Methodology for Risk Based Fire Resistance Design of Structural Members

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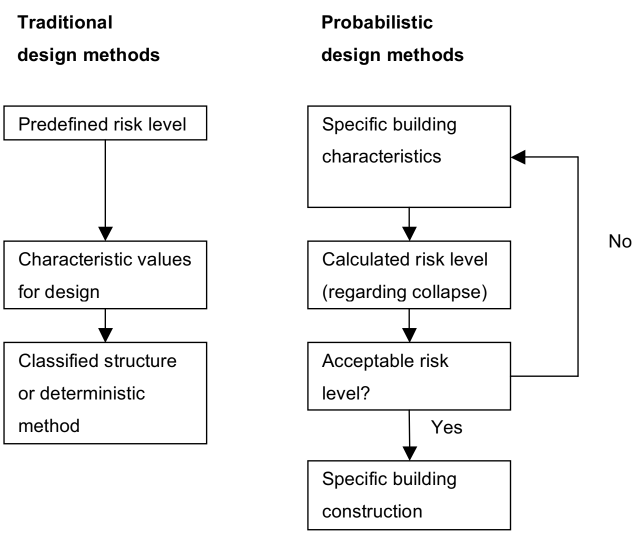
BACKGROUND

The performance-based codes currently used for design of fire resistance of structural members are, implicitly or explicitly, based on maintaining a certain risk level, which is based on potential consequences. The design starts with predefined risk criteria and ends up with a specific design of the structural members for the building. When using risk analysis instead of the traditional methods the design starts with the characteristics of the building and the risk level is calculated, if the risk is unacceptable risk reducing actions have to be taken. The difference between traditional design methods and designing with risk analysis is presented in the figure below.



One benefit with using a design method based on risk analysis is that the risk level is stated explicitly and hence it is possible to see the effects of various risk reducing systems such as sprinkler or smoke evacuation systems. Once the effect of a system is determined it is possible to see if it is economically defensibly to introduce the system in the building or not. With a design method based on risk analysis it is also possible to incorporate the failure rate of such a system.

METHOD FOR FIRE RESISTANCE DESIGN OF STRUCTURAL MEMBERS WITH RISK ANALYSIS

The purpose of fire resistance design of structural members with risk analysis is to quantify and present the risk in case of fire regarding the consequences that occurs if the building collapses so that risk reducing actions can be taken and a reasonable risk level is obtained. Once the risk level is stated explicitly it is possible to determine how risk reducing systems affect the risk level and therefore it is possible to design fire safety systems so that the risk level for the building is acceptable and the final solution is cost efficient.

The method developed for fire resistance design of structural members with risk analysis follows the flow chart presented on the next page. As described above a method using risk analysis starts with the characteristics of the building.

