An Approach towards a Simple Risk Based Design Method

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ABSTRACT

The paper presents an approach for deriving design values for fire safety engineering design which are based on a numerical value of acceptable risk. The method used is based on the First Order Second Moment (FOSM) reliability index β. The paper gives an overview of the results which have been obtained and discusses the advantages and weakness problems associated with the method. Clearly factors like model uncertainty, occupant load and occupant response time are very important for a successful result. Therefore, efforts must be made to find good scientific data on uncertainty of these variables.

Keywords: First Order Second Moment method, FOSM, reliability index β, fire, risk, uncertainty analysis.

INTRODUCTION

The current procedure in the fire safety design of a building depends to a high degree on the competence of the fire protection engineer. This is especially true when so-called engineering design methods are used. The fire protection engineer must specify input parameters, decide which scenarios are the most appropriate and decide whether the proposed measures are adequate or not. This puts pressure on the fire protection engineer to define a solution, which is acceptable to both to the building owner and the authorities. If prescriptive solutions are chosen, the result will be more strictly according to traditionally accepted solutions and rather easy to verify. The engineering solution is more difficult to verify according to acceptable risk levels, but gives more flexibility. The two methods or design strategies are denoted

- the prescriptive or standard method and
- the engineering method.

The first relies on historically accepted solutions and will, in some cases, result in a design that is not very efficient in terms of costs involved and safety. The engineering method costs more during the design stage, but will hopefully result in a more long-term cost-effective solution. However, the task depends on the integrity of the architect to provide an acceptable solution. The problem is that there are neither generally accepted engineering methods available in fire safety engineering nor are any tolerable risk levels available.

In other engineering fields, such as in structural engineering, so-called design values have been derived which can be used together with accepted calculation methods. This results in an accepted engineering solution to the problem. The design values in, for example, structural engineering lead to a predefined safety level as they are derived from a specified target risk.

This risk is usually described as the target reliability index β which can be translated into a probability of failure for the system.

There are procedures which can be used in fire safety design but design values based on risk measures have not been developed (ISO/CD 13387, 1997; NKB, 1997; BSI, 1997 and Fire Engineering Guidelines, 1996). The procedures rely heavily on the use of expert teams, credible worst case scenarios and sensitivity studies.

This should not be considered irrational, but there is a need for an engineering method which is based on the use of predefined design values derived from an accepted risk level. The engineering procedures in the above mentioned references can be used for the more complex buildings where it is impossible to derive design values due to the small number of buildings of that type.

THEORY OF THE METHOD

The method by which the design values are derived is based on the FOSM analytical reliability index β_{HL} method (Hasofer & Lind, 1974). This index can be used to estimate the probability that the system will fail, in this case equivalent to the situation where at least one person is unable to escape safely.

The method has been used in the area of structural engineering to derive design values and partial coefficients (Thoft-Christensen & Baker, 1982 and Sørensen et al., 1994). The principle has been demonstrated for fire safety in assembly rooms where both the design values and partial coefficients were derived (Frantzich et al., 1997, Magnusson et al., 1997 and Frantzich, 1998). The general procedure for deriving design values as outlined by Thoft-Christensen et al. (1982):

- set limits on the range of scenarios or sub-scenarios for which the deterministic equation shall be valid
- identify the main uncertainty contributors
- select the desired safety format, i.e. the number of partial coefficients and their position in the design equation
- select the appropriate characteristic values to be used as fixed deterministic quantiles
- determine the partial coefficients, to be used together with the corresponding characteristic values, or design values to achieve the required reliability or level of safety.

The last of these points will be analysed using an optimisation procedure.

THE DESIGN PROBLEM

The design problem can be formulated in terms of a limit state function

$$t_{critical} - t_{evacuation} = 0$$

The objective is to find a solution that satisfies the condition

$$P(G < 0) < p_{target}$$

The procedure is to specify the target reliability index β_{HL} and the variables, both random and constants, and to vary the design parameter until the target reliability index β_{HL} is obtained. The design parameter may, for example, be the escape door width, which is the parameter the designer wants as the result using the deterministic design equation. A design guide must be valid for a class of buildings with, for example, the same occupancy type, using the same safety concept. The safety concept may be defined in terms of the same type of installations, for example, sprinklers and escape alarm systems.

The solution to the problem is to derive the design point vector, using an optimisation procedure that fulfils two conditions, namely keeping the average safety level constant for the class of buildings and minimising the difference in the required and obtained safety level, taken over all individual buildings within the class.

