Preface

In the past two decades, researchers from different countries have conducted series of experimental and theoretical studies to investigate the behavior of structures in fire. Many new insights, data, and calculation methods have been reported, which form the basis for modern interdisciplinary structural fire engineering. Some of these methods are now adopted in quantitative performance-based codes and have been migrated into practice. Difference between the observed behavior of structures in accident fires and the expected behavior determined by calculation methods based on the standard fire has increased interest in the performance of structures in natural fires but simultaneously questions the adequacy of both traditional and modern methodologies.

Intumescent coatings (IC) are passive fire protection materials widely used in steel construction. ICs are reactive materials, the behavior of which under heating condition is complex. The thermal insulation property of ICs cannot be measured by the current standard test methods which were originally developed for the traditional inert fireproofing materials. Besides, due to the organic components, ICs have aging problem. The reliability of structures protected by ICs in their service life is widely concerned by code authorities, fire bridges, engineers and coating manufacturers.

In a performance-based fire safety design through a rational approach, the risk of potential fire hazards on structures, which generally includes investigation of the fire occurrence probability, the failure probability (or reliability) of structures in fire, and the consequence of structural failure, should be assessed quantitatively. Steel columns are the most critical elements in a building, the failure of which usually leads to progressive collapse of the local or global structures. This research studies the reliability of steel columns protected by ICs in the potential fires occurred during their service life, and develops a probabilistic approach to determine the service life of ICs. A comprehensive investigation of all three aspects in structural fire engineering which include fire modeling, heat transfer analysis, and structural analysis is conducted, and several new theoretical models and engineering approaches are developed.

Post-flashover fires are considered as hazardous fires for structures. A modified one-zone model which considers the heat sink effect of steel members in the fire compartment by adding a quantity to the heat balance equation for the traditional one-zone compartment fire model is proposed, and an FE model is developed to simulate the modified one-zone model. The modified one-zone model can output both the fire (gas) temperature and the temperature of the steel members through a single calculation, and can yield more economical fire resistance design than the traditional one-zone model.

Background and shortcomings of current formulae for predicting steel temperature of insulated steel members are investigated. The current formulae are originally developed for calculation in standard fires so that they might give unacceptable results in natural fires, and the formulae are developed as simplified methods so that their applications are limited to situations where the properties of the insulation materials are or can be treated as constant or temperature-independent. Besides, when using the current formulae, iterative computations should be always processed, which is not convenient for the daily design work, and which is not efficient for probabilistic analyses which usually include hundreds of thousands of simulation loops.

A simple approach is proposed to calculate the maximum steel temperature of insulated steel members subjected to natural fires. The approach adopts time equivalent to relate natural fires with the standard fire, and uses a simple closed-form equation for calculating the maximum steel temperatures. The equation is obtained from curve fitting of the numerical data predicted by the program OZone V2, and is verified by the aforementioned modified one-zone model. The equation is also validated by test data. The equation gives satisfactory prediction of maximum steel temperatures in the range from 300 to 600 °C. The profession factor of the simple approach is characterized by test data, which has a mean of 0.955 and a COV of 0.014, and can be best described by a lognormal distribution. Professional factor is used to account for model error in calculation approaches, which is defined as the ratio of measured and predicted results.

ICs react at high temperatures and the thermal properties of ICs cannot be directly measured using the current standard test methods which are originally developed for traditional inert fireproofing materials. A simple procedure is proposed to assess the fire resistance of ICs by using the concept of equivalent constant thermal resistance. The procedure is based on an approximate formula for predicting the limiting temperature of protected steel members subjected to the standard fire. Test data from investigations on both small-scale samples and full-scale steel members are used to calculate the equivalent constant thermal resistance. Using the equivalent constant thermal resistance of ICs, the calculated steel temperatures agree well with the test data in the range of the limiting temperatures from 400 to 600 °C. Recent study on the effect of aging on the thermal insulation property of ICs is reviewed and the values of equivalent constant thermal resistance of ICs with different aging years are calculated.

The fundamental behavior of steel columns under fire conditions and experimental studies on steel columns in fire are reviewed. The accuracy and limitations of current calculation approaches to predict the buckling or critical temperature of

steel columns are investigated by comparing with test data reported in the literature. The calculation approaches adopted in the Eurocode for predicting buckling temperature of steel columns are found to give acceptable prediction for tests with moderate utilization factor or load ratio, and give unacceptable prediction for tests with either high utilization factor ($\mu_0 > 0.83$) or low utilization factor ($\mu_0 < 0.16$). The professional factor for the simple closed-form equation in the Eurocode has a mean of 0.949 and a COV of 0.016, and can be best described by an extreme value distribution.

Monte Carlo simulations are conducted to get the reliability index or failure probability of steel columns protected by ICs in natural fires. The proposed simple closed-form equation is used to calculate the maximum steel temperature of the protected columns in natural fires and the simple closed-form equation in the Eurocode is used to calculate the column failure or buckling temperatures. The probability distributions of the investigated random parameters in the reliability analysis are determined from the literature. The effect of aging of ICs on the reliability index of protected steel columns is investigated. Case studies are conducted. The study finds that the aging of ICs has an effect of decreasing the reliability index of the protected steel columns in fire. That decreasing effect increases with increasing the aging years. The decreasing effect is more serious for columns with high load ratio than for columns with low load ratio. For the investigated cases with low load ratio ($\mu_0 \leq 0.3$), the amount of the decrease in reliability index due to aging is less than 0.2 and the corresponding increase in failure probability is less than 3 %. For the investigated cases with high load ratio ($\mu_0 > 0.3$), the maximum decrease in reliability index is about 0.24 and the corresponding maximum increase in failure probability is about 9 %. However, the ratio of failure probability change is large (can be about 45 %).

Based on the reliability analysis, a probabilistic approach is given to determine the service life of ICs for steel columns. In this approach, the failure probability of the protected steel columns is compared with the target probability of the structural fire design. The probability of fire occurrence and the probability of flashover are considered and are determined from codes. An example is given to determine the service life of ICs for protecting steel columns in an office building.

The approaches given in this study are also applicable for probabilistic analysis of steel columns protected by conventional inert fireproofing materials. Limited by test data on thermal insulation properties of intumescent coating with aging effects, the current study only considers steel columns protected by two different thicknesses of coatings. Also, many assumptions are made on the coating properties. Further studies using different coatings with various thicknesses are needed to obtain a general conclusion on the aging effect on reliability of intumescent coating protected steel columns in fire conditions. Suggestions for possible further work are made.

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