申请同济大学工学博士学位论文

实际火灾下膨胀型防火涂料保护钢柱的可靠度研究

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Study on Reliability of Steel Columns Protected by Intumescent Coatings Subjected to Natural Fires

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摘要

膨胀型防火涂料是当前流行的钢结构防火保护材料。膨胀型防火涂料为非惰性材料，高温下会发生反应。膨胀型防火涂料在火灾下的行为非常复杂，其热工参数不能通过现有的测量传统惰性防火材料的热工参数的标准方法直接测量得到。此外，因为含有有机材料，膨胀型防火涂料有老化问题。由膨胀型防火涂料保护的钢结构在使用寿命内的可靠度问题已成为工程中急待解决的一个迫切问题，引起了消防主管部门、工程设计施工单位和涂料厂商等各方的广泛关注。

本研究的目的是考察由膨胀型防火涂料保护的钢柱在实际火灾下的可靠度。研究采用“轰燃”后火灾代表实际火灾，详细介绍了模拟“轰燃”后火灾的单区域模型及其子模型。介绍了等效火灾强度概念及计算等效爆火时间的各种方法和公式，研究中采用欧洲规范给出的公式计算实际火灾的等效标准爆火时间。

提出了改进的单区域模型用于计算“轰燃”后火灾下钢构件的温度。该模型在单区域模型的热平衡方程中添加了一项，用于考虑室内钢构件的吸热作用。基于该模型可以通过数值求解或分析方法得到“轰燃”后火灾环境中的钢材温度和火灾温度。研究中，借助有限元程序ANSYS中的单元给出了求解该模型得到保护钢构件在实际火灾下的最高温度。

介绍了计算火灾下有防火保护的钢构件的钢材温度的一维理论模型及现有的不同计算公式。现有各国规范给出的计算有防火保护的钢构件的钢材升温的公式均是基于标准火灾得到，可能不适用于实际火灾环境下的计算。并且使用现有公式计算时，需要进行迭代计算，不便于日常使用，也不适合用于可靠度分析（因为计算效率低）。

提出了一个简单方法用于计算自然火灾下有防火保护的钢构件的最高钢材温度。该方法通过等效火灾强度将实际火灾等效为标准火灾，并用一个简单的二次公式计算实际火灾下的最高钢材温度。通过与数值结果和试验数据的比较验证，所提出的简单公式的适用范围为300到600 ^{o}C. 简单公式的误差因子符合均值为0.955，变异系数为0.014的对数正态分布。本方法只需手算便于日常使用，且为闭合公式，计算效率高可用于可靠度分析。

考察了火灾下膨胀型防火涂料的性能，给出了模拟热作用下膨胀型涂料传热的理论模型。介绍了评价膨胀型防火涂料的隔热性能的现有方法及其缺点。提出了利用等效常数热阻评估膨胀型防火涂料的隔热性能的简单方法，利用得到的等效常数热阻计算得到的钢材温度在400 ^{o}C到 600 ^{o}C范围内与试验数据符合良好。

介绍了老化对膨胀型防火涂料隔热性能影响的相关研究并给出了不同老化年限的膨胀型防火涂料的等效常数热阻值。

介绍了钢柱在热作用下的基本力学性能和相关试验研究。利用文献中报道的试验数据，考察了欧洲规范中给出的计算钢柱失稳温度的计算公式的准确性和适用范围。对于中荷载比情形，计算方法能给出可接受的结果；但对于高荷载比或低荷载比的情形，计算方法给出的结果不理想。考察了计算轴向约束钢柱的失稳温度和临界温度的简化方法的有效性和适用范围。通过与文献中报道的轴向约束钢柱的试验数据比较，目前使用的通过欧洲规范中给出的高温下钢柱的承载力公式并考虑轴向约束引起的附加轴力后求解轴向约束钢柱失稳温度的方法不能给出理想的结果；文献中给出的计算轴向约束钢柱的临界温度的公式能给出可接受的结果。研究中，利用报道的试验数据，归纳给出了计算方法的误差因子的统计特性。

考察了由膨胀型防火涂料保护的钢柱在实际火灾下的可靠度。通过蒙特卡罗模拟考察了老化对钢柱可靠指标和失效概率的影响。老化会降低膨胀型防火涂料保护的钢柱在实际火灾下的可靠度。可靠指标β随荷载比μ_0的增大而减小，随使用年限的增加而减小。对荷载比较大的工况，老化对可靠度的影响较大；反之，对荷载比较小的工况，老化对可靠度的影响较小。对于$\beta \geq 1.5$或$\mu_0 \leq 0.3$的工况，老化引起的可靠度的减小$\Delta\beta$不超过0.2（对应的时效概率的增加ΔP_{fail}不超过3%）。对于$\beta < 1.5$或$\mu_0 > 0.3$的工况，$\Delta\beta$的最大值约0.24 （对应的ΔP_{fail}的最大值为9%）。但，老化引起的失效概率的变化率较大，可达40%以上。

初步探讨了根据可靠度降低确定膨胀型防火涂料使用年限的问题。讨论中使用了可靠度分析结果，利用国外规范给出的火灾发生概率和“轰燃”发生概率的理论模型和统计数据，通过与目标（失效）概率比较来确定使用年限。并通过一个例子计算了膨胀型涂料的使用年限。

受试验数据限制，当前研究仅考察了两种防火涂料厚度，并且计算中对防

火涂层的性能引入了很多假设。为得到老化对膨胀型防火涂料保护钢柱的可靠度的影响的一般结论，需要在获得相关试验数据后，考虑不同厚度的影响。另外，我国尚缺乏能用于结构抗火分析的火灾统计数据，应进行相关统计工作，为确定膨胀型防火涂料的使用年限提供依据。

关键词：火灾，膨胀型防火涂料，钢柱，可靠度，老化，使用年限

Abstract

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 those methods are now adopted in quantitative performance-based codes and have been migrated into practice. Difference between the observed behavior of structures in real fire accidents and the expected behavior determined by calculation methods based on standard fire have increased interest on the performance of structures in real fires but simultaneously question the adequacy of traditional and modern methodologies.