In order to use this method, two criteria must be met. First, it must be possible to define the limit state function $G(X)$ and second, statistical information on the variables X_i must exist. These two criteria are rather obvious. The limit state function can be defined as expressing the number of people not able to escape within the available time.

EXAMPLE OF APPLICATION

To illustrate the procedure of deriving the design values and the corresponding partial coefficients, one example of application is being provided (Frantzich et al., 1997, Frantzich, 1998, Olsson & Frantzich, 1999). The example derives a design equation for the required escape door width, *W* in large assembly buildings. A number of scenarios are defined which represents the presence of different fire protection installation e.g. fire alarm and various kinds of evacuation alarms. In order to achieve design equations that are valid for a whole building class, for every scenario, sets of calculation must be established. These sets are the different combinations of ceiling height and floor area that represent the building class. The limit state function is solved for each set of calculation by using response surfaces for fire development, detection- and evacuation times.

The following scenarios are included in the study:

Scenario	Escape alarm	Smoke detectors	Sprinkler system
1	Voice	Yes	Yes
2	Voice	Yes	No
3	Voice	No	Yes
4	Voice	No	No
5	Bell	Yes	Yes
6	Bell	Yes	No
7	Bell	No	Yes
8	Bell	No	No

For each of the scenarios a design equation will be presented which has been derived on the bases of the calculated risk. By using the design equation, the engineer will get the building's required escape door width. The large assembly building is represented by a shopping mall with principle design illustrated in Figure 1 below.

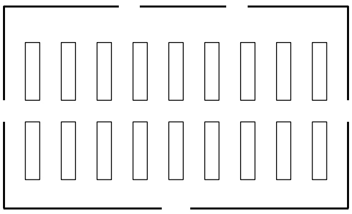

Figure 1 *Schematic drawing of the shopping mall representing the assembly building.*

A ceiling height of 4-6 m and a floor area of 600-1500 m^2 characterise the building type.

The limit state function

The limit state function consists of the time to reach critical i.e. untenable conditions and the time to evacuate the building. The function could be described as below when the evacuation time has been divided into its main components.

$$t_{critical} - t_{detection} - t_{reaction} - t_{movement} = 0$$

The response surface for $t_{critical}$ is derived using data from CFAST (Peacock et al, 1994). In order to derive the response surface, using regression analysis, the critical conditions for evacuation must be established. One definition of these conditions is found in the Swedish building regulations (Boverket, 1998). This definition contains the following criteria.

- Visibility: level of fire gases not lower than 1.6+(0.1xH) m, where H is the height of the room.
- Thermal: a short-term radiation intensity of maximum 10 kW/m^2, radiation: a maximum radiant energy of 60 kJ/m^2 in addition to the energy from a radiation of 1 kW/m^2.
- Temperature: air temperature not higher than 80°C.

Time to critical conditions is expressed by:

$$t_{critical} = 3.07\alpha^{-0.29}H^{0.27}A^{0.48}$$

where α is the fire growth rate, kW/s^2
H is the ceiling height, m
A is floor area, m^2

The response surface is valid for a fire growth rate of 0.01-0.07 kW/s^2. As there are large difficulties in assessing time to critical conditions for a sprinkled fire, the equation is only valid for the non-sprinkled case, i.e. scenario 2, 4, 6 and 8.

The detection time depends on the presence of smoke detectors. If smoke detectors are present, the detection time could be calculated with the software DETACT-T2 (Evans et al, 1985). The detection time is expressed by:

$$t_{detection} = 21.8\alpha^{-0.31}H^{0.34}$$

The response surface is valid for the same fire growth rate as above. If no smoke detectors are available the detection time is expressed as a function of the number of people present and expressed by:

$$\overline{t_{detection}} = 250 - 200N$$

where N is the density of people, persons/m^2. Default value for N is 0.5

After the people have detected the fire there is a delay time until they start to move out of the building. This time is called reaction time. The reaction time is assumed to depend on the size of the building and is expressed as follows:

$$t_{reaction} = R_0 + \delta \cdot A$$

where R_0 is the minimum reaction time, s
δ is a constant of linear displacement

R_0 is one of the stochastic variables in the study. The constant δ is 0.025 for the voice alarm and 0.05 for the alarm bell.