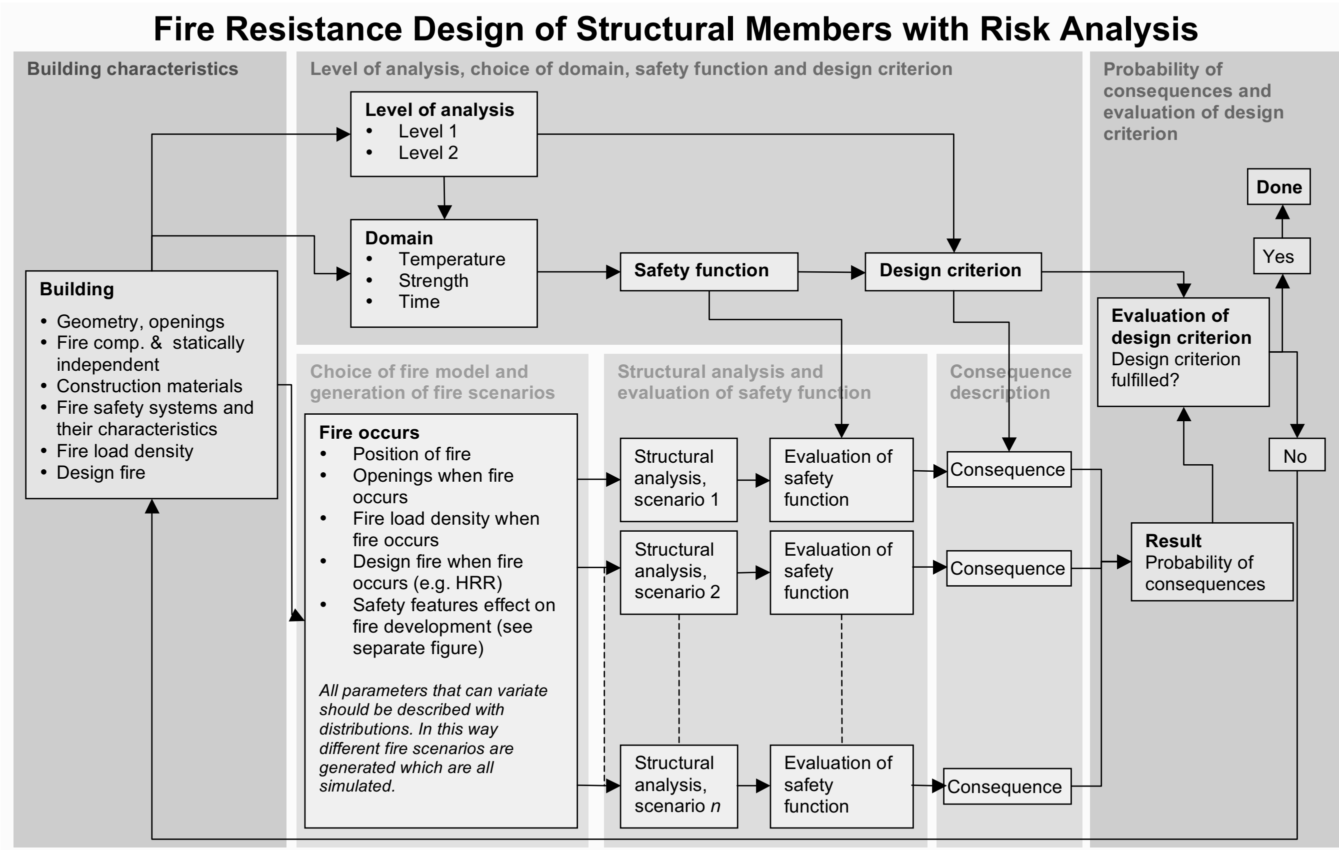
Building characteristics

When describing the building's characteristics it is important to include variables that affect the fire development and the load bearing structure. Depending on the choice of models to describe the fire development and the impact on the structure the needed variables deviate. The building characteristics described below may be of importance, a short explanation is also given to the importance of every factor.

The building geometry and openings affects the fire development as well as the possibility that flashover will occur. Of importance is also where the fire starts in relation to the structural members since the view factor strongly varies with the distance when analyzing the effect of a localised fire. Further a design fire has to be made; variables that are uncertain must be described with distributions in order to be able to generate a lot of fire scenarios. Also the fire safety systems in the building and their characteristics are important since they affect the fire development. The effect on the fire development has to be determined, e.g. activation condition and the failure rate has to be known for each system.

The construction material is of importance for the heat balance within the fire enclosure but most of all important because it is the structure itself that is analyzed. Hence the construction material's thermal and mechanical properties must be known. Relative load bearing capacity is of great importance since it is crucial for what fire severity the structural members can withstand. Fire compartments and statically independent may make it possible to delimit the problem into smaller parts that can be analyzed separately without affecting each other.

Further the activity in the building and the geographical location are two factors that will affect the potential consequences and hence the acceptable risk level. The acceptable risk will give the design criterion as described below.



