# Probabilistic modelling of exposure conditions

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## Summary

Probabilistic models are discussed with respect to various types of exposures like wind, snow, earthquakes, explosions and fire. In the discussions about robustness, however, also other items play a role like unforeseen actions, human errors and human actions aiming at destruction of the structure. At the moment, and maybe also in the future, there seems to be hardly sufficient structured data to assess firmly statistically based models. Some way out may be to neglect the actions themselves and concentrate on the extent and nature of the direct exposure effects. This is also the idea behind the popular design method of the missing column. However, even with those limitations most of the models have a highly notional character. In finding optimal and consistent design solutions these notional models are nevertheless believed to be helpful.

## Keywords

Probabilistic, models, exposure, structures.

## Background / Introduction

According to the Memorandum of Understanding the Activity 4 of COST TU0601 concerns the engineering modelling of the relevant exposures. The task includes the modelling and assessment of the probabilistic characteristics of the extreme exposure events in the first place. In addition one needs information on other (normal) loads and structural properties as they determine to a large extent the effect of the event.

## Problem statement / Key issues

Potential hazards may be split up into various categories. Hazards may be [Schneider]:

- unknown or *unforeseeable*
- in principle known, but *unrecognized or ignored*
- known and *dealt with*

So the risks corresponding to the last category are considered in the design and either accepted without additional measures or reduced to a level that is considered as acceptable. For those events we need models with respect to occurrence rate and magnitude. These models need to be realistic and operational. In principle this is possible, but for the short term only rather primitive and weakly underpinned models may be expected.

Even more difficult is the modelling task for the other categories of hazards. Lack of knowledge, human errors and even deliberate malicious human actions are well known to happen, but it is almost impossible to find the relation between, say a calculation error at the designers desk and the collapse of a structure 5 years later. Some short cuts need to be found.

## Methodology

Table 1 gives an overview of foreseeable hazards. The list is not claimed to be complete, if such completeness would ever be possible. The first three columns refer to more or less extreme or accidental actions. The distinction between natural and manmade hazards is not

| Accidental /natural | Accidental/manmade | Human influences | Normal loads | Human Errors |
|---|---|---|---|---|
| | | | | |
| Earthquake | Internal explosion | Vandalism | Self weight | Design error |
| Landslide | External explosion | Demonstrations | Imposed loads | Material error |
| Hurricane | Internal fire | Terrorist attack | Car park loads | Construction error |
| Tornado | External fire | | Traffic | Misuse |
| Avalanche | Impact by vehicle etc | | Snow | Lack of maintenance |
| Rock fall | Mining subsidence | | Wind | Miscommunication. |
| High groundwater | Environmental attack | | Hydraulic | |
| Flood | | | | |
| Volcano eruption | | | | |

Table 1: Overview of the foreseeable actions

important when discussing counter measures. The distinction by the way is not even straightforward in all cases: what is natural to a flood occurring in an artificial living area 10 m below average sea level or to landslides because of removing trees? The column of human influences shows actions that are not accidental but deliberately. The fourth column shows the normal loads and the last column the various types of human errors.

Whether or not these foreseeable actions are relevant for the design depends on the nature and location of the structure. In some cases, based on experience and or calculations, the risks may be considered so small that no further analysis and measures need to be considered. To provide sufficient robustness against the relevant set of foreseeable actions is in principle a matter of advanced engineering activities, like non-linear dynamic calculations and risk analysis. Reference is made to the JCSS documents on risk analysis.

So, next to the actions taken explicitly into design we have (see problem statement):

- the group of foreseeable but neglected actions

- the group of unforeseen and unforeseeable actions

For these actions the codes usually formulate a set of generic design requirements (ductility, redundancy, removed column approach). Whether or not these standard rules give sufficient and economically adequate protection has never been checked. If we want to find decision rules on the cost benefit effects of certain measures for certain buildings, we need at least to generate some kind of model. So the ultimate modelling question is:

> *Is there a reasonable probability of the (effects of) unforeseeable, unrecognised or otherwise neglected actions?*

In the next section we will present the state of the art with respect to the hazards mentioned in Table 1 as well as structural properties. We will also return to the above question later.

## Main findings / Discussion

### *Accidental loads*

In a quantitative risk analysis the risk is often presented as the product of a probability and consequence of an adverse event. This definition holds in the case of a single valued outcome. More generally the risk definition is given as "the mathematical expectation of the consequences". The model for such the adverse event may consist of the following components (see Figure 1):

- a triggering event $H$ at some place $\mathbf{x}$ and at some point in time $t$.
- the magnitude or amount of released energy (like Richter Magnitude, fire load, etc) involved and possibly some other parameters.
- the physical interactions between the event, the environment and the structure S, leading to the exceedance of some adverse state in the structure
- the consequences corresponding to the state of damage.

The occurrence of the triggering event $E$ for hazard $H$ may often be modelled as events in a Poisson process of intensity $\lambda(t, \boldsymbol{x})$ per unit volume and time unit, $t$ representing the point in time and $\boldsymbol{x}$ the location in space $(x_1, x_2, x_3)$.

