Fire Safety Journal 86 (2016) 41–52

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Complex and comprehensive method for reliability calculation of structures under fire exposure

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ARTICLE INFO

Keywords:
Fire safety
Structural reliability
Reliability analysis
Steel tapered frame
Intumescent coating

ABSTRACT

Numerous recent studies have pointed out that in case of extreme effects (such as fire or seismic effects) the reliability level of structures is lower than in case of conventional effects. Proper estimation of reliability in fire design situation is complicated since there is no comprehensive methodology defined for it; and the commonly used methods apply great simplifications. In former studies the reliability calculations are carried out mainly for simple, separated elements, while simple structural behaviour is assumed. Further research work is needed to refine rules and define targeted safety levels required by fire codes. The current study presents methodology for calculating the reliability of structures subjected to fire; its main novelties are as follows: a) the reliability calculation is not limited to a single, isolated element but the whole structure as a complex system is considered; b) the methodology is capable of taking any type of fire curve into account; c) in the reliability analysis nonlinear global analysis of the whole structure is involved; d) the structural reliability is assessed on time basis. To justify the applicability of the proposed methodology, reliability analysis for a tapered steel frame protected by intumescent coating is presented as an illustrative numerical example. Probability of its failure is calculated by using First Order Reliability Method; the computed failure probabilities are verified by using Monte Carlo Simulation. FORM approximation underestimates the failure probability, the observed error is within −1% to −34%. Based on the results, it has been found that for low and moderate consequence classes the calculated reliability indices are in better agreement with the recommendations of ISO 2394 standard and Joint Committee on Structural Safety than with the values recommended in EN 1990:2002 standard.

1. Introduction

1.1. Literature review

Reliability analysis of structures subjected to fire is inherently associated with significant uncertainties. The major source of uncertainties is the fire effect itself: spatial distribution and quantity of combustible materials, uncertainties in fire development, spatial distribution of developed fire and gas temperature, etc. The reliability assessment is further complicated by the fact that the structural problem is characterized by high nonlinearity (nonlinear and time-dependent material properties, stability failure modes, nonlinear temperature-time relationship, etc.) and complexity in the structural behaviour and design problem (large number of influencing design variables, modelling of complex structural response, etc).

Holický et al. in [3] analyse the reliability of unprotected simply supported steel beams designed in accordance to Eurocode 3 Part 1–2 (EC3-1-2) [2] with Second Order Reliability Method (SORM, [4]). They also point that further research is needed for calibration of components in design codes (such as Eurocode 1 Part 1–2; EC1-1-2, [1]) in order to ensure sufficient reliability level. Jeffers et al. in [5] analyse protected simply supported steel beams subjected to both ISO standard fire curve (equivalent fire effect commonly used for fire design given in temperature vs. time format) [43] and parametric fire curves as per EC1-1–2 (Eurocode conform curves that were obtained on the basis of the properties of the compartment and the combustible material) to model the temperature in the compartment. The reliability of the beam is assessed using Monte Carlo Simulation (MCS, [4]) with Latin Hypercube Sampling (LHS, [4]). They conclude that probability calculation is needed to ensure a consistent reliability level in fire resistant design and further discussion on the acceptable risk level in fire is necessary. Guo and Jeffers [6] present a detailed discussion on reliability theory extended to calculation of failure probability under fire exposure. They calculate the reliability of a simple pinned column with First Order Reliability Method (FORM, [4]), SORM and MCS. Flexural buckling governs the behaviour of the investigated protected steel column. Comparison of the computed probabilities confirms large differences between MCS and FORM, typically having conservative

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http://dx.doi.org/10.1016/j.firesaf.2016.09.002
Received 5 August 2015; Received in revised form 21 September 2016; Accepted 22 September 2016