Fire Resistance Design of Structural Members with Risk Analysis
Building characteristics
Level of analysis, choice of domain, safety function and design criterion
Probability of consequences and evaluation of design criterion
Level of analysis
• Level 1
• Level 2
Domain
• Temperature
• Strength
• Time
Safety function
Design criterion
Done
Yes
Building
• Geometry, openings
• Fire comp. & statically independent
• Construction materials
• Fire safety systems and their characteristics
• Fire load density
• Design fire
Evaluation of design criterion
Design criterion fulfilled?
Choice of fire model and generation of fire scenarios
Structural analysis and evaluation of safety function
Consequence description
Fire occurs
• Position of fire
• Openings when fire occurs
• Fire load density when fire occurs
• Design fire when fire occurs (e.g. HRR)
• Safety features effect on fire development (see separate figure)
All parameters that can variate should be described with distributions. In this way different fire scenarios are generated which are all simulated.
Structural analysis, scenario 1
Evaluation of safety function
Consequence
No
Structural analysis, scenario 2
Evaluation of safety function
Consequence
Result
Probability of consequences
Structural analysis, scenario n
Evaluation of safety function
Consequence

Level of analysis, safety function, choice of domain and design criterion

The probabilistic analysis can be performed on two levels, defined as level 1 and level 2. A choice has to be made between the two levels and what level to choose is dependent on how detailed the results must be. If the result only has to be a probability of failure level 1 is chosen, but if a more detailed is of interest, e.g. such as the magnitude of failure, level 2 has to be chosen.

Level 1 is a probabilistic evaluation of a safety function (see equation 3). On this level it is assumed that if one single structural member does not fulfil the safety function during a fire scenario, the whole building collapses in that specific fire scenario. If the scenarios are generated with Monte Carlo analysis the probability of collapse can be calculated as described in equation 1.

$$\frac{N(\min(R_i - S_i) < 0 \mid fire)}{N(fire)} \rightarrow P(\min(R_i - S_i) < 0 \mid fire), \qquad when\; N(fire) \rightarrow \infty \quad and \quad i = 1, 2, \ldots, n-1, n \tag{1}$$

Index *i* is used to denote a structural member, all structural members of importance have to be evaluated in every fire scenario. Minimum is used because the only consequence studied in analysis level 1 is collapse of anyone of the structural members in one scenario. *N* in the equation is the total number of fire scenarios studied.

On analysis level 2 the magnitude of the consequence in each fire scenario is studied. The probability of a consequence exceeding a certain limit is of interest and can be described according to equation 2.

$$P((C > c) \mid fire) = \sum_{C>c} p_f, \qquad p_f = P(C = c \mid fire) \quad f \in Z^+ \tag{2}$$

C denotes a consequence in case of fire and *f* each fire scenario studied in the analysis.

The safety function is in the general case defined according to equation 3 and expresses the resistance as being greater than or equal to the severity:

$$R_i \geq S_i \qquad where \quad R_i = Resistance, \quad S_i = Severity \tag{3}$$

According to Buchanan (2001) the safety function can be evaluated in three different domains, which are given in table 1. Evaluation of a safety function alone can correspond to verifying the fulfilment of a safety criterion in traditional, deterministic and prescribed design methods.

Table 1 Safety function expressed in different domains from Buchanan (2001).

Domain	Fire Resistance	≥	Fire Severity	$R_i \geq S_i$
Temperature	Temperature causing failure	≥	Maximum temperature during fire scenario	$T_{collapse} \geq T_{\max}$
Strength	Load bearing capacity	≥	Maximum load during fire scenario	$R_{fire} \geq S_{fire}$
Time	Time to failure	≥	Duration of fire	$t_{collapse} \geq t_{fire}$

The temperature domain may be suitable if critical temperatures that cause collapse can be determined for the structural components. For evaluation of the safety function in the temperature domain the load bearing capacity is expressed in terms of critical temperature. It is commonly used in combination with simplified section factor methods for steel profiles as well as for evaluation of simple concrete slabs where a single point reinforcement temperature can be relevant.

