ON THE USE OF FIRE BRIGADE STATISTICS FOR STRUCTURAL FIRE SAFTY ENGINEERING

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Abstract
In this paper the fire brigade intervention is considered for the assessment of structural fire safety through the concept of a maximal controllable fire area. Based on a literature survey probabilistic models are developed to consider the uncertainties associated with the fire development and the fire brigade intervention. A sensitivity analysis identifies the most important parameters and suggestions for future data collection are made to improve the probabilistic models.

Keywords: fire brigade intervention, statistical data, probabilistic models, sensitivity analysis

INTRODUCTION

The fire brigade intervention is an important fire safety measure and an integral part of the fire safety concept of a building. Therefore, it should be considered in structural fire safety design. This paper focuses on the probabilistic modelling of the fire brigade intervention including the discovery of the fire, the emergency call as well as the response and fire suppression by the fire brigade.
In this paper literature on fire brigade statistics is listed and used to develop probabilistic models. The listed literature provides a methodical basis for future statistical fire brigade surveys. Limitations and problems using the literature when developing the probabilistic models are discussed and methods to address these problems are presented.
Fire development has a mayor influence on structural safety. Therefore, the effect of the fire brigade on the development of natural fire conditions must be carefully modelled. Early detection by a smoke alarm system should also be considered. In a sensitivity study the most important parameters affecting the impact of a fire on a steel structure are analysed. Based on this sensitivity analysis, suggestions for further data collection and studies are made to improve the probabilistic models and consistently implement fire brigade intervention into fire safety design.

1 FIRE MODELING CONSIDERING THE FIRE BRIGADE INTERVENTION

This chapter emphasises on engineering models used to assess the thermal action on the structure taking into account the fire brigade intervention.

1.1 Compartment fire model

A fire can be characterized through three phases: the pre-flashover phase, the full engulfed fire (post-flashover) and the decay phase. According to Eurocode 1 (EN 1991-1-2:2002) the pre-flashover phase is modelled by a t-square approach characterizing the increase of the rate of heat release Q before the maximal rate of heat release per m^2 RHR_f is reached (see Fig. 1). The fire growth parameter t_α is the basic parameter in this model and is defined by the time needed for the fire to reach a rate of heat release of *1 MW*. The basis for this model is the assumption of a constant radial fire spread velocity in all directions. Given the maximum rate of heat release RHR_f (per m^2) the fire spread area A_F can be assessed through *Eq. (1)*.

$$A_F(t) = \begin{cases} 10^3 \left(\dfrac{t}{t_\alpha}\right)^2 \dfrac{1}{RHR_f} & \text{before flashover} \\ A_{Comp} & \text{after flashover} \end{cases} \qquad (1)$$

The full engulfed fire – when the fire engulfs the total compartment area A_{Comp} – is characterized through a constant rate of heat release depending on the fire regime, limited by the fuel or the oxygen. A fuel controlled fire reaches the maximal rate of heat release RHR_f per m^2 and depends on the surface and the material properties of the combustible material. For ventilation controlled fires the maximal rate of heat release is limited by the available oxygen. The fire load q determines the full engulfed fire. Eurocode 1 proposes the start of the linear decay phase after 70% of the fire load has been combusted.

1.2 Intervention of the fire brigade

The intervention of the fire brigade in the European standard Eurocode 1 is considered through a reduction of the design fire load. Thus, the decay phase of the fire will start earlier. This reduction of the fire load can barely be quantified through statistical data. Therefore, in this paper a model is presented that considers the fire brigade intervention based on measurable quantities.

The success of the fire brigade depends among other parameters (e.g. crew size, equipment etc.) on the intervention time T_I when the fire brigade starts with the fire suppression activities. This time T_I consist on several consecutive time intervals as illustrated in Fig. 2. The time when the extinguishment procedure starts is expressed through the sum of all these times:

$$T_I = T_{Detect} + T_{Call} + T_{Disp} + T_{Turnout} + T_{Travel} + T_{Setup} \qquad (2)$$

If the fire is grown too large, the suppression of the fire cannot be successful and a full burnout will occur. The fire brigade must then focus on preventing further fire spread. Hosser et al. (2008) proposed a model based on a maximal controllable fire size A_{Limit} used as an indicator for the fire suppression capability of the fire brigade. If the fire grows larger than this area $A_F(t) > A_{Limit}$ then a complete burnout must be accepted; otherwise the fire suppression action starts reducing the rate of heat release. Then, the decay phase occurs earlier compared to the complete burnout fire (Fig. 1). It is assumed that the decay phase starts at the intervention time T_I of the fire brigade. The relation $A_F(T_{IV}) > A_{Limit}$ determines the probability of failure for fire suppression by the fire brigade.