The final component in the evacuation process is the movement to safety. The travel time largely depends on the available escape width. Since queuing is assumed to start almost immediately after the travel has begun the movement time could be expressed by:

$$t_{movement} = \frac{N \cdot A}{f \cdot W}$$

where f is the specific flow through the door, persons/(s m). Default value is 1.3
W is the available escape door width, m

Stochastic variables

The method has been developed to handle two stochastic variables. These are:

- The fire growth rate, α, kW/s^2
- The minimum reaction time, R_0, s

Assigned values are illustrated in the table below.

Variable	Mean value	Standard deviation	Unit
α	0.04	0.01	kW/s^2
$R_{0,voice}$	60	20	s
$R_{0,bell}$	70	30	s

Deriving design equations

The optimisation to derive design values is carried out in MATLAB. The calculations are initially performed under the following prerequisites:

- Critical conditions as they are defined by the regulations.
- A target safety index of 1.04 (corresponds to a statistical derived probability of failure of 15% on condition that a fire has started).
- Manual detection time is assumed to be 150 s.
- The density of people is 0.5 persons/m^2.

By solving the limit state function for the escape door width, *W*, the design equation for scenario 2 looks as follows:

$$W = \left(\frac{N \cdot A}{f}\right) \cdot \left(\frac{1}{3.07 \cdot \alpha^{-0.29} \cdot H^{0.27} A^{0.48} - 21.8 \cdot \alpha^{-0.31} \cdot H^{0.34} - \left(R_{0,voice} + 0.025 \cdot A\right)}\right)$$

The design equations for scenario 4, 6 and 8 will have similar appearance. Output from the MATLAB routines will look as illustrated in Figure 2 below.

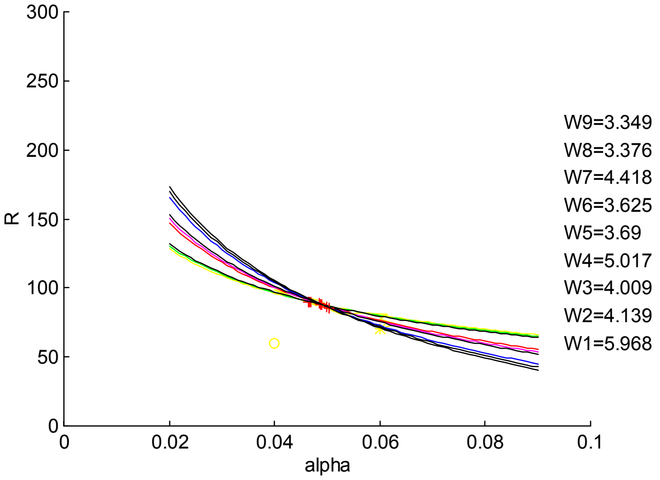

Figure 2 *Output from the MATLAB optimisation. The variables W1-W9 represents the required escape door width for the different sets of calculation, where W1 is H = 4 m, A = 600 m^2, W2 is H = 5 m and A = 600 m^2 and so on until W9 is H = 6 m and A = 1500 m^2.*

The design values for scenario 2 is a fire growth rate of 0.0457 kW/s^2 and a minimum reaction time of 77.53 s. The complete design equation, ready to be used by the engineer has the following expression:

$$W = 0.385 \cdot A \cdot \left(\frac{1}{7.51 \cdot H^{0.27} \cdot A^{0.48} - 56.74 \cdot H^{0.34} - 77.53 - 0.025 \cdot A}\right)$$

The required escape door width varies from 4.4 m to 3.0 m pending on the ceiling height and the floor area. The optimisation process is later carried out for all scenarios. The results are not shown in this paper.

Sensitivity analysis

Unfortunately the routines do not deliver reliable results for the scenarios with less fire safety equipment, e.g. scenario 6 and 8. This is especially true for combinations of low ceiling height and floor area. In order to investigate the model strengths and weaknesses a sensitivity analysis is carried out. The sensitivity analyses is conducted for the following variables:

- The definition of critical conditions
- The fire growth rate
- The probability of failure
- Occupant density
- Model uncertainty

Another set of critical conditions stating that the smoke layer should not be closer than 1.5 m from the floor if the temperature is above 100 °C, otherwise a maximum temperature of 100 °C in the room is analysed. The difference between the default definition and the new one is rather large, especially in buildings with small floor area and low ceiling height. The primarily reason for this difference is that $t_{critical}$ increases with the change of critical conditions. The time to critical conditions increases with 35 s in a building with a ceiling height of 4 m and 600 m^2 floor area. This time difference let another 110 people exit the building.

