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Probabilistic approach for failure assessment of steel structures in fire by means of plastic limit analysis

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ABSTRACT

The issue of fire scenarios approach to fire protection is often subject of ongoing discussions within the fire safety engineering community. The choice of an adequate number and type of fire scenarios is not always univocal and straightforward. The fire scenarios to be used in structural assessment are quite complicated to obtain. Their definition often involves significant large-scale fire tests and sophisticated numerical simulations, taking into account numerous factors. For this reason, it seems appropriate to introduce probabilistic tools to assess the most probable fire scenarios. This work proposes a probabilistic approach integrating the Monte Carlo simulation with plastic limit analysis in order to assess the probability of failure of a structure subjected to fire. The underlying assumptions related to spatial–temporal evolution of the fire action and the response of materials and structural members comply with Eurocode provisions. The procedure, mainly devoted to identify the most critical fire scenarios for the structural response, is illustrated by means of a case study represented by a steel braced structure, used as parking. Beyond the limitations related to the simplified assumptions, the outcomes of the analyses demonstrate the potential of the approach for choosing fire scenarios by means of a probabilistic procedure and for evaluating the probability of fire-induced progressive collapse.

1. Introduction

Codes and guidelines in Italy, as well as in a large number of European countries, employ the principles of Fire Safety Engineering to quantify and reduce fire hazard and risk [1–5]. Sound definition of fire scenarios, i.e. the spatial and time evolution of fire actions, is a key aspect in the process of structural fire design [6–8]. For the purpose of structural fire safety analysis, most onerous fire scenarios for structural response need to be considered. However, the choice of an adequate number of fire scenarios is not always univocal and straightforward. Indeed, for each considered scenario, it is necessary to evaluate type and amount of fuel, to determine the quantity of available air during combustion, to determine the effect of active fire-fighting measures (e.g. sprinklers), and finally to define thermal properties of the barriers of any compartment in which the structure can be divided. Hence, given the uncertainty involved in characterizing these parameters, it seems suitable to address the assessment of the fire action by means of a probabilistic framework [15,16].

On the other hand, a structure is often subject to more than one action during its life in addition to fire (e.g. earthquake or blast). Therefore, it is necessary to consider all the possible critical actions which the structure could be subjected to, by following a multi-hazard approach [9–11].

From the structural point of view, fire actions induce decreasing material properties and further internal action on structural members, leading to possible progressive collapse mechanisms.

Therefore, a probabilistic model for fire structural performance associated with a prescribed limit state (e.g. failure) can be a very useful tool. In such a model, target structural reliability is represented by the probability of failure for the limit state in consideration.

The standard Monte Carlo (MC) simulation is used increasingly for fire risk analysis. For example, it is utilized in order to consider the variability of material properties in structural analysis and to examine the randomness of fire parameters in fluid dynamic analysis. In particular, Brandyberry and Apostolakis [12,13] used MC simulation in order to account for the uncertainties in both the ignition source (e.g., surface area, amount of radiated heat) and also in the target scenario (e.g., density, specific heat of furniture substrates). An advanced MC simulation method called Subset Simulation was applied in order to calculate the compartment fire risk using CFAST in [14], incorporating parameter uncertainties associated with zone modeling. In this study, the sensitivity of critical temperature to individual uncertain parameters was investigated. It was concluded that the characteristic rate of heat release per unit area showed the most critical effect on CFAST calculations.