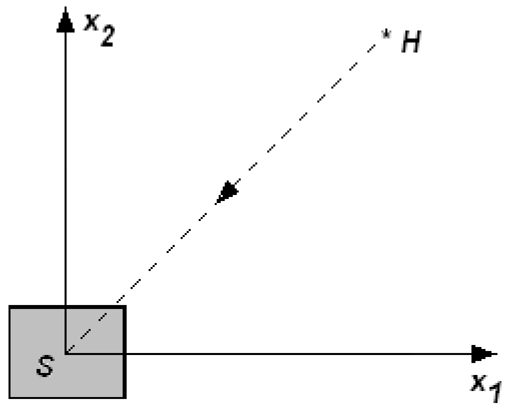


Figure 1: Components for the extreme event modelling (S=Structure, H= Hazard event with magnitude *M* at time *t)*

Based on the above models the exposures to the structure and endangered persons and goods can be estimated. In combination with other (normal) loads and events, *hazard scenarios* can be formulated as a basis for the estimation of the consequences. Non structural elements like sprinkler installations and damper devices may play an important role. Also for these devices failure probabilities need to be known.

***Normal loads (including extreme tail values)***

For several reasons also normal loads like wind, snow and traffic need to be considered in the analysis. First of all, the value can be so large that local failure happens. Also in those cases the robustness of the structure plays a role in the total damage related cost. In addition one should keep in mind that those loads are present at the same time and after the extreme event. For the probabilistic description of those loads reference can be made to the JCSS Probabilistic model code (see Webpage JCSS).

***Human errors and human influences (vandalism, terrorist attack)***

Generally, the human error is considered as the main cause of accidents. Most estimates give values in the order of 60-90 %. Errors may be made during the design (conceptual errors, misinterpretations of rules, calculating errors, software errors, drawing errors), during execution (misreading of specifications, bad workmanship, inferior materials) and use (operation, inspection, maintenance, refurbishment). Reference is made to a separate Fact sheet.

The category of vandalism and terrorist attack is a type of action where typically there is a deliberate aspect involved. This complicates the modelling task. The intention of the action is destruction and for the destroyer the strength of a structure is the starting point. To some extent it does not help to make the structure stronger, as it can provoke more action on the loading side.

Of course, by proper design, one can make it more difficult for persons who want to destroy the structure as a whole. Furthermore indications as to the likelihood of a terrorist attack, however, can be given. It will depend on:

- The strategic role of the structure in society (energy supply, water supply, etc)
- The possibility of a large number of victims
- The type of structure (monuments, embassies, governmental buildings, bridges, power stations, life lines).

A list of notional numbers for actions against such buildings could be helpful in taking the most (cost) effective counter measures.

***The (effects of) unforeseeable, unrecognised or neglected actions***

The simplest category of this group, of course, is actions that are known, but neglected for certain design situations. For these actions at least some idea must exist about intensity and frequency of occurrence. It often happens that a detailed consideration of an action is neglected for less important structures or structures where collapse has less serious consequences. The action is sometimes considered as being "outside the normal design envelope".

By definition no specific information is available for unrecognised or ignored actions and unforeseeable action. The category "unrecognised or ignored" is a kind of human error, the second category is a shortcoming of the whole profession. Nevertheless, when making an inventory of failed structures, one could categorize the cause of collapse as unforeseen or unforeseeable at that time. The flutter mechanism of the Tacoma Narrow Bridge, for instance, could be considered as unforeseeable at that time. So, in principle, although difficult, it is possible to find for past failures frequencies of unforeseeable and unforeseen failures. To some extent these numbers may have a meaning for future structures yet to be built, although of course reactions of the society and the profession always will disturb the quality of the numbers. We may indeed succeed to avoid the same mistakes, but for sure new mistakes will always be made. This holds in particular when new materials or concepts are being used. But even if the number is not correct from several points of view, it may help to have such a number in order to find a consistent set of mitigating measures.

From a methodological point of view the difference between human errors and professional lack of knowledge is small. This may be a reason to treat them as one group. A distinction however should be made between new areas (large scale, new structural concepts, new materials, etc) and proven technology.

In all the above cases the designer often wants to do "something". One of the most popular design tools is to consider a fully removed column or beam element as an adequate model for (the consequences) of these types of actions. Two main questions to be answered in this COST project are:

(1) Is this a useful model. Maybe a reduced resistance of one or more elements would be more appropriate. Some structural shortcomings may affect a larger number of elements than just a single one. But maybe we should, for the time being, make things not unnecessarily complicated.

(2) What order of likelihood do we choose for this event. Note that the number may depend on the type of structure and on the hazards already taken into account explicitly. The choice

of a likelihood is necessary if we want to compare costs and profits of various safety measures.

## Limitations

Within the present COST project will not be feasible to generate reliable statistical data for all relevant exposures. However, estimates based on expert judgments may be provided.