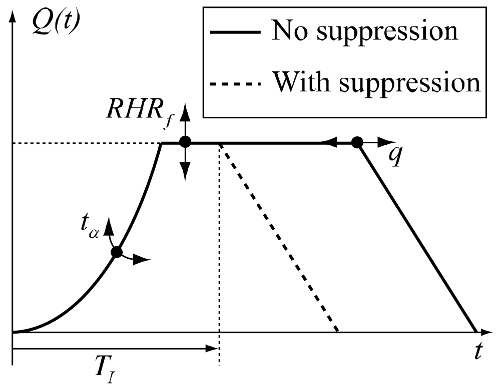

Fig. 1 Rate of heat release including the fire suppression

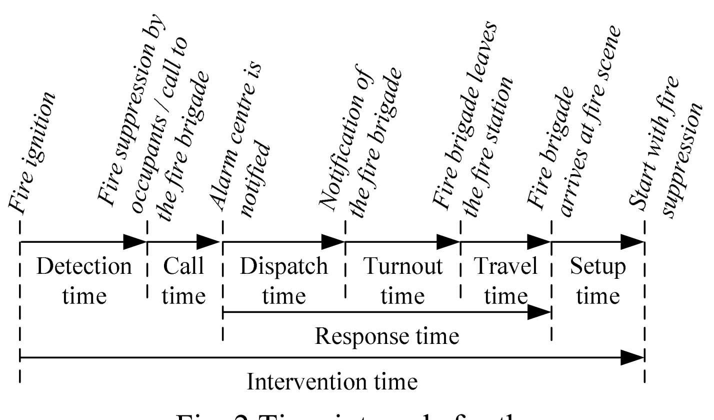

Fig. 2 Time intervals for the fire brigade intervention

2 DATA AND LITERATURE SURVEY

Statistical analyses of different authors are performed by different authors (see references) based on national or local fire brigade reports with the aim to quantify the parameters

introduced in Chapter 1. The literature contains summarized and structured information on fire brigade statistics.
The most difficult time interval to quantify is found to be the detection time. The difficulty is that the time of ignition is unknown. Thus, the time has to be estimated indirectly through some physical relationships. Holborn et al. (2004) estimated the detection time as well as the fire growth time based on *Eq. (1)* and providing some sample statistics. The data they used were collected by fire investigators interviewing persons who discovered the fire. It should be noted that not all of the fires merit such an investigation. Only fires which meet some criteria, i.e. fires where four or more fire engines are sent to the scene and fires where persons has to be rescued, have been reported (584 reported fires). Besides the detection time and the fire growth rate Holborn et al. provide sample statistics for the call time as well. The same database has been used by Särdqvist (2000) to analyse the correlation between the fire spread and the different time intervals of the fire intervention. Because of the small number of data, the results of this analysis should be treated carefully.
Lots of information on the response time of the fire brigade is given, e.g. Holborn (2004), London Fire Brigade (LFB 2011), Schwanitz (2009), Tómasson et al. (2008), Tillander (2004), etc. The reason is that the response time is easy to measure and is often used to check if the performance criteria of the alarm centres and the fire brigades are fulfilled. Some authors provide suggestions for probabilistic models, too (e.g. Schwanitz, Tillander, Tomasson et al.).

Limitations in the use of fire brigade statistics

Fire brigade statistics do not include fires where no fire brigade attention is needed, e.g. small fires which can be extinguished by occupants. This implies that the probability of a fire event is underestimated when fire brigade statistics are used to assess this probability. Moreover, the efficiency of detection systems and smoke alarm is underestimated, because the rate of small fires extinguished by the user increases. However, insurance data includes also small damages (see Fontana et al. 1999) and could be used – also in combination with fire brigade statistics – to assess the probability of a fire event as well as the efficiency of smoke alarms and detection systems. Further, fire brigade statistics are always related to the fire brigade performance level and local conditions e.g. target criteria for fire brigades (e.g. target response time). Therefore, it is difficult to compare the response times of different fire brigades. Fire brigade statistics should include the performance level of the fire brigade that reported the data as done by the London Fire Brigade (LFB 2011) and Schwanitz (2009).
Often, severe fire incidents merit a detailed investigation and additional valuable data are collected and reported. It is important to report the number of such detailed investigations related to all cases. Otherwise, the results of a statistical analysis might be biased.