The strength domain is more versatile and can be used for most load bearing evaluation of individual structural members, including more detailed analysis that cannot be translated into a 1-D problem, i.e. where the section factor method may not be applicable. An example of this could be evaluation of columns where the interaction of buckling and compression is too complex to be expressed just in terms of critical temperature.

The time domain is used when performing global, full scale FE analysis of structural systems, as opposed to individual evaluation of each structural member in a system (Jeansson, 2002).

The time domain can be used if the time to structural failure is of interest, for instance when fire exposure is according to prescribed standard fires with a time criterion. It should also be mentioned that methods involving time equivalent formulas are available, e.g. Eurocode (2002) and Thomas (1986). Although practical for probabilistic evaluation, most time equivalent formulas have limitations, related to construction materials as well as to size of the fire compartment (Buchanan, 2001).

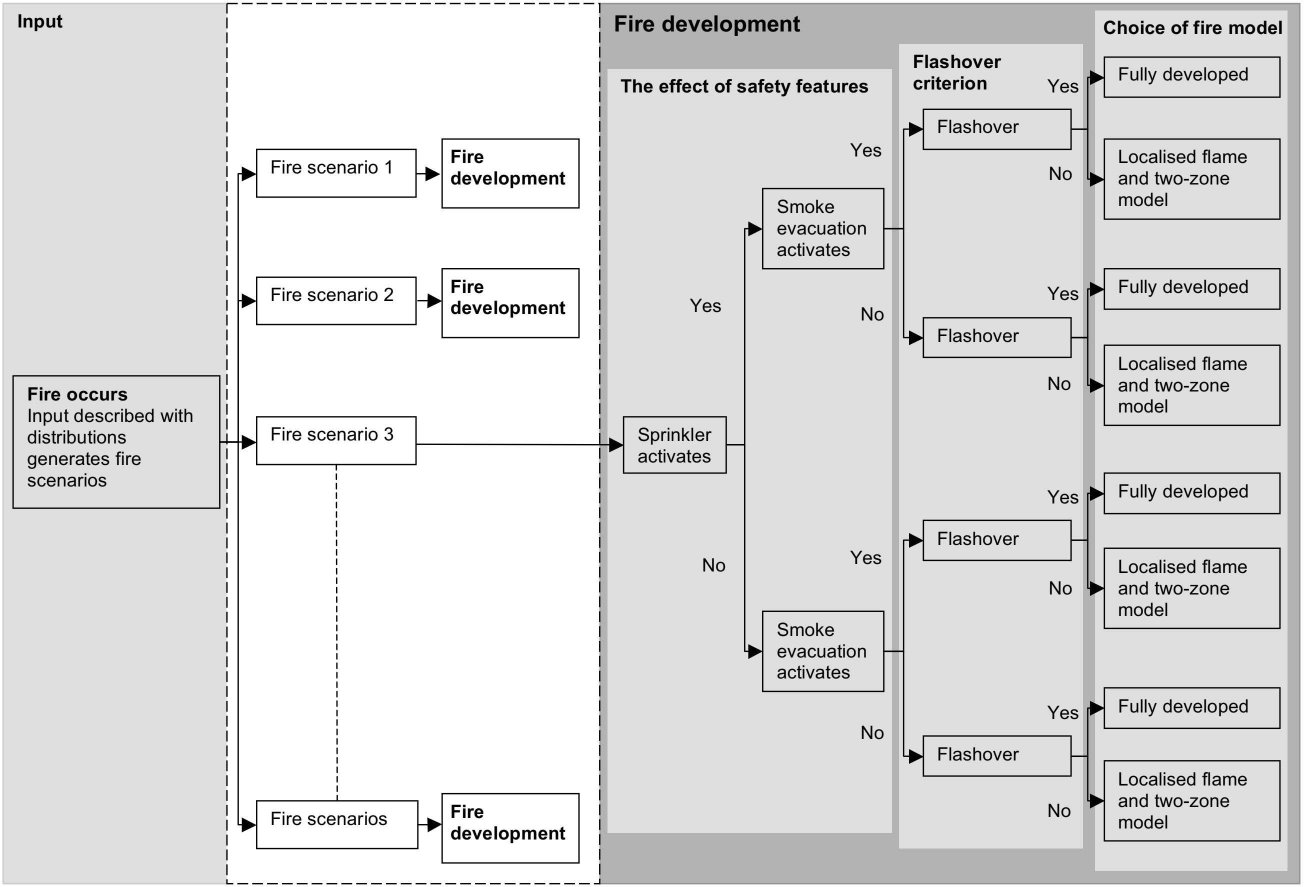
Choice of fire model and generation of fire scenarios

