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Probabilistic analysis of steel columns protected by intumescent coatings subjected to natural fires

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ABSTRACT

Probabilistic analysis is needed to yield a rational fire safety design. Intumescent coatings are passive fire protection materials widely used in steel construction. Due to the organic components, intumescent coating has an aging problem. This paper presents a probabilistic analysis of steel columns protected by intumescent coatings subjected to natural fires. Monte Carlo simulations were conducted to investigate the aging effect of intumescent coatings on the reliability of protected steel columns. The study found that aging has an effect of decreasing the reliability index of steel columns protected by intumescent coatings. That decreasing effect increases with increasing aging years. The decrease is more serious for cases with high load ratio, μ_0, than for cases with low μ_0. For the investigated cases with low load ratio ($\mu_0 \leq 0.3$), the amount of the decrease of reliability index, $\Delta\beta$, due to the effects of aging is less than 0.2; and for the investigated cases with high load ratio ($\mu_0 > 0.3$), the maximum $\Delta\beta$ is about 0.24. Based on the calculated reliability index, a probability based approach with a design example was given to assess the service life of intumescent coating for steel structures. The approaches given in this paper can also be used for probabilistic analysis of steel columns protected by conventional inert fireproofing materials.

1. Introduction

In prescriptive codes, steel structures are commonly requested to be protected with thermal insulation to achieve the specified fire resistance ratings. The fire resistance rating of a building component is usually determined by standard fire tests conducted on isolated members subjected to the standard fire exposures such as ISO834 [1]. Since the standard fires are regarded to be the worst-case post-flashover fires, design based on the prescriptive codes are usually too conservative. It should be noted that if the potential real fires are pre-flashover fires like localized fires, design based on the prescriptive codes may be unsafe, as found in the work performed by Zhang et al. [2–4]. As an alternative, performance-based codes have been developed worldwide for more reasonable fire safety design. In a performance-based fire safety design by a rational approach, the risk of real fire hazards on buildings 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 [5,6].

So far, some studies on reliability of structures in fire have been issued. Magnusson and Pettersson [7] summarized the early studies on reliability of fire-exposed members. Magusson [8] constructed a framework for probabilistic analysis of fire exposed steel structures. In his study, the real fires were represented by "Swedish "fire curves. Woeste and Schaffer [9] reported a reliability analysis of fire exposed wood joist floor assemblies by using second moment approximations. In their study, the fire severity was considered by using standard fire duration time calculated from a "t-equivalent" formula developed for ventilation controlled fires. Lange et al. [10] reported reliability analysis of a composite floor slab in fire by using Monte Carlo simulation (MSC). The fire model used was the Eurocode parametric fire model [11]. Hietaniemi [12] reported probabilistic simulation of fire endurance of a wooden beam. In his study, a sophisticated computational fluid dynamics (CFD) model was adopted for fire modeling.

Intumescent coatings, as passive fire protection materials, are widely used in industrial and public steel buildings [13] because of their advantages such as attractive appearance, potential for off-site application, and practically taking no space. The coatings, which are mostly composed of inorganic components contained

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in a polymer matrix, are inert at low temperatures and will expand and degrade to provide a charred layer of low conductivity materials at temperatures of approximately 280 to 350 °C [14,15]. The charred layer, which acts as thermal barrier, will prevent heat transfer to the underlying substrate. In practice, when specifying a coating fire protection for a steel structure, the designer assumes that the coating is correctly applied and its performance meets the fire protection needs without degradation over time. However, because of the organic components of intumescent coatings, the fire protection function of intumescent coatings over time would not be as reliable as when freshly applied [16].

2. Probability based design approach

2.1. Probability of fire ignition

The probability of fire occurrences in a given building or a given area depends upon the number and type of ignition sources presented. This varies during any day and over a period of time and is a strong function of human activity. In stochastic modeling, fire occurrences are always assumed as random point events in time according to the Poisson process [17]. Thus the probability of the occurrence of x fires in a time interval, t, within a particular building is given by

$$P(X = x) = \frac{1}{x!}\lambda t^x e^{-\lambda t} \tag{1}$$

where X is the number of fire occurrences in the time interval t; λ is the mean fire ignition rate or the average number of fire occurrences per unit time interval.

