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PhD thesis

Reliability of the selected steel structures under fire

Promoter:

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My dissertation is devoted to the reliability analysis of selected steel structures in fire conditions with the use of the Stochastic Finite Element Method. It consists of an introduction, mathematical section, Stochastic Finite Element Method description, a part devoted to computer simulations, Conclusions, References as well as of four appendices. This is the final result of my diverse research activity carried out in the period 2010-2015 including four years of the PhD School at the Faculty of Civil Engineering, Environmental Engineering and Architecture. During that period I wrote as the coauthor three papers in major international engineering journals and participated in at least two engineering conferences with my presentations.

The principal research purpose of my dissertation is to determine whether Higher Order Stochastic Finite Element Method (HOSFEM) implemented according to the 10^{th} order generalized stochastic perturbation technique can be used for the reliability analysis of steel structures subjected to the fire conditions. This method is based on the general order Taylor series expansion of all input random parameters and the resulting state functions about their mean values. This approach uses also classical Finite Element Method (FEM) extended with the Response Function Method (RFM) based on the Least Squares Method (LSM) to account for the random nature of loads as well as material characteristics of the carbon steel. My formulation is based on thermo-elastic equilibrium equations for isotropic media and allows for both steady-state as well as transient thermos-elastic analysis in both non-incremental and incremental formulations. The very important aspect is temperature-dependent character of all physical and mechanical parameters of the steel – Young modulus, plastic stress, heat conductivity, heat capacity as well as thermal elongation. The adjacent equivalent temperature curves reflecting fire conditions are directly adopted after the relevant *Eurocode* document. More specifically, the primary purpose is to specify precise validity range of the input coefficient of variation α of the input uncertainty in case of the steel structures under consideration that admits the HOSFEM usage. The second purpose of this dissertation is to determine reliability index β for selected steel structures exposed to the elevated temperatures and to create at the same time an efficient numerical algorithm that allows the HOSFEM computations to directly determine of failure probability.

The introduction presents various methods of estimating the safety of steel structures such as the analytical method, deterministic method of partial factors, the Monte-Carlo simulation method and probabilistic methods like the First Order Reliability Method (FORM) and the Second Order Reliability Method (SORM). Mathematical considerations section includes all necessary formulas in probability theory, statistics, generalized stochastic perturbation method as well as variational equations of thermo-elasticity including these adjacent to the uncertainty analysis. Further, the Higher Order Stochastic Finite Element Method is presented together with its implementation in two Finite Element Method commercial programs – ROBOT and ABAQUS. The section devoted to the numerical analysis consists a variety of the case studies including thermo-elastic behaviour of the steel structures with temperature-dependent properties subjected to both steady-state as well as the unsteady fire temperatures. Computational approach ranges from uncoupled elastic model through the sequentially coupled thermo-elastic analysis up to the fully coupled transient heat transfer with the nonlinear elasto-plastic deformation of the isotropic solid; each time the HOSFEM is applied as the main engine for the numerical reliability modelling. Four important technical applications of my approach are studied – (a) elementary probabilistic study of the elastic steel rebar under tension and under uniform temperature increase along its length, (b) high steel telecommunication tower under a fire on the terrain level (two different models), (c) hot-rolled I-beam (basic structural element of the roof in high building under fire) in fully coupled thermo-elastic analysis (d) nonlinear deformation of the elasto-plastic steel cylindrical specimen subjected to high temperature. All these computational experiments have been carried out to verify quite natural uncertainty in fire conditions, probability of its occurrence and the overall consequences while applied to widely applied steel structures. It should be highlighted that the input random parameter is each time fire temperature, which makes my analysis highly nonlinear in probabilistic context as this temperature affects all material and physical parameters of the structural steel and makes them random too. My procedure of the reliability index determination for the given steel structures is modern alternative to the commonly used deterministic method based on partial safety factors to ensure the required level of reliability of an object. These factors are designed to take into account in quite deterministic way the overall random nature of environmental actions on the structures (snow, wind, ice and, separately, fire), way of uploading of various structures, material properties and the assumed static schemes (graphical representation of the structure). Mechanical properties temperature variations (Young modulus, yield stress) and physical characteristics (thermal conductivity, specific heat, thermal coefficient of expansion) are also adopted directly after the additional Eurocodes statements. An important aspect of my work is that various algebraic forms of the response functions (polynomial, exponential, power, hyperbolic) have been examined by the way to optimize a choice of the base function in further probabilistic analysis of the structural response. This optimal choice should guarantee final probabilistic convergence of the basic probabilistic characteristics under considerations (expected values, coefficients of variations, skewness and kurtosis) for the temperatures, deformations and stresses. It should be mentioned that these state functions have been computed also by the use of the semi-analytical method based on symbolic integration of the same response functions as well as by using of the widely known Monte-Carlo simulation method. Final validation of the HOSFEM applicability range is its consistency with the alternative probabilistic methods tested in the dissertation. Skewness and kurtosis of different state functions are computed (or estimated) each time to check if the final probability distribution (of temperatures, of stresses and of deformations independently) can be modelled with good accuracy as the Gaussian processes.

This dissertation obeys computer simulation of time-dependent stochastic reliability of the steel structures, where the reliability index β is a function of the fire duration period. A precise numerical determination of the time moment when the structure starts to exceed the admissible safety level of safety is of the paramount importance to the public safety and its procedures. We all need this information to declare for any type of the steel structure the additional evacuation time and its fire resistance (e.g. REI 120 for 120 minutes in case of the high-rise buildings).

The final conclusion of my PhD thesis is that the Higher Order Stochastic Finite Element Method apparatus may be efficiently applied in the reliability analysis of the steel structures for input uncertainty not exceeding about 5% of the initial expected values of the fire temperature. This level may be further additionally extended by systematic increasing of the Taylor expansion order as well as by inserting of higher order reliability models.