Intumescent coatings are current popular fire protection materials in steel construction. Intumescent coatings are reactive materials, the behavior of which under heating condition is complex. The thermal insulation property of intumescent coatings can not be measured by the current standard test methods which are originally developed for the traditional inert fireproofing materials. Besides, due to the organic components, intumescent coating has aging problem. The reliability of structures protected by intumescent coatings in their design life have been widely concerned by code authorities, fire bridge, engineer and coating manufacturers.

The purpose of this research is to study the reliability of steel columns protected by intumescent coatings subjected to natural fires. Natural fires are represented by post-flashover fires. One zone model for predicting the gas temperature of post-flashover fires and its sub-models have been described in detail. The concept of equivalent fire exposure is used to model the fire behavior. Different approaches to calculate the equivalent fire exposure time have been reviewed, and the formula recommended by Eurocode is used in our study.

Natural fires are represented by post-flashover fires. Time equivalent is adopted to model the fire behavior, and the formula recommended by Eurocode is used to calculate the equivalent fire severity. A modified one zone model has been proposed to predict the mean temperature of steel members subjected to post-flashover fires. In the

model, a quantity which considers the heat sink effect of steel members within the fire compartment is added to the heat balance equation for the traditional one zone compartment fire model. A FE model has been developed to solve the heat balance equation of the modified one zone model.

Background and shortcomings of current formulae for predicting steel temperature of insulated steel members provided by fire codes in different countries have been investigated. The current formulae are originally developed for calculating in standard fire, that they might give unacceptable results in natural fires; and the formulae are developed as "simplified" methods, 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 calculating using the current formulae mentioned above, iterative computations should be always processed, which is not convenient for daily design works and not efficient for probabilistic analysis which usually includes hundreds of thousands of simulation loops.

A simply closed-form expression has been proposed to calculate the maximum steel temperature of insulated steel members subjected to natural fires, and has been used in reliability analysis. The equation is obtained from curve fitting of the numerical data predicted by program OZone V2, and has been verified the above modified one zone model. The equation has also been validated by test data. The equation only need hand calculations and is valid in the range of maximum steel temperatures from 300 to 600 ^{o}C.

The behavior of intumescent coatings under heating has been studied and mathematical heat transfer model for intumescent coatings has been reviewed. Current procedures for assessing the thermal insulation property of intumescent coatings has been reviewed and their shortcomings are presented. When using the current procedures for calculation, complex compute simulations or iterative calculation procedures are usually required. A simple procedure has been proposed to assess fire resistance of intumescent coatings by using the concept of equivalent constant thermal resistance, which is used in reliability analysis. Current study on aging effect on thermal insulation property of intumescent coatings has been reviewed and the values of equivalent constant thermal resistance of intumescent coatings with different aging years have

been calculated.

The fundamental behavior of steel columns under fire conditions and experimental studies on steel columns in fire have been reviewed. The accuracy and limitation of calculation approaches to predict the buckling and limit temperature of steel columns have been investigated by comparing with test data reported in literature. The calculation approaches adopted in Eurocode for predicting buckling temperature of steel columns are found to give acceptable prediction for tests with moderate utilization factor, give unacceptable prediction for tests with either high utilization factor ($\mu_0 > 0.83$) or low utilization factor ($\mu_0 < 0.16$). The simple approach based on Eurocode gives unacceptable prediction of buckling temperatures for axially restrained steel columns.

The model errors or professional factors for calculation approaches have been characterized. The statistics of parameters in reliability analysis of steel columns protected by intumescent coatings to natural fires have been determined from literature. Basic of reliability theory has been presented and Monte Carlo simulations have been conducted to obtain the failure probability and reliability index. The reliability analysis finds that aging has effect of decreasing the reliability index of steel columns protected by intumescent coatings. That decrease effect increases with aging year increases. 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 aging effect is less than 0.2 (the corresponding increase in failure probability ΔP_{fail} is less than 3%); and for the investigated cases with high load ratio ($\mu_0 > 0.3$), the maximum $\Delta\beta$ is about 0.24 (the corresponding maximum ΔP_{fail} is about 9%).

Limited by test data on thermal insulation properties of intumescent coating with aging effects, the current study has only considered steel columns protected by two different thickness of coatings. Also, many assumptions have been made on the coating properties. Further studies using different coatings with various thickness 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.

Key words: Fire, Intumescent coating, Steel column, Reliability, Aging effect

目录

主要符号对照表

HRR	热释放速率，kW
$\dot{q}$	热吸收或热损失速率，kW
$\dot{m}$	质量流率，kg/s
$\triangle H$	燃烧热，kJ/kg
α	火灾发展系数，或热扩散系数，或热膨胀系数
q_f	火灾荷载密度，kJ/m^2
A	面积，m^2
H	高度，m
c	比热，kJ/kg K
ρ	密度，kg/m^3
k	导热率（W/m K），或轴向刚度（N/mm）
T	温度，^{o}C
ε	发射率，或应变
κ	消光系数
L	长度，m
h	对流或辐射传热系数，W/m^{2}K
t	时间，min
F_o或O	开口因子，m$^{1/2}$
σ	斯提芬-波尔茨曼常数（5.67×10^{-8} W/m^{2}K^4），或应力
A_i/V	构件截面系数，m$^-$1
d	厚度，m
f_y	屈服强度，N/mm^2
E	弹性模量，N/mm^2
λ	长细比
P	轴力，N