3 PROBABILISTIC MODELS BASED ON FIRE BRIGADE REPORTS

Probabilistic models are developed to address the stochastic variation of the parameters defined in Chapter 1. These models are intended to be used for risk analysis or for code calibration. The probabilistic models are developed for Switzerland based on the literature (see Tab. 1).

3.1 Fire growth rate

The probabilistic model of the fire growth rate is chosen based on the analysis done by Holborn et al. (2004). Because they included also smouldering fires a large scatter of the fire growth time has been observed. As the impact of a smouldering fire is negligible for structural engineering, it is assumed that only fires with a fire growth rate t_α of less than 800sec might affect the structure considerable. Therefore, a Truncated Lognormal (TruncLN) distribution is used to model this parameter.

3.2 Detection time

Holborn et al. (2004) estimated the detection time based on reports of London's fire brigade and *Eq. (1)*. The data indicate a large scatter of the discovery time. A Gamma distribution is fitted to the 95% fractile (53 min) and the 51% fractile (5 min) of the data. The distribution of the detection time in Switzerland is assumed to be identical as in London. As the detection time for flaming fires (which affect the structure) is probably shorter as for smouldering fires, it is assumed that the detection of the fire occurs in less than 15 min. Therefore the Gamma distribution is truncated at 15 min. Holborn et al. supposed the existence of a dependency between fire growth rate and detection time. This is not considered in the present model.

Tab. 1 Probabilistic models (related to Swiss office buildings)

			Distr. X	Mean $E[X]$	Std. dev. $\sqrt{Var[X]}$	Reference
Fire	**Fire load** [MJ/m²]	q	Lognormal	420	126	Eurocode 1
Fire	**Heat release rate** [kW/m²]	RHR_f	Normal	250	50	Hosser et al. (2008) (est.)
Fire	**Fire growth parameter** [sec]	t_α	TruncLN	454	197	Holborn et al. (2004)
Fire brigade	**Max. controllable fire size** [m²]	A_{Limit}	Normal	200	30	Hosser et al. (2008) (est.)
Fire brigade	**Detection time** [min]	T_{Detect}				
	without fire alarm		TruncGam	3.67	4.09	Holborn et al. (2004)
	with fire alarm		TruncGam	2.74	3.77	Holborn et al. (2004)
	with detection system		Eq.(4)	(1.53)	(0.70)	Fischer et al. (2012)
	Call time [min]	T_{Call}				
	without detection system		Lognormal	2.50	1.88	Holborn et al. (2004)
	with detection system		Det.	0	0	estimated
	Dispatch Time [sec]	T_{Disp}				
	without detection system		Lognormal	155.39	31.01	estimated
	with detection system		Lognormal	77.69	15.54	estimated
	Turnout and travel time [min]	T_{T+T}	Lognormal	6.60	3.41	LFB (2011)
	Setup time [min]	T_{Setup}	Lognormal	3.50	0.50	estimated

3.4 Influence of a fire detection system (with automatic alarm transmission)

Fire detection systems detect smoke or heat, raise an alarm and call the fire brigade automatically. The detection time is reduced because the alarm of the detection system notifies automatically the alarm centre. The reduction of the detection time depends on the fire growth rate. The faster the fire develops the faster the detection system will raise an alarm. Fischer et al. (2012) proposed a regression model for office buildings (Eq. 3) to quantify the activation time of the devices. The detection time depends only on the fire growth parameter t_α.

$$\ln\left(T_{Detec,FDS}\right) = \beta_0 + \beta_1 \ln\left(\frac{1}{t_\alpha^2}\right) \tag{3}$$

3.5 Influence of a fire alarm without automatic alarm transmission (home detectors)

A detached fire alarm raises an alarm when the device detects smoke. But in contrast to the detection systems they do not transmit an alarm to an alarm centre. A fire alarm which only raises an alarm increases just the probability of an early detection of the fire and reduces the discovery time. According to fire brigade statistics from UK (NFBS 2011) the detection time of a fire with the presence of a detached fire alarm will occur in 63% of the fires within 5 min. The probabilistic model for the detection time is adjusted to this value.