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Nomenclature

ν_C	annual rate of failure
ν_E	annual rate of occurrence of a considered critical action
ν_F	fire hazard
$P(C\vert E)$	structural fragility or failure probability given that a critical event E has occurred
$\dot{h}_{net}$	net heat flux per unit area
$\dot{h}$	heat flux
α_c	the convective heat transfer coefficient
ϑ_m	temperature of the surface of the member
φ	configuration factor
ε_m	emissivity of surface
ε_f	emissivity of flame
σ	Stefan–Boltzmann constant
Q	rate of heat release
$\Delta\vartheta_{a,i}$	temperature increase in steel in the time interval between t_i and t_{i+1} [°C]
Δt_i	time interval between t_i and t_{i+1}
A_m	area of the lateral surface, per unit length, exposed to fire [m^2/m]
V	volume, per unit length, of the member [m^3/m]
A_m/V	section factor of the unprotected steel member [m^{-1}]
c_a	specific heat of steel [J/Kg K]
ρ_a	density of steel [kg/m^3]
$M_{fi,\vartheta,Rd}$	plastic moment of the cross section at temperature θ
M_{Rd}	plastic moment of the cross section at ambient temperature
$\gamma_{M,fi}=1$	partial safety factor for steel subject to fire action
$\gamma_{M,0}=1.05$	partial safety factor for steel at ambient temperature
$k_{y,\theta}$	factor that reduces the yield strength of steel for the effect of temperature θ in the cross section
k_{res}	factor limiting the residual strength of steel after a possible decrease in temperature
$M_{fi,\vartheta,Rd}$	bending moment reduced for the effect of temperature θ in the cross section
N_{ed}	normal force in the column
$N_{fi,Rd}$	plastic column capacity reduced by $k_{y,\theta}$
u	internal work done during the formation of the collapse mechanism
e	external works done during the formation of the collapse mechanism
$\theta_j=\sum_{i=1}^{m} t_i\theta_{ij}$,	plastic rotation at the hinge location j
λ_C	failure load factor
λ_c^1	first tentative failure load factor
$q=G_k+\psi_{2,1}\cdot Q_{k,1}$	quasi-permanent load on beams
G_k	characteristic values of dead loads
Q_k	characteristic values of live loads
$\psi_{2,1}$	combination coefficient
M_p	hinge plastic resistance
$N_{fi,Ed}$	normal force in fire situation
$M_{y,fi,Ed}$	bending moment in fire situation (y axis)
$M_{z,fi,Ed}$	bending moment in fire situation (z axis)
f_y	yield strength of steel
A	cross section area
$\chi_{\min,fi}$	the reduction factor for flexural buckling in the fire design situation
$N_{cr,fi}$	Eulerian load in fire

Guo et al. [17] sought to investigate a probabilistic framework to evaluate the fire resistance of structures, given the uncertainties in the fire load and structural resistance parameters. The study demonstrated that probabilistic analysis of structural fire resistance provides an enhanced understanding of the factors affecting the resistance of structures to fire and offers means for rationally improving structural design to meet target performance objectives.

In [18] the PEER Performance Based Earthquake Engineering methodology was applied to Structures in Fire. Due to the high number of FE numerical analyses necessary to illustrate the application of the framework to Structural Fire Engineering, author applied simplified analytical models.

This study presents a novel approach to evaluate the probability of fire-induced progressive collapse. This approach employs a Monte Carlo simulation procedure in order to generate a large number of plausible fire scenarios. For each scenario, plastic limit analysis is used to investigate, in a very efficient manner, whether a progressive collapse mechanism is going to occur or not. In the following sections, this efficient probability-based approach is presented and the main results of a case-study application are discussed.

2. Research significance

The application of MC simulation for detailed fire risk analysis can be computationally challenging due to long execution time required for the analysis of several sub-structures. The novelty of the proposed approach lies in adopting the limit analysis as a simple and efficient means of assessing the probability of failure for the entire structure.

In particular, the proposed procedure, through the application of the limit analysis for each fire scenario, allows for calculation of the fire exposure time necessary for activating partial or total collapse of the structure. In the next step, application of MC simulation for generating a large number of fire scenarios leads to calculation of the time-dependent curve of vulnerability for the entire structure.

Post-processing the results, by means of disaggregation of MC simulated scenarios, allows for identifying the areas in which active fire fighting systems can be placed or the elements to be protected with passive protection systems. This is of particular interest in order to determine suitable risk mitigation strategies.

Finally, using hazard curves obtained on actual data related to each structural typology, one can provide time-dependent risk curves, which are particularly useful for rapid risk analysis.

3. Methodology

In order to define the annual frequency of failure of a structure due to a specific hazard, the following expression can be used:

$$\nu_C = P(C|E)\nu_E \tag{1}$$

where ν_C stands for the annual rate of failure and ν_E stands for the annual rates of occurrence of a considered action. $P(C|E)$ is the structural fragility, representing the probability of failure, given that the action in question has taken place. Note that the focus of the paper is on the evaluation of building vulnerability to fire. Therefore, the numerical values for rates of occurrence of various actions are not discussed herein.

The methodology proposed focuses on evaluating the fire structural fragility $P(C|F)$ and is applied through the following simulation-based two-step procedure:

1. a large number of plausible fire scenarios are simulated, by randomizing the location and intensity of fire in the structure, and the time evolution of the fire action;