Incremental fire analysis (IFA) for probabilistic fire risk assessment

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ABSTRACT

In this paper, the concept of a probabilistic fire risk analysis method is presented in line with the seismic risk assessment approach. The probabilistic fire risk assessment approach runs through a series of probabilistic interrelationships between different variables representing fire severity (called the Intensity Measure IM), structural response (called the Engineering Damage Parameter EDP) and damage/loss (called the Damage Measure DM). The paper explains the development of a probabilistic interrelationship between IM and EDP through incremental fire analysis (IFA). For this purpose, a series of SAFIR analysis of a simple two span reinforced concrete beam subjected to different fire profiles have been conducted and are used to illustrate the required approach. Although a single EDP (maximum deflection) is considered in this investigation, two different IMs (maximum temperature and total radiant energy) are used. It is found that the radiant energy is more efficient than the maximum temperature in representing fire severity.

KEYWORDS

Fire, risk assessment, incremental analysis, fire damage, probabilistic design.

INTRODUCTION

The design of structures in fire conditions currently assesses structural response under a worst-case scenario fire. This has traditionally been a post-flashover compartment fire with the highest peak temperature, based on the fuel in the compartment, the room geometry, lining materials and the ventilation available. However, the worst structural response could be as a result of a long-duration low peak-temperature fire, a localised fire or a travelling fire, which may occur with a slight variation of any of the parameters mentioned earlier. As the uncertainty in defining a reasonable worst-case fire is large, a probabilistic assessment of structural behaviour is ideal to ensure that buildings are adequately suited to the worst probable fire that may occur in their lifetimes. A probabilistic approach will account for the likelihood (i.e. probability) of different magnitudes of the various parameters in addition to accurate predictions of structural behaviour (temperature, deflection, failure time, etc.), currently provided by the deterministic process. In earthquake engineering, a probabilistic risk assessment approach has already taken momentum, and the adoption of a similar approach in structural fire design will yield considerable benefits.
In order to conduct a probabilistic risk analysis, it is necessary to form relationships between the
multiple facets of the assessment process. This can be accomplished by implementing the PEER triple
integral equation [Deierlein et al., 2003] originally developed for performance-based earthquake
engineering:

\[
\nu(dv) = \int \int \int G(dv \mid dm) \, dG(dm \mid edp) \, dG(edp \mid im) \, df_a(im)
\]

in which \( f_a(\bullet) \) = the annual rate of exceedance of \((\bullet)\); \( im \) = intensity measure (e.g. peak ground acceleration); \( edp \) = engineering demand parameter (e.g. inter-storey drift, floor accelerations); \( dm \) = damage measure (e.g. repairable/irreparable damage, collapse); \( dv \) = decision variable (e.g. loss ratio,
downtime); and \( G(x|y) = P(x \geq X|Y = y) \); the conditional complimentary cumulative distribution function
(CCDF). Absolute value signs are required for each of the terms in Eq.1, as some of the derivatives of
the CCDF’s may be negative. In its standard form, the process computes annual probabilities but the
process can be easily modified to compute the probability of exceedance of different hazards during a
certain period; most notably the design life of the structure.

For structures in fire conditions, the process starts with the definition of an intensity measure (IM) for
a fire hazard model. This is a variable that efficiently and sufficiently describes the intensity of fire.
Examples of potential intensity measures include fire duration, peak fire temperature, fuel load,
cumulative radiant heat, heat release rate, normalised heat release rate, etc. For a given type and value
of IM, several time temperature profiles can exist and a single fire profile can be scaled to cover a
wide range of the IM from a small value that results in no damage to a large value that causes
structural collapse. The next interrelation required in the process is between the IM and an engineering
demand parameter (EDP). An EDP is a critical response parameter that has a strong correlation with
damage and forms a strong basis for design decisions. Examples of potential EDPs are maximum
deformation, maximum section temperature, time of failure and maximum bending moment. The EDP
needs to be correlated with a damage measure (DM), such as no damage, spalling, collapse, etc.,
which is indicative of loss/cost.