4 SENSITIVITY ANALYSIS

A probabilistic approach is used to assess the maximum steel temperature of a beam under natural fire conditions as an indicator for structural safety. The room temperature is assessed with the two-zone model OZone (Cadorin et al. 2001) and the maximal steel temperature is assessed with the simplified calculation method described in Eurocode 3 (EN 1993-1-2:2005). Using the probabilistic approach the uncertainties of the input variables (Tab.1) are considered consistently leading to a variation of the steel temperature (output). With this approach the sensitivities of the input parameters to the output are assessed. This paper distinguishes between local and global sensitivity analysis.

4.1 Local sensitivity analysis

A measure of the sensitivity of an output Y_j versus an input X_i can be estimated by the derivate $\partial Y_j / \partial X_i$. This derivate can only be computed at a base point defined through a set of input variables X_i. In the context of code calibration the most common base point is usually chosen by the set of variables which lead to the most probable failure based on a limit state function. This point is defined as the design point. An efficient algorithm to find the design point is provided by the First Order Reliability Method (FORM). The derivate of the input variables at the design point indicates the relative influence on the failure state and can be used for code calibration. This paper focuses on the enhancement of the probabilistic models by improving the input parameters through statistical data. Therefore, no local sensitivity analysis is carried out.

4.2 Global sensitivity analysis

A measure to decide what kind of data should be collected is to assess the relative participation of the input parameters (see Tab.1) on the variance of the output (e.g. maximal steel temperature). Saltelli et al. (2008) propose a decomposition of the variance of the output in first-order effects and total effects. The first-order effect represents the main contribution of an input factor X_i to the variance of the output Y and is defined through the first-order index S_i. The total effect S_{Ti} is a measure for the total contribution of an input parameter X_i including the interactions with the other parameters $X_{\sim i}$. The total effect index S_{Ti} provides an indication whether the variance of an input parameter X_i can be neglected ($S_{Ti} \cong 0$). The total effect and the first-order- index are defined in *Eq. (3)* (Saltelli et al. 2008).

$$S_i = \frac{Var\left[E\left(Y \mid X_i\right)\right]}{Var\left(Y\right)} \quad \text{and} \quad S_{Ti} = 1 - \frac{Var\left[E\left(Y \mid \boldsymbol{X}_{\sim i}\right)\right]}{Var\left(Y\right)} \tag{3}$$

The difference of the first-order indices and the total effect indices of a variable provides an indication of the interaction effects of the model (non-linearity of the model). Parameters with high interaction effects should be considered accordingly in the assessment of the model output.

The sensitivity indices are assessed for different compartment areas. Further, it is distinguished between the cases where the uncertainties related with the fire brigade intervention are considered (Fig. 3a) and where they are not considered (Fig. 3b) (only non-zero parameters are illustrated).

The highest indices are obtained for the fire growth time t_α in the case where the fire brigade is considered (Fig. 3a). One of the reasons is due to the high variability of this parameter. The detection time and the turnout and travel time have also a major influence on the outcome.

Interaction effects of all the parameters have a large influence (non-linearity) and should be considered in the assessment of the temperature when considering the fire brigade. The fire load has only a minor influence on the variability of the outcome.

Without considering the uncertainties related with the fire brigade (Fig. 3b) the variation of the output is only dominated through the uncertainty of the fire load. It is seen that the interaction effects of all parameters have only a minor effect on the variance of the output (linear model).

5 CONCLUSIONS AND SUGGESTIONS FOR DATA COLLECTION

The sensitivity analysis shows that reducing especially the uncertainty of the fire growth time t_α will reduce the variance of the steel temperature. A way to reduce the variance of the fire growth time is to report pre-flashover data of fire incidents that affect only the structure, respectively excluding smouldering fires. In this context all data which describe the pre-flashover phase are helpful. For example, data about the time and the area of fire spread (encountered by occupants or by the fire brigade) could be reported to enlarge the knowledge about the fire spread in the pre-flashover phase. The knowledge about the detection time could be increased simultaneously. Additionally, reporting the presence and the operability of fire safety measures helps assessing the effect of the measures on the time intervals.

Often the turnout and travel times are already reported from fire brigades. Such data should be included in the assessment of structural safety. In doing so, the performance criteria of the fire brigade should be reported, too. In this way a comparison of different fire brigades might be possible.

Data on suppression capability of the fire brigade should be collected to verify the engineering model used in this paper. The maximal treatable fire size could be an indicator for this capability. Accordingly, data on the fire size and success of the fire brigade should be collected.

