve” where the discrepancy between theory and reality manifests itself.

Where probability theory described the behavior of events of a random nature, the product of building construction is not so random, thanks to the involvement of human agents as we now know. It makes the tail end of the bell curve “thicker”, with more frequent “outlayers” than the theory would have it. The sources and manifestations of that involvement are varied and manifold. To control it through the organization of checking and review processes has always been the goal of the builders, and is recently being made the object of research. At best, this will be partially successful, leaving a residue of unhappy circumstances as “facts of life”.

This is where robustness comes in, mostly in the physical sense, i.e. making structures respond in less unfavorable ways to the unforeseen which now includes the faults produced by human agents.

Robustness was always implied in the work of thoughtful builders; it has recently been approached in a more systemic way mostly by researchers with experience in real life construction (2,4). In its practical application it is not a quality lending itself to be measured in the traditional sense by units of some sort. It must be adapted to particular circumstances which may themselves include elements that cannot be quantified meaningfully, e.g. the omission or misplacement of physical parts of a construction, errors of calculation or interpretation, lack of attention, ignorance, the unforeseen exposure to destructive agents, bad workmanship etc.

Robustness will help to attenuate the consequences of all this. However, as an answer to the problem of the unforeseen, it cannot be a final and all-encompassing solution, for two principal reasons:

- Robust structures are not meant to “survive” the unforeseen unaffected but their state “after the event” must only satisfy certain criteria, e.g. for buildings to remain standing after a strong earthquake, permitting the occupants to leave. Other examples include structures which have been “massacred” by thoughtless destructive alteration, for instance in connection with the installation of new piping or electrical and mechanical systems, or have simply been overloaded. Local deformations, cracks or slight damage may be acceptable, collapse is not.
- The scope and variety of human “action” and its effects are limitless and cannot be compensated entirely by ever so thoughtful and targeted measures and strategies. In this context the wilful destruction by war or sabotage, or the degradation through rot or corrosion over time due to lack of maintenance are not events that can be compensated in all circumstances by measures of robustness.

Robustness is a concept that has its limits, at least within “reason”, and must be seen as complementary to the elimination of errors and flaws through control processes. It could be brought to extreme degrees if it must, at commensurably high cost. Some fortifications of the Second World War still exist – they were built so massive that their destruction became too onerous and expensive. Some of the Egyptian pyramids have survived more or less unscathed – some historians say that their construction was instrumental in ruining Egypt’s economy of the period.

Robustness has been included in modern building codes as a requirement for new construction (most codes are intended principally for this, at the exclusion of existing structure being altered, modified or extended.) How to do this is mostly left to the insight of the engineer – only recently has research on structural robustness been undertaken in academia. It was recognized as a rather vague concept with less than well defined parameters and aspects that does not lend itself to the abstraction and quantification most research calling itself scientific, needs as a prerequisite.

Mostly, it is presently treated, in the form of hypothesized scenarios, “what will happen if. . .” the selection of which is very much a matter of insight and thoughtfulness of the people involved. Obviously, this methodology has failed in the case of Fukushima. It may be said however, that we now command the tools to analyze what happens to structures when they are taken beyond the traditional limits of stress and deformation that were mostly based on the classic elastic theory. Forgetting about minute precision, behaviour of materials in the non-linear, inelastic range can be evaluated and applied to structural systems, predicting their response to loads or deformations exceeding codified values. Research on seismic response has spearheaded this and it’s findings can be transposed to other scenarios. There will always be limits to this, however.

An example from real life may illustrate a number of things discussed above: The case involves a small bridge with two pylons and stays made from steel rods. Everything went well at first and the bridge was opened for use by normal road traffic. However, the cumulative effects of a number of faults ultimately led to an accident scenario where the structure suffered severe damage, the bridge had to be closed for traffic and repaired at a cost comparable to the initial cost of construction, including the expense for all the legal and procedural action that accompanies such events.

- The tight schedule had caused problems of procurement, and among numerous other concessions, the substitution of an inferior class of steel had to be accepted. Instead of the specified quality which would have had a favourable behaviour at cold temperature,
- A steel with a transition temperature well above the winter weather was used for the guys. With temperatures to be expected in the low -30’s, this turned out to be a serious problem. Forensic investigation, following the failure, turned up the fact that the steel for the bridge had been procured from 24 different sources, all with impeccable certificates...
- The guys were made from  $3\frac{1}{2}$  inch (89 mm) diameter solid rods, each guy consisting of four units arranged in blocks of four in section, with a spacing of 8” (200 mm). (The use of solid rods for this purpose has recently been discouraged or prohibited by some authorities, presumably due to an accumulation of bad experience).
- The mode of attachment at both ends of the rods did not permit rotation without secondary bending moments.
- The damping associated with vibration of the guys was nearly nonexistent, and no tying of the four rods had been provided because no reason had been identified to do this.

In a cold winter night (-20° or so) a blizzard with winds of moderate speed blowing principally across the bridge apparently caused the leeward members of each guy to vibrate vertically (wake buffeting). Because of the very low damping, the movement in and out of the wind shade of the windward rods, was excited to a damaging amplitude for a number of cycles of the order of 20000 during this particular storm. This led to low cycle fatigue failure of 4 rods in 4 different places, at the anchorage points, due to the secondary moments. The bridge did not collapse however, since the three units remaining at each guy provided sufficient reserve resistance. The cumulative effect of several errors caused this accident. Its consequences were limited, thanks to robustness which had been provided through redundancy (four rods for each guy).

## 4 Conclusion

Human shortcomings will always be with us and the research into the circumstances that bring it about and the ways and means how it can be counteracted is an exercise aimed at minimizing injury, loss of life or value and the cost of “making good”.

One of the ways to deal with the effects of human error in the construction industry is to try and mitigate these by designing structures to be robust. Robustness can loosely be described as the ability of structures to withstand the unforeseen without losing their function where that function may change with the unforeseen event, to be reduced to, e.g. merely standing up rather than collapse, while other functions are permitted to be lost. In this discussion, the effects of human error or shortcoming are treated as “unforeseen” events, as are natural catastrophes surpassing the limits of the hypothetically expected. This may be justified by the fact that the distinction of what exactly was the human ingredient in an unfortunate outcome is sometimes difficult.

In any case, the effect of unforeseen circumstances is no different whether caused by human agents or not, or to which degree, and to deal with them usefully through structural design measures, no distinction is needed. Robustness is a strategy which has always been useful for this.

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