Structural fire analysis is required to calculate the EDPs due to a given fire profile (i.e. for a given
value of IM). By conducting fire analyses on a member/structure with a suite of fire profiles scaled to
a wide range of IM, several different values of EDPs can be generated for each discrete value of IM,
and these data can be probabilistically interpreted in terms of medians and standard deviations. The
authors propose this process be called incremental fire analysis (IFA), analogous to incremental
dynamic analysis (IDA) in earthquake engineering. IFA forms the crunch of the probabilistic fire
risk assessment process, and is the main focus of this paper.

For conducting IFA, proper parameters for IM and EDP have to be identified first. The efficiency of
an IM is measured by the variation of EDP; i.e. a more efficient IM results in smaller dispersion of
EDPs at a given value of the IM. In this study, only two parameters (maximum fire temperature MFT
and the total radiant (heat) energy RHE) are tried as IM and only the maximum displacement of the
beam is used as an EDP. The total radiant heat energy for any given fire is calculated as the area under
the radiant heat flux vs. time curve. It is effectively the total radiant energy the structure is exposed to.
The IM that results in the least dispersion of results for maximum displacement (EDP) is selected as
the more efficient intensity measure. The concept of the IFA is demonstrated through an example.

**EXAMPLE: Continuous Two-bay Beam**

A series of SAFIR analysis of a simple two span reinforced concrete beam (see Figure 1) subjected to
different fire profiles are conducted herein. The beam has only one support horizontally restrained; the
other supports are free to move longitudinally. Both bays of the beam are subjected to a four-hour
parametric fire (EC1, 2002) from the bottom and the sides. The use of the software SAFIR is ideal
because its modelling of thermal and structural fire behaviour of structures has been extensively
validated against test results (Franssen, 2005; Werther et al., 2012).
The beam was designed according to the rules of DIN 1045-1 (2002). The possibility of the occurrence of a fire was not taken into account during the design process. The top reinforcement was curtailed following the given design rules. The bottom reinforcement is continuous through the beam and was not curtailed. The arrangement of the reinforcing bars is shown in Figure 2. The cross-section of the beam used in the analyses is shown in Figure 3. The properties of the beam are given in Bernhart et al. (2005).

**IFA METHODOLOGY**

The authors believe that fire severity is gauged by the time-temperature curve of the fire; so any appropriate IM should obviously be related to its time-temperature curve. IFA can be conducted either by using arbitrary time-temperature curves representing practical ranges of intensity measures or by generating more realistic time-temperature curves using existing parametric fire models. In this study, different time temperature curves for the IFA are derived from the Eurocode (EC1, 2002) parametric fire equation which allows for fuel load, ventilation openings, and wall lining materials and has both a burning period and a cooling period. By using a range of different values for the ventilation factors and the fuel load, a suite of fires is generated in the form of time-temperature relationships. It is important to note that although rooms are constructed with fixed window sizes glazing failure is not always 100% during fires (Wong, 2011), and for most fires the loss of glazing is progressive, thereby necessitating the inclusion of a distribution on ventilation. IFA requires a large suite of fire profiles, the development of which involves two main steps: fire profile generation and scaling of the generated fire profiles.

**Generation of Fires**

**Series 1.** A series of parametric fires were generated using four ventilation factors, 0.02, 0.04, 0.08, and 0.12, and fuel loads of 200, 400, 800, and 1200 MJ/m². The resulting fire curves (time-temperature relationships) peaked at different times, reaching different peak temperatures. This series produced 16 ‘fires’.

**Series 2.** A number of additional time-temperature relationships were generated using the same ventilation factors as in Series 1 above, but varying the fuel loads so as to produce peak temperatures ranging from 550-1000°C.
Scaling of Fire Profiles

Selected time-temperature curves from the above two series were taken as a baseline for generating further relationships by scaling them to peak temperatures ranging from 200, 400-1000°C, using the same scaling factor for both the burning and cooling phases of the fires. Figure 4a shows the scaling method, using the chosen IMs; i.e. MFT and RHE. While scaling, the temperatures of a fire during the different stages (i.e. time) are multiplied by a constant factor so that the resulting time-temperature profile has the desired value of the IM. The same scaling approach can cater for both IMs as the MFT as well as the RHE are scaled simultaneously.