Nomenclature

Symbols

$A(\mathbf{x})$	cross-section area
c_p, c_s	specific heat of insulation/fire protection material and steel, respectively
d_p	thickness of insulation/fire protection material
$f(\text{-})$	joint probability density function
f_y	yield strength
$G(\text{-})$	limit state function
k_E, k_{fy}	reduction factors for Young modulus and yield strength at elevated temperature, respectively
K_φ	connection rotational stiffness
$M_y(\mathbf{x})$, M_{cr}	bending moment around major axis and critical bending moment
$N(\mathbf{x})$, $N_{cr,z}$	design axial load and critical compression force related to the minor axis, respectively
P	probability (ignition, failure, flashover, etc.)
t, t_R	time and failure time (exposed time till failure), respectively
V	volume
$W_{y,\,el}$	elastic section modulus
$\mathbf{x}$	vector of discrete variables
$\mathbf{X}$ ($\underline{\mathrm{U}}$)	vector of random variables (in standard normal space)
α	sensitivity factor (negative normalized gradients of the limit state function
α_{cr}, $\alpha_{cr,\,op}$	minimum load amplifiers to reach the elastic critical buckling load
$\alpha_{ult,k}$	minimum load amplifier to reach the characteristic resistance of the most critical cross section
β, $\boldsymbol{\beta}$	reliability index, reliability index vector, respectively
ρ, $\boldsymbol{\rho}$	correlation coefficient, correlation matrix, respectively
ρ_p, ρ_s	unit mass of fire protection and steel material, respectively
μ, σ	mean value and standard deviation, respectively
θ_g, θ_s, θ_{cr}	gas, steel and critical (failure) temperature, respectively
η	utilization ratio (demand to capacity ratio)
$\boldsymbol{\Phi}(\text{-})$, $\boldsymbol{\Phi}_m(\text{-})$	single- and multivariate standard normal cumulative distribution function, respectively
∇	gradient vector
λ_p	thermal conductivity of insulation/fire protection material
$\bar{\lambda}_{op}$	non-dimensional slenderness parameter
χ_z, χ_{LT}	reduction factor due to flexural and lateral torsional buckling, respectively

Abbreviations

CC1	Consequence Class 1 as per Euorocde 0
CFD	Computational Fluid Dynamics
CoV	Coefficient of Variation
D/C	Demand to Capacity ratio
EC	Eurocode
ECCS	European Convention for Constructional Steelwork
EN	European Norm
FB	Flexural Buckling
FORM	First Order Reliability Method
GM	General Method
GMNI	Geometrically and Materially Nonlinear Imperfect (analysis)
HLRF	Hasofer-Lind-Rackwitz-Fiessler iteration method
JCSS	Joint Committee on Structural Safety
LHS	Latin Hypercube Sampling
LN	Lognormal Distribution
LTB	Lateral Torsional Buckling
MCS	Monte Carlo Simulation
MPP	Most Probable failure Point
N	Normal (Gaussian) distribution
PEER	Pacific Earthquake Engineering Research Center
PBSD	Performance Based Seismic Engineering
SORM	Second Order Reliability Method

failure probabilities obtained from FORM analysis. Li et al. in [7] investigate the reliability of steel column elements protected with intumescent coating. The equivalent time concept [1] is applied, thus using the ISO standard fire curve. The aging effect of intumescent coating on structural reliability is assessed.

Lange et al. [8] discuss a structural reliability calculation method for fire exposure, based on the framework originally developed by the Pacific Earthquake Engineering Research Center (PEER) for Performance Based Seismic Engineering (PBSD) applications. A composite steel floor system is provided for illustration in their study; the maximum compartment temperature calculated from parametric fire curve is selected as the intensity measure. Their work was a significant improvement towards the implementation of performance based design concept in everyday fire resistant design.

Reliability analysis of complex structures is discussed in [9,10]. Boko et al. in [9] analyse an unprotected steel roof structure, using SORM and FORM analysis. They point that regulations of EC1-1-2 and EC3-1-2 assure appropriate safety level. Note that, however, the study calculates reliability indices single elements, and the correlation between failure modes is not considered via proper system reliability calculations. Boko et al. in [10] present the analysis of a steel portal warehouse without fire protection. The fire curves are calculated from zone model; and parametric study is completed to determine the reliability of the beam element subjected to varying fire curve: with varying fuel load, fire area and opening factor. The paper concludes that the application of ISO standard fire curve yields conservative results of the structural reliability; conservatism is a result of the large compartment size of the investigated structure.

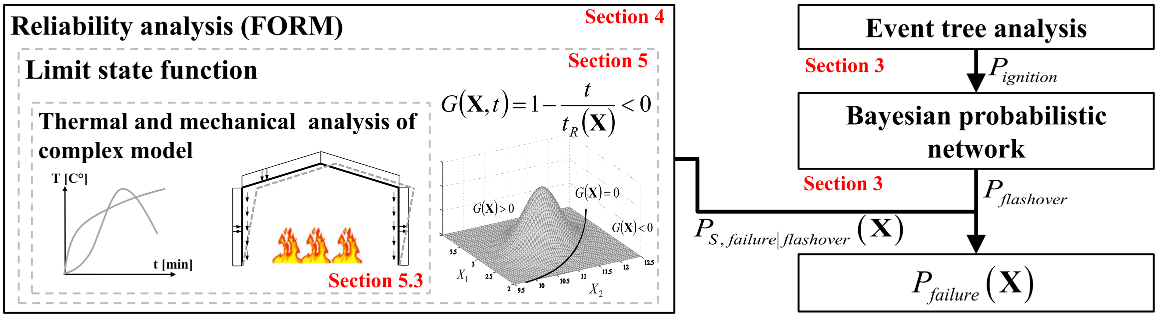

Fig. 1. Overview from the proposed methodology and limit state function.