Generally, the probability of fire occurrences in a building which is divided into fire resisting compartments or storeys increases with the size of the building. For a uniformly compartmented building (each compartment in the building has the same floor area, is equally equipped, and is used in the same way), the rate of fire ignition per unit time interval, λ, can be calculated by

$$\lambda = A_F \lambda_p \tag{2}$$

where A_F is the floor area of the building; and λ_p is the rate of the fire ignition per unit floor area per unit time interval.

In practice, only a few buildings such as offices, apartments and hotels can be approximated as being uniformly compartmented. Most buildings are multi-purpose buildings which have unequal compartments or various sectors. A multi-purpose building can be subdivided into several different sectors, each of which is composed of a number of equal compartments. Let Y_i be the number of fire occurrences in time interval t within sector i, the number of fire occurrences within the building is the sum of $Y_i, \sum Y_i$. Consider $Y_1, Y_2, \ldots,$ are all independent Poisson random variables, the distribution of $\sum Y_i$ is Poisson distribution with parameter $\sum \lambda_i$, where λ_i is the fire ignition rate per unit time interval in sector i. $\sum Y_i$ is the same as X in Eq. (1) and $\sum \lambda_i$ is the same as λ in Eq. (1).

Table 1 gives the values for the rate of the fire ignition per unit floor area per unit time interval λ_p for different types of buildings in JCSS (Joint Committee on Structural Safety) probabilistic model code [18].

Table 1
Values for λ_p given in JCSS [18].

Type of building	λ_p
Dwelling/school	0.5 to 4×10^{-6}
Shop/office	1×10^{-6}
Industrial building	2 to 10×10^{-6}

2.2. Probability of flashover occurrence

From the structural point of view only these fully developed or post-flashover fires may lead to failure, while pre-flashover or localized fires also may lead to structural damage [2–4]. The probability of flashover occurrence, $P(flashover)$, is calculated by

$$P(flashover) = P(flashover|ignition) \times P(ignition) \tag{3}$$

where $P(flashover|ignition)$ is the probability of flashover for a given ignition, which depends on the type of active protection measures, and $P(ignition)$ is the probability of ignition. Table 2 gives the values for the probability of flashover for a given ignition in JCSS probabilistic model code [18].

2.3. Probability of structural failure by fire

The probability of structural failure by fire, $P(fail)$, is calculated by

$$P(fail) = P(fail|flashover) \times P(flashover) \tag{4}$$

where $P(fail|flashover)$ is the probability of structural failure in a post-flashover fire, determined by reliability analysis as given in the following sections.

2.4. Service life of intumescent coating

The probability of structural failure by fire should not exceed a target probability. In Eurocode EN 1990 [19], the target probability for structural fire design is 7.23×10^{-5} (the corresponding reliability index β is 3.8). The service life of intumescent coating can be derived from

$$P(fail) = P(target) \tag{5}$$

where $P(target)$ is the target probability for structural fire design.

3. Deterministic models

3.1. Fire modeling

Post-flashover fires were considered as natural fires. The concept of equivalent fire severity, commonly referred as "time equivalent or t-equivalent", was used to relate natural fires with the standard fire. The concept was originally proposed by Ingberg [20]. So far, several formulae, which are based on different assumptions, have been developed for "t-equivalent"calculations [21]. The concept has been adopted by the probabilistic model for fire load given by JCSS [18]. In our investigation, the formula recommended by EC1 [11] is used for evaluating the equivalent fire severity. The formula is based on a maximum temperature method shown in Fig. 1 which defines the equivalent fire severity as the time of exposure to the standard fire that would result in the same maximum temperature in a protected steel member as would occur in a realistic fire, and is given in a simple form,

$$t_{eq} = q_f k_b w_f \tag{6}$$

Table 2
Values for $P(flashover|ignition)$ given in JCSS [18].

Protection method	$P(flashover|ignition)$
Public fire brigade	10^{-1}
Sprinkler	10^{-2}
High standard fire brigade on site, combined with alarm system (industries only)	10^{-3} to 10^{-2}
Both sprinkler and high standard residential fire brigade	10^{-4}