It is seen that the interaction of the parameters is important for determining the outcome. Therefore, data should be reported completely as possible for fire incidents. This provides a basis to assess the correlation between the different parameters. Further, if the fire brigade intervention is considered in the structural safety design then the interaction effects of the parameters should be considered, too.

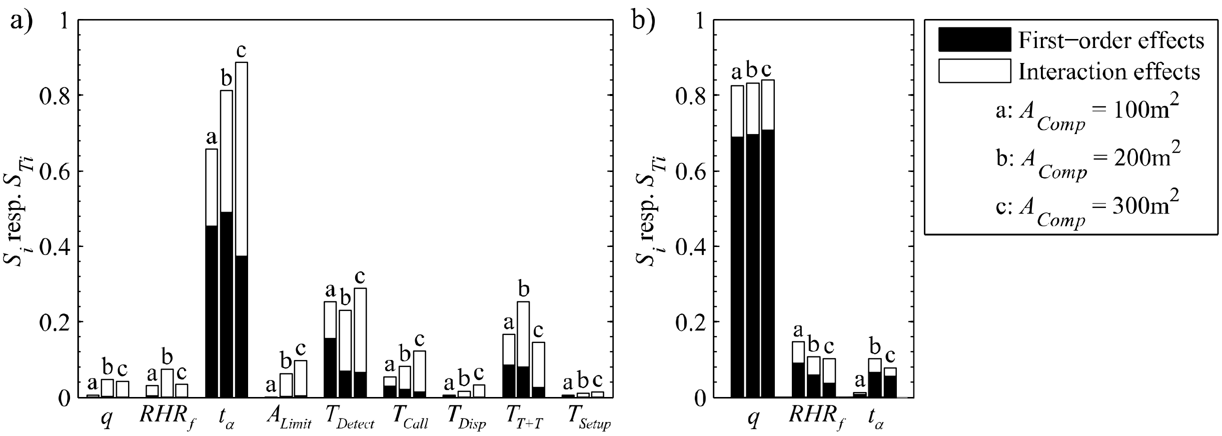

Fig. 3 Sensitivity indices with (a) and without (b) considering the uncertainties associated with the fire brigade intervention

REFERENCES

Cadorin, J., D. Pintea & J. Franssen (2001) The Design Fire Tool OZone V2.0 - Theoretical Description and Validation on Experimental Fire Tests, University of Liege, Belgium.

Fischer, K., J. Kohler, M. Fontana & M. H. Faber (2012) Wirtschaftliche Optimierung im vorbeugenden Brandschutz, Institut für Baustatik und Konstruktion, ETH Zürich.

Fontana, M., J. P. Favre & C. Fetz (1999) A survey of 40,000 building fires in Switzerland, Fire Safety Journal.

Holborn, P. G., P. F. Nolan & J. Golt (2004) An analysis of fire sizes, fire growth rates and times between events using data from fire investigations, Fire Safety Journal.

Hosser, D., A. Weilert, C. Klinzmann, R. Schnetgöke & C. Albrecht (2008) Sicherheitskonzept zur Brandschutzbemessung, Braunschweig, Institut für Baustoffe, Massivbau und Brandschutz.

London Fire Brigade (2011) Our Performance 2010/11, London, UK, LFB.

NFBS (2011) Fire Statistics - Great Britain, 2010-2011, Department for Communities and Local Government.

Saltelli, A., M. Ratto, T. Andres, F. Gampolongo, J. Cariboni, D. Gatelli, M. Saisana & S. Tarantola (2008). Global sensitivity analysis, John Wiley.

Särdqvist, S. (2000) Correlation between firefighting operation and fire area: analysis of statistics, Fire Technology.

Schwanitz, B. (2009) Bewertung der Versagenswahrscheinlichkeit von Löschmassnahmen der Feuerwehr durch Auswertung von Einsatzstatistiken und Integration der Ergebnisse in ein probabilistisches Versagensmodell, TU Braunschweig, Diploma Thesis.

Tillander, K. (2004) Utilisation of statistics to assess fire risks in buildings VTT Building and Transport, Espoo, Finland, Helsinki University of Technology, Ph.D.Thesis.

Tómasson, B., J. Bengtsson, D. Thorsteinsson & B. Karlsson (2008) A Probabilistic Risk Analysis Methodology for High-rise Buildings taking into Account Fire Department Intervention Time, Proceedings of the 9th International Symposium on Fire Safety Science, Karlsruhe, Germany.