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Quantifying life safety
Part I: Scenario-based quantification

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ABSTRACT

With increasingly complex architecture, new building technologies, etc., compliance with prescriptive code requirements for life safety is often times a sub-optimal solution, overly expensive, and sometimes simply impossible. This leads to the more and more frequent use of performance-based numerical tools in fire protection engineering, especially for the life safety design. Yet the level of safety achieved using those tools remains unknown due to uncertain deterministic input parameters and more or less arbitrarily chosen safety factors. In this paper, an approach is shown to quantify the level of safety for a life safety design using probabilistic risk analysis. The resulting failure probability $p_{f,i}$ of a life safety design given a specific scenario i yields a metric for the safety level and allows for the objective comparison with other design approaches. Additionally, the approach considers the uncertainty of the input parameters and yields information about the sensitivity of the design to the various input parameters chosen. The methodology will be demonstrated for a multi-purpose community assembly building and the levels of safety are derived based on various scenarios and for different tenability criteria.

1. Introduction

In fire protection engineering, one of the main objectives is the protection of the life and safety of building occupants during a hostile fire. In order to achieve this objective, various approaches exist, ranging from the compliance with the requirements manifested in the various so-called "deemed-to-satisfy" prescriptive codes to advanced and performance-based numerical methods. The latter can account for specific occurrences within the fire development and the egress process and are usually used in more complex modern buildings, where prescriptive requirements are limited in their applicability or simply do not exist.

In this case, the available safe egress time (ASET) is derived from a fire simulation and compared to the outcome of an egress simulation in order to determine the required safe egress time (RSET). For a safe design, ASET must be greater than RSET. The simulation models can be varying complexity but the most commonly used, state-of-the-art models are computational fluid dynamics (CFD) models for the fire simulation and so-called individual models for the evacuation simulation.

In order to utilize these tools, the fire protection designer choses representative fire scenarios and design fires which are derived from values for fire loads, fire spread velocity, heat release rate, etc. These values are usually assumed as deterministic, even though they are subjected to major uncertainties. In order to account for the uncertainties, usually an arbitrary safety factor κ for RSET is chosen, so that ASET $> \kappa \cdot$ RSET. κ is usually chosen between 2.0 (e.g. [1,2]) and 3.0 for specific occupancies (e.g. shopping center, [3]). Despite these rather large safety factors, they remain uncalibrated and thus it remains unclear whether the solution found is optimal, overly safe, or too conservative.

In the following, this problem is tackled by performing probabilistic analyses in order to quantify the probability of failure p_f of a life safety design using state-of-the-art performance-based numerical simulation tools.

The main challenge in order to utilize highly complex numerical tools with run-times in the magnitude of several hours is to reduce the number of required evaluations to a minimum while keeping the results as accurate as possible. For obvious reasons, a plain Monte Carlo analysis is not feasible in this case. Hence, a newly developed response surface method was employed. The methodology is outlined in greater detail in [4,5] and thus will only briefly described in the next section.

2. Probabilistic response surface method

In order to reduce the high number of required evaluation of the needed simulation cases, various methodologies were applied to significantly reduce the number and thus the overall numerical costs. The methodology starts with a preliminary scan of the

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random hyperspace using the so-called design of experiments (DoE) schemes as described by Mason [6]. The results of the calculated points are then analyzed for the sensitivity of the input parameters given in Section 3.3 by using simple methods like linear and rank, or stepwise regression [7]. Non-significant parameters can be subsequently omitted for the further steps. This reduces the problem dimensionality and thus the computational effort.

The next step is the construction of a surrogate model, the so-called response surface. Hereby, a mathematical model is fitted to the calculated results (support points), enabling a prediction of simulation results in between those supports. Common approaches are linear or quadratic regression models [8]. Herein, an interpolative approach based on moving least squares [9] was used for greater accuracy. The reason for the response surface is simply that the mathematical model found can be exploited faster than the underlying numerical CFD-based fire simulation model. The exploitation of the response surface was then conducted with a variance-reducing Monte Carlo approach, the so-called adaptive importance sampling (AIS) [10]. In order to account for the goodness of fit of the surrogate, an iterative approach was chosen in which new support points were created around the design point (ASET=RSET) of the previous iteration until a convergence criterion was met.