A Swedish investigation (Angerd, 1999) of fire growth rates in stores shows that the growth rate could be expressed in terms of a normal distribution with a mean value of 0.02 kW/s^2 and a standard deviation of 0.005. Using this alternative fire growth rate changes the results remarkably. The door width varies between 2.2-2.8 m instead of 3.0-4.4 m. The selection of fire growth rate is therefore of great importance to the required escape door width. A mentioned before the optimisation routines fails to deliver reliable results for scenario 6 and 8. When the fire growth rate is changed, this is no longer the case.

The required door width corresponds to a pre-defined acceptable risk, expressed as the probability of failure. The default value of 15 % is changed to 10, 5 and 2.5 % respectively. The model shows great sensitivity to the choice of acceptable risk. In some cases three additional exits are required. The definition of acceptable risk is however an issue for the authorities and is not discussed any further in this paper.

The occupant density has great influence to the required door width. According to the Swedish building regulations a default value of 0.5 persons/m^2 should be used for assembly halls. This value is however quite conservative. Johansson (1999) shows that the occupant density could be expressed as a lognormal distribution with a mean value of 0.08 persons/m^2 and a standard deviation of 0.06. The probability of that the occupant density will be equal or greater that the default value is only 0.001, when using this distribution. The model sensitivity was investigated by the use of the distribution's 95th percentile value, i.e. 0.2 persons/m^2. The result shows that it is possible to decrease the number of exits required for escape. Approximately two exits could be removed. One remarkable conclusion is that the building with a ceiling height of 6 m and 1500 m^2 floor area requires only one exit of 1.2 m to handle safety escape. This is, of course, not allowed according to the regulations, which states a minimum of two mutually independent escape routes from each building.

The last parameter that was investigated in the sensitivity analysis was the model uncertainty. The fire growth and smoke transport model (CFAST) is associated with a number of uncertainties. According to Lundin (1999) it is common that the model overestimates both the temperature and the smoke filling time. Magnusson et al (1997) assesses that the time to reach critical conditions should be increased with 35 % in order to cope with the model uncertainty. This increase leads to reduced requirement on escape door with by 2-3 times. The routines will provide reliable solutions for all scenarios when the model uncertainty is taken into account.

Conclusions from the sensitive analyses states that the model is very sensitive to changes in most of its vital components. The change is most observable when both the ceiling height and the floor area are assigned to the lower values.

DISCUSSION

A number of limitations must be assigned to the method due to its sensitiveness to the input. The marginal of safety is sometimes to small and door widths of 40-60 m are required. Another difficulty is the uncertainty of the sub models involved. This discussion is aimed at finding out why the model behaves the way it does and give suggestions on future research.

Margin of safety

In trying to answer why the model does not deliver reliable result the margin of safety is investigated. The margin of safety is very similar to the limit state function and is expressed as:

$M(t) = t_{critical} - t_{detection} - t_{reaction} - t_{movement}$

As stochastic variables are involved in the margin of safety it is possible to analyse the margin expressed as statistical distributions. The characteristic appearance of the margin of safety with default values of scenario 2 is shown in Figure 3 below.

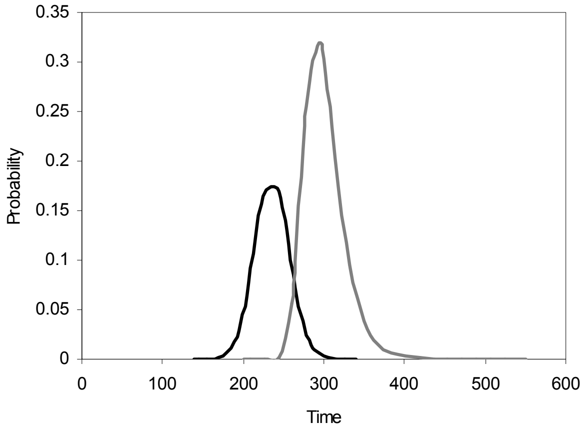

Figure 3 *Graphical illustration of available safe egress time (grey line) and the actual evacuation time (black line) for scenario 2 when using default input values.*

The probability that the safety margin will be equal or less than zero is 0.003. It is therefor no problem to find solutions for the sets of calculations representing scenario 2. For scenario 8 this is not the case. Figure 4 shows a graphical illustration of the safety margin.