The method for designing fire resistance of structural members with risk analysis requires that a great number of fire scenarios are analysed. Hence it is an advantage if the fire models, used in the analysis, are not too demanding in terms of computational power. In order to achieve this, the fire scenarios can be divided into two subcategories, a fire that reaches flashover and becomes fully developed and a fire that does not reach flashover. For every fire scenario that is evaluated it has to be analysed whether flashover occurs or not. Many variables influence the fire development in an enclosure and it is important to analyse the effects of building characteristics and various safety features, such as sprinklers and smoke evacuation, including their failure function. When generating the fire scenarios the flow chart on the next page can be used. The flow chart is divided into four steps which altogether characterize the fire development in the building.

The first step in the flow chart includes information about the building and the potential fire scenarios. Every uncertain input has to be described with distributions in order to generate a series of possible fire scenarios. The fire does not become affected by these variables but the variables are postulations of the fire itself. The variables depend on each other and vary with time.

The next step describes the effect of various safety features; in the flow chart sprinkler and smoke evacuation have been included. The failure rates of the safety features have to be included, as well as how the systems influence the fire development in the enclosure.

Once the effects of fire safety systems have been included, all parameters that influence the fire development are known and with a flashover criterion it can be analysed whether flashover occurs or not. This is done with a criterion according to the MQH-method (Karlsson and Quintiere, 2001). A zonal model or a CFD model can be used if a temperature that causes flashover can be determined. Then a suitable fire model has to be chosen for the specific fire scenario. The fire model has to be able to generate time-temperature curves, e.g. parametric temperature time curves and localised fire according to Eurocode 1 (2002) can be used. The localised fire should be combined with a zonal model such as the MQH-method (Walton and Thomas, 1995) or CFAST (Jones, Peacock, Forney and Reneke, 2006).


Input
Fire occurs
Input described with distributions generates fire scenarios
Fire scenario 1
Fire scenario 2
Fire scenario 3
Fire scenarios
Fire development
Fire development
Fire development
Fire development
The effect of safety features
Sprinkler activates
Yes
No
Smoke evacuation activates
Smoke evacuation activates
Yes
No
Yes
No
Flashover criterion
Flashover
Flashover
Flashover
Flashover
Yes
No
Yes
No
Yes
No
Yes
No
Choice of fire model
Fully developed
Localised flame and two-zone model
Fully developed
Localised flame and two-zone model
Fully developed
Localised flame and two-zone model
Fully developed
Localised flame and two-zone model

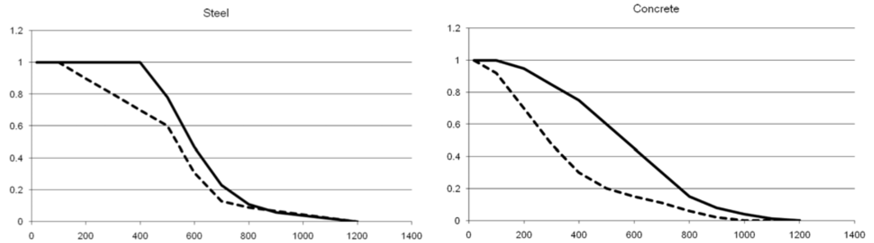
Structural analysis and evaluation of safety function
Inputs for the structural analysis consist of two parts, the structural design and fire severity. Both parts have been described in the steps in previous sections and the list below gives a summary.