## Recommendations

The set up of a European data base for serious errors, accidental actions and structural failures is recommended.

## Outlook to further research

Main developments to be envisaged:

- development of standardized quantitative risk analysis, including items like errors and unforeseen actions

- check on economic efficiency of prescriptive measures presented in Eurocode 1991-1-7.

## Example / Illustration / Case studies

***Proposal for an example study***

Working Group 2 takes care of the activities 4 and 5 for exposure models and structural behavior models respectively. The key words for activity 4 are the normal and accidental loads, human deliberate malicious actions, human errors and unforeseeable actions. Activity 5 deals with the response of structures in the presence of extreme loading conditions. Key words are dynamic response, large deflections, deformation capacity and missing elements.

Consider the basic equation for the risk calculation under an abnormal load:

$$Risk = \Sigma \; p(H)\, P(D|H)\, P(S|D) C(S) \qquad (1)$$

where *H* represents the hazard, *D* the damage, *S* a failure scenario and C the cost in Euros. The summation is over all relevant hazards, damage types and scenarios. In this equation, the activity 4 is mainly concerned with the probability and modeling of the hazard and activity 5 with the damage and failure scenarios.

Until now WG2 has produced or dug up from literature a number of helpful documents in these fields. In order to complete this list and to put all information into the right perspective it could be helpful to consider and elaborate a numerical example structure, resulting in values for the risk defined above.

As possible structure for such a demonstration calculation could be a building as indicated in Figure 2. As central event we could consider the *removal of a column*. This failure scenario is often considered in codes and is also performed in practical design. In literature one may find quite a number of example calculations that could be of a help. It would match perfectly with papers and notes within WG2/Activity 5 already available, in particular the notes on concrete, steel and composite structures.

***Robustness analysis***

The start calculation should be on the basis of best guesses (average values) for structural properties. The outcome is an estimate for the load that can be carried by the damaged structure. The value will depend on the type of structure and the robustness measures taken. Next to this best estimate we may want to see the sensitivities with respect to the main assumptions in the analysis. From that point it is a small step to estimate the probability $P(S \mid D)$ in the basic equation the risk, where $S$ now stand for "failure" and D stands for "removed column".

***Vulnerability analysis***

The next question of course is to estimate the probability of the column removal itself:

$$P(D) = P(D|H)P(H) \qquad (2)$$

Table 1 gives a tentative overview of possible loads and hazards. We could have the column removed because of an explosion, a fire or an error. Here a limited number of possible sources should be considered and analyzed.

| | p(H) [50 years] | P(D\|H)) |
|---|---|---|
| | | |
| explosion | $2x10^{-3}$ | 0.10 |
| fire | $20x10^{-3}$ | 0.10 |
| human error | $2x10^{-3}$ | 0.10 |

Table 2: Estimated probabilities for the column removal case (somewhere in the building)

No human act of violence (terrorist action) is considered here as this may be not the most likely cause for the average building.

***Evaluation***

The next step would be to calculate the total risk:

$$Risk = p(H)\, P(D|H)\mathbf{\{}\, P(F|D)\, C(F) + P(Fnot|D)C(D)\mathbf{\}} \qquad (3)$$

The first term in the equation indicates the cost expectation if the robustness of the structure is not enough to prevent a full collapse, the second one, on the opposite, if there is only the limited damage of the removed column (indirect and direct costs). Given this result we may vary the design of the structure and find out whether certain robustness measures are cost effective or not. Some link with the measures proposed in Eurocode EN1991-1-7 (Accidental

Actions) could make the analysis interesting form a practical point of view. Many countries have difficulties in how to deal in particular with Annex A of this document (tying rules etc).

The exercise gives also an opportunity to explore for a practical case the various expressions proposed to make the notion of robustness objective and quantifiable.

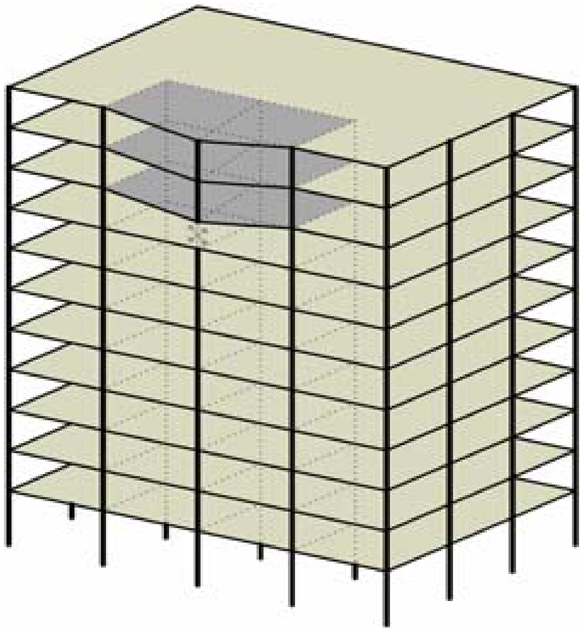

Figure 2: Example of an example structure

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