This methodology allows for a very fast and accurate calculation of failure probabilities using state-of-the-art numerical simulation tools. It also yields the most sensitive input parameters which provides a good basis for efficient improvements in the design.

3. Considerations and input data

The quantification of the safety levels of performance-based life safety analyses is demonstrated herein for a medium-sized multipurpose community assembly building as depicted in Fig. 1. This rather small building was chosen instead of larger or atrium type buildings for various reasons: firstly, many of the most severe fires with high numbers of casualties during the last decade have happened in buildings of this size and occupancy, such as The Station Fire [11], the Gothenburg Disco Fire [12] or the Lame Horse Fire [13]. This type of building can be assumed as the most critical regarding occupant life safety, since the comparably low volume of this type of building due to, for example, rather low ceiling heights or small compartmentalization leads to higher concentrations of smoke faster than in large atria with high ceilings. Secondly, it was found that all the effects of the various scenarios, influence of fire

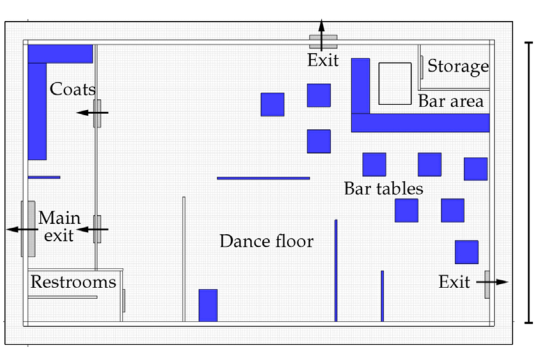

Fig. 1. Layout of the assembly building. The ceiling height is 4 m.

protection systems, etc. can be demonstrated in this exemplary application so that a larger sized example would not lead to significant additional information at exponentially higher numerical cost.

Additionally, fire codes usually require the escape routes to lead to a "place of relative safety" [14, p. 79], which can also be a place in an adjacent compartment which is separated by fire-rated doors and walls. Thus, the building herein could also be regarded as one (critical) fire compartment within a larger complex building such as a shopping mall, a hotel, etc.

3.1. Threshold models

In order to derive the ASET, performance or threshold criteria have to be assumed in order to set a tenability limit for the occupants. These can be based on various output parameters. Since this can significantly influence the results, two different criteria were regarded herein:

- The mean optical density is analyzed for the threshold of 0.15 m^{-1}, allowing for a visibility of approximately 10 m. This is based on the preliminary analyses [15] where it was found that the visibility thresholds are usually reached before any toxic criteria. The occupants need the visibility in order to locate the nearest available exit.
- The asphyxiant criteria become important during a later phase of the evacuation, when the occupants are usually already in the process of egress. ASET is set to be reached if maximum fractional effective dose (FED, [16]) is reached. This is assumed to be the ultimate threshold where people will be severely harmed by the fire.

The FED_{total} model used herein is an overall FED based on Speitel's model [17], including asphyxiant species as well as flux and temperature criteria. Safety factors within the FED (e.g. 0.3 in NFPA 101 [18]) were omitted. Hence, the complete incapacitation model used reads

$$FED_{total} = F_{I,asphyx.} + F_{I,heat} \overset{!}{\leq} 1.0, \tag{1}$$

where F_I represents a fraction of the time-integrated experienced dose compared to the incapacitation dose according to Purser's model.

3.2. Fire scenarios

To assess the current level of life safety within a standard assembly building, various scenarios have to be taken into account along with their corresponding probability of occurrence which can be derived from fire statistics. Herein, the scenarios were chosen loosely based on some of those required in the NFPA 101 [18]:

1. Standard design fire on the basis of NFPA Scenario 1 where a commonly used t-squared HRR(t) [19] is modified for life safety analysis [5, Section 4.4.] and applied. This scenario and the corresponding probabilities of failure of life safety will be regarded as a *baseline scenario*. The fire will be located in the bar due to the high fire initiation potential.
2. A hidden slowly developing (smoldering) fire is assumed to develop in the storage room. Instant fire and smoke spread occurs when the door is opened or fails (burn-through). In order to account for the incomplete combustion, the yields will be conservatively doubled according to Hull [20] and Forell [21].
3. Fire near the main entrance/exit blocking the primary means of egress and thus leaving the occupants to use only the emergency exits. This scenario is roughly in approximate accordance