- Constitutive properties (structural materials including thermal and mechanical properties)
- Relative load bearing capacity
- Geometry of structural members and their position within the enclosure
- Temperature time curves for the gas surrounding the structural members in different positions for each fire scenario

The time-temperature curve for a fire scenario varies within the fire enclosure in the case when flashover does not occur. Therefore it is necessary to describe the position of critical structural members and a temperature time curve for each of them.

The temperature distribution in the structural members can for instance be calculated using the finite element method where the time-gas temperature time curve is an input defining the heat transfer.

The next step is to evaluate the safety function, which has to be made for every structural member in every fire scenario. If the temperature domain has been chosen, critical temperatures for each structural member must be determined. The critical temperature is then compared with the temperature in the structural members reached in the fire scenario. The evaluation is made in the same way for the other domains according to table 1. Examples of mechanical properties for evaluation of the safety function, temperature-dependent strength and elastic modulus for different materials, are given in the figures below.



Mechanical properties of different materials, from Eurocode (1995 and 2004) and Anderberg (2000).

Consequence description
On analysis level 1, the only consequence analysed is if collapse occurs or not. It is not taken into consideration how extensive the collapse is.

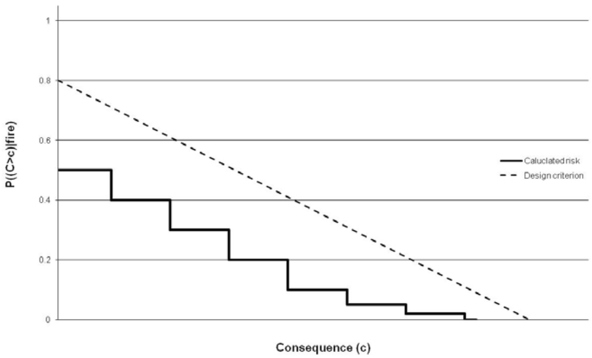
On analysis level 2 it must be determined how extensive the failure is for every included fire scenario. In order to be able to quantify the extent of the collapse, the interactivity between the structural members has to be analysed. To do this the strength domain can be preferable since it has a larger potential to study the interactivity. If statically independence between different parts of the structural system can be determined a rough approximation of the extent of the collapse can be made by assuming that once one structural member within the statically independent part collapses that whole part collapses and it does not affect the rest of the building. Another simplified assumption that sometimes can be made is that the extent of the collapse could follow the temperature distribution within or along the structure. This could be one way to handle the problem if the structure can be treated as 1- or 2-dimensional, such as a tunnel (Jeansson, 2002).

Probability of consequences and evaluation of design criterion
In level 1 analysis only one consequence is studied, collapse of any of the structural members in the building. Hence the probability of consequences on analysis level one is delimited to determine the quota between fire scenarios causing collapse and the total number of fire scenarios studied, this is made by using equation 1.

It then has to be evaluated whether the probability satisfy the design criterion or not. The design criterion is decided in the second step of the method and for analysis on level 1 it can be expressed according to equation 4.

$$p_{acceptable} \geq P(\min(R_i - S_i) < 0 \mid fire), \quad i = 1, 2, 3, ...(n-1), n \qquad (4)$$

On analysis level 2 the consequence has been studied in greater detail and hence the design criterion somehow has to pay regard to this. On this level there is a balance between the probability for collapse and the extent of the collapse. That small parts of the building collapse will be accepted more frequently than collapse of great extent. The design criterion can be expressed as a probability-consequence graph as shown in the figure below.



Uncertainties and sensitivity analysis

In the method there are different types of uncertainties, according to Hofer (1996) the uncertainties can be divided into two different types, stochastic and epistemic. Epistemic uncertainties are uncertainties that have their origin in the lack of knowledge. The stochastic uncertainties vary in the sense that the fall-out is always uncertain while the epistemic uncertainties can be reduced by gathering better information.