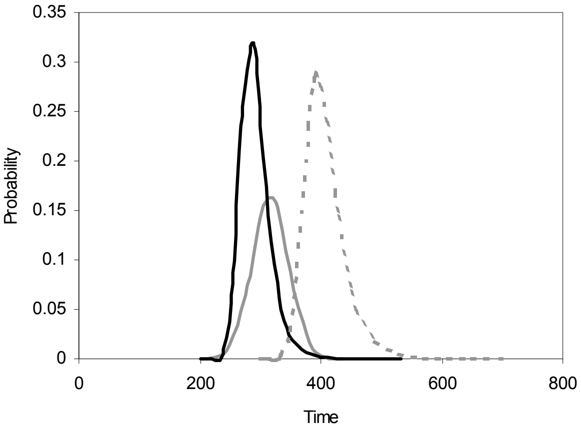

Figure 4 *Graphical illustration of available safe egress time (grey line) and the actual evacuation time (black line) for scenario 8 when using default input values.*

For scenario 8 the probability of a safety margin equal or less than zero is as high as 0.72. The optimisation routines therefore have an impossible task trying to find a door width that leads to a probability of failure of 15%. This is the explanation why the method delivers unreliable results for some scenarios.

The available safe egress time is based on the time it takes for the fire to develop critical conditions in the building. The main parameter is the fire growth rate, which is assessed to be a normal distribution (0.04,0.01) kW/s^2. A fire growth rate of 0.04 kW/s^2 could be translated to a rather fast developing fire. This distribution only encounters fires that lead to critical conditions. All fires do not follow this development and the non-dangerous fires are therefore not taken into account. If it would be possible to define a distribution that covers all possible fires, the distance between available safety egress time and actual evacuation time would increase. Finding a solution to the problem in this way is similar to how the methods were used in structural reliability engineering, where the load effect consist of a number of different loads as the permanent, variable and accidental load.

Uncertainties

The uncertainties within the optimisation routines are quite small and the response surfaces correlates well with the input data. As stated before, the model for fire growth and smoke transport is associated with quite a few uncertainties. The sensitivity analysis clearly shows that the model uncertainty is very important for the required escape door width. The dotted line in Figure 4 illustrated the available safe egress time for scenario 8 after a model uncertainty of 35 % has been taken into account. The probability that the safety margin is equal or less than zero has decreased from 0.72 to 0.012. This mainly depends on the fact that the mean value of the safety margin has increased from –25 s to 78 s. As the model uncertainty plays such an important role, there is a need for in-deep verification of the calculation tools used in fire safety engineering.

Model weaknesses

It is evident that there are some problems associated with this method in addition to the general limitations explained in the beginning of this chapter. The numerical solutions may encounter convergence problems if too broad building classes are chosen. The class should incorporate similar building types and occupancies and the class bounds must be evaluated and examined more than once to find an optimum interval. In order to ensure reasonably large classes, the variable uncertainty must be low and the scenario must be described as accurately as possible.

This can, for example, be achieved by considering the correlation between variables defining the representative buildings in the class during the evaluation. In the example in this chapter, a correlation between the occupant response time and the room area should perhaps have been included in order to give a better description of the limit state. If this correlation had been included in the limit state function, the building type class could have been larger.

Another problem is encountered in cases where more than two variables are subject to uncertainty. It may be difficult to find one well-defined design point as the elementary problem in R^3 results in a line of design points as the limit state functions are defined as planes in the space. The solution may be to force the common design point towards the design points of the individual limit state functions. The choice of object function is then very important.

Suggestions on future research

The purpose of using simple risk-based design equations in fire safety engineering is too pleasant to be rejected due to the reliability problems of the method. This study has clearly identified the reason why the model is unreliable and following proposals on future research in the field hopefully leads to a more stable model in the future.

- Investigate the possibility how to take fire frequency into account. There is a strong need for taking the actual number of fires into consideration.
- A more careful investigation of the values and distributions that are assigned to the input variables. The mean values and the standard deviations of the stochastic variables should be representative to real world situations.
- The model that describes the margin of safety ($M(t) = t_{critical} - t_{detection} - t_{reaction} - t_{movement}$) could be to simplified and there is need to create more appropriate model on human behaviour.
- Study what fire safety applications are suitable for deriving design equations. Such applications could be the design of smoke vents and separation distance between buildings in order to limit flame spread.

It is of great importance to find applications and solutions where this method could be used. By reducing the general recommendations in the building regulations to a minimum and replacing the with design equations based on risk, there would be an improvement in building fire safety.

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