The fire profiles generated from the first two series scaled to a constant MFT = 800°C and constant RHE = 30MJ/m² are shown in Figures 4b and 4c respectively. As can be seen, although the value of the chosen IM (i.e. MFT or RHE) is constant in these profiles, other characteristics (fire duration, time at maximum temperature, rates of burning and cooling etc.) are different. In these plots, the dark continuous lines represent the median of the scaled fire profiles derived using lognormal distribution to represent the scatter of the temperatures at a given time in the profiles. Below these plots are shown the dispersion of the temperatures at different times in these profiles. These dispersions give the fire-to-fire randomness (similar to record-to-record randomness in earthquake engineering); which is indicative of the chosen IM to solely represent the fire severity.

(a) Scaling with respect to Temperature (IM1). The unscaled fire is shown dashed.

(b) Temperature scaling (IM1) to 800°C  

(c) Radiant energy scaling (IM2) for 30 MJ/m²

Figure 4. Scaled time-temperature relationships for typical fires and the resulting dispersions
RESULTS AND DISCUSSION

Once sufficient fire profiles (in the form of time–temperature curves) are generated, the continuous beam is subjected to each of these fires from the bottom and sides together with the vertical load. The maximum vertical displacement along the length of the beam is monitored in all analyses. The maximum value of the maximum displacement during the fire duration (including cooling phase) is extracted from the results of all analyses as the EDP. Completing this process for a number of fire profiles scaled to a given level of IM gives the same number of EDPs. These EDP data can be processed statistically to check the distribution they follow. In earthquake engineering, displacement or drift related EDPs have been proved to conform to lognormal distribution. Assuming a lognormal distribution, the median and the dispersion of the EDPs at a given IM value can be estimated. The larger the number of fire profiles used, the less will be the bias of the database.

The abovementioned process needs to be repeated for different levels of IM scaling covering the whole possible range of fire severity. In the IM-EDP plot, connecting the response points corresponding to a single fire profile scaled to different IM levels will result in the IFA curve corresponding to that fire profile. Similarly, connecting the median EDPs at different IM levels will yield the median IDA curve and connecting points corresponding to a specific percentile EDP values will result in that percentile IFA curve.

Figures 5 and 6 show the scatter of the EDP (i.e. maximum displacement) at different values of the two chosen IMs; i.e. the MFT in Figure 5, and the RHE of the fires in Figure 6. The dispersion (assuming lognormal distribution) of the EDPs at different fire intensity (represented by IMs) is shown beside the IFA plots. It can be seen that when the MFT is used as an IM, there is increasing scatter of the EDP as the temperature increases. This is a feature of the fact that low temperature fires have less effect on the material properties of the concrete and steel reinforcing. When the RHE is used as an IM, there is more or less uniform scatter in the results, but only a few fires result in input heat energy above about 100 MJ/m$^2$.

Comparing the two plots, it can be deduced that the RHE more efficiently represents the fire severity as it produces less dispersion (of about 0.06 at intensity levels less than 100 MJ/m$^2$) in the prediction of the maximum displacement. Also, as the RHE gives an almost constant dispersion, it may be easier to account for in the probabilistic fire risk assessment to follow.

![Figure 5. Maximum displacement and dispersion for IM1, plotted against temperature](image-url)
CONCLUSIONS

Incremental fire analysis (IFA), which is an integral part of probabilistic fire risk assessment methodology, has been proposed in this paper. IFA involved a large number of structural fire analysis on a structure with a suite of fire profiles scaled to different levels of fire severity represented by a chosen intensity measure (IM). Using the maximum fire temperature MFT and cumulative radiant heat energy RHE as the IMs and the maximum displacement as the engineering demand parameter (EDP), IFA was conducted on a two-span continuous RC beam using a range of parametric fire profiles. From the results, median IFA curves as well as the associated dispersion profiles were generated, which showed that the RHE is a more efficient IM as it results in less variation of the predicted EDPs. More investigations are underway to scrutinise different aspects of the IFA process and to assess the suitability and efficiency of other different parameters as IM and EDP. With the identification of ideal intensity measures (IM), engineering demand parameters (EDP), damage measures (DM) and decision variables (DV), probabilistic assessments of structural behaviour will become common, and will ensure that buildings are adequately constructed to suit to the worst probable fire that may occur in their lifetimes.

REFERENCES