Within the method it is possible to use whatever model that is appropriate for the specific case. Uncertainties within the chosen model can be characterized as an epistemic uncertainty. The model uncertainties are often hard to quantify but one possible way to do this is to verify the chosen model with other models. If all models generate about the same results it is more probable that the chosen model describes the reality.

It is also important to do a sensitivity analysis to determine what variables the models are most sensitive to by using for instance a regression analysis. Furthermore, it is then important to minimize the uncertainties in the variables that the models are most sensitive to.

The method becomes fairly complex and hence it can be hard to analyze how the uncertainties propagate through the analysis. Especially if complex models to simulate the fire scenarios and structural analysis are used the quantification of uncertainties becomes hard to do. However the sensitivity for collapse is highly dependent on the temperature within the fire enclosure. Since the input data, that are uncertain, mainly affects the fire development, one way to handle the uncertainties is to determine what variables that have the greatest impact on the temperature within the fire enclosure.

Stochastic uncertainties and epistemic uncertainties sometimes treat the same variables. Fire load density is one variable that would be possible to determine almost exactly for an office where the variation of combustible material is small. The knowledge about the fire load density can in this case be almost perfect. If the analysis on the other hand is made for a storage, where there is a large variation over time for the fire load density, it is fairly uncertain what the fire load density will be when fire occurs. Nevertheless the knowledge about the variation in fire load density in the storage can be almost perfect but there is still the uncertainty what the fire load density is when fire actually does occur. These kind of stochastic uncertainties are treated by describing the variables with distributions.

The method is based on an event tree when generating the scenarios and uncertain variables are distributed. This way of performing an analysis is a way of managing the uncertainties and that the result is a probability implicates that the uncertainty is quantified (Morgan and Henrion, 1990).

DISCUSSION AND CONCLUSIONS

The primary advantage with the method is that the risk is quantified explicitly and hence the result can be used to see the effects of various, for the fire safety, risk reducing actions. Further it is also possible to use the method to determine if it is cost-efficient to introduce fire safety systems or to reduce the fire safety systems in the studied building. The method can also be used to see what type of risk reducing action that generates the largest effect on the risk level. E.g. it may be better to introduce a sprinkler system than to protect the structural members with insulation.

It is also possible to add the probability of fire to the method and hence it can be evaluated in what extent fire protection is needed depending on how often fire occurs in the specific building. This also makes it possible to account for management system that handles the fire safety within the building.

Since the method uses an approach that starts with the characteristics of the building, the fire protection for the building can be made more flexible and suited to the building in order to obtain an optimal level for the fire safety in the building.

The method itself is not limited to analyse load bearing structures. If a safety function can be formulated for another purpose, the risk that the safety function is not fulfilled can be evaluated. One such example would be for separating structures.

The method treats uncertainties in some extent since uncertain inputs are described with distributions. Further failure rates for fire safety systems are included and a large number of possible fires are studied. If the distributions well describe the uncertain parameters and the number of studied fire scenarios is large the result will reflect a large range of possible fires in the building. On the other hand it is hard to see how assumptions and approximations propagate through the analysis since the method has to be automated with separate models for describing the fire development and performing the structural analysis. Sometimes the models are quite complex and it is even hard to quantify the uncertainties with a specific model itself.

One disadvantage with the method is that a lot of calculations have to be carried out and hence the current practical use of the method may be limited to use of models that do not demand a lot computer capacity. The use of a simple model leads to that approximations have to be made in a large extent and that accuracy may be lost.

There is a need for development regarding guidelines on acceptable risk considering collapse. It is not accurate to set specific criteria for different type of buildings since the acceptable risk has to vary with a lot of different variables such as geographical location, use of the building and so on. Therefore guidelines would be better a better way to help decision makers to evaluate the results from an analysis with the method.

Finally it can be concluded that the method is far from fully developed and should be seen as a starting point for further development in this area. The method has a large potential of determine and accounting for effects of various fire safety systems introduced in a building and making cost effective designs.

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