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Reliability based determination of material partial safety factors for cast iron beams in jack arched construction exposed to standard and natural fires

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ABSTRACT

Cast iron beams were extensively used in many 19th century structures, especially in fireproof flooring systems (such as jack arch). Many such structures are still in use today and it is important that they fulfil the current requirements of fire resistance when there is a change of use. These structures are out of scope of modern design codes and old design codes do not provide guidance for fire resistance design. Furthermore, cast iron is a brittle material weak in tension, and there are many uncertainties in its mechanical properties at ambient and elevated temperatures due to material flaws. It is necessary to quantify the probability of structural failure and to introduce safety factors to reduce the probability of structural failure in fire to an acceptable level. This paper presents the results of a detailed study whose purpose is to derive appropriate safety factors to achieve different levels of reliability, for fire safety design of cast iron beams. In this study, a fibre analysis method has been used to calculate the moment capacity of four different types of cast iron cross section. Using randomized stress-strain-temperature relationships, based on variability of the different governing parameters (under tension: maximum stress, 0.2% proof stress, corresponding strains at maximum stress (strength) and failure; under compression: Young's modulus, proportional limit, 0.2% proof stress and the maximum stress), the probability distribution of moment capacity has been calculated. Based on the criterion of cast iron beam failure not exceeding probabilities of 10^{-1}, 10^{-2} and 10^{-3}, material safety factors of 1.5, 3.0 and 5.0 respectively have been obtained.

1. Introduction

Many 19th century historic buildings in the UK, Central and Western Europe as well as the US were built with cast iron structural elements, as main loadbearing columns and beams, especially during the period of 1820–1850 [1]. Cast iron beams are typically partially fire protected using various types of thermal insulation systems [2–4], with the jack arch floor, as illustrated in Fig. 1, being the most widely applied. Because of limited use of cast iron structures in modern construction, there has been very limited research on cast iron structures, at ambient temperature and in fire.

Cast iron structural beams exhibit different behavior from that of modern steel beams. When cast iron beams are used as part of the jack arch construction, the temperature distribution in the cast iron cross-section is severely non-uniform. Also, the stress-strain curve of cast iron does not possess the same degree of plastic behavior of steel, which makes analyzing cast iron beams using the plastic analysis method problematic. Furthermore, cast iron behaves differently under tension and compression.

Based on extensive assessments of thermal and mechanical properties of cast iron and associated insulation materials at ambient and elevated temperatures [5–7], and new experimental data [8], the authors have proposed thermal properties for the relevant thermal insulation materials, and thermal and mechanical properties for cast iron, including the thermal expansion coefficient and stress-strain-temperature relationships [8]. More recently, the authors have developed a simplified method to calculate the moment capacity of jack arch beam cross-section at elevated temperatures [9]. The fire resistance of this type of flooring systems [7] is very sensitive to variations in the mechanical properties of cast iron at elevated temperatures. Because of large variability in these properties, there is a need to develop material safety factors for fire safety design of cast-iron structures. This is the aim of this paper.

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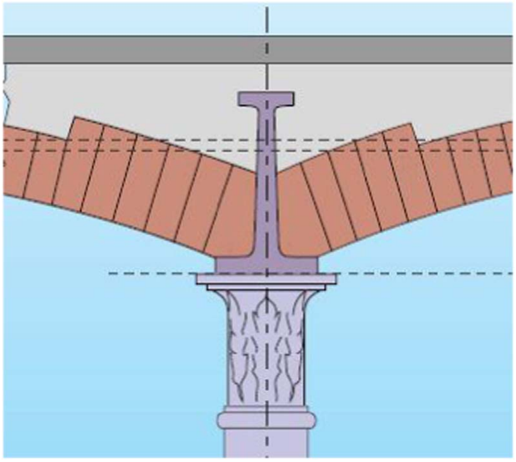

Fig. 1. Typical jack arch beam [2].

The paper presents a reliability analysis in order to estimate appropriate safety factors for fire resistance design of jacked arch cast iron beams. Four different characteristic cross section types have been studied, using randomised stress strain temperature relationships (eight random material property parameters per temperature) in conjunction with a fibre cross section analysis method. From these analyses, the probability distribution of moment capacity has been calculated and material safety factors have been proposed.

The methodology used in this paper is similar with that used successfully by others [10,11] for different types of structure.

2. Conditional probability of structural failure in fire

This paper will derive material partial safety factors for cast iron under fire conditions to achieve different levels of reliability, each with a corresponding probability of failure. To estimate the range of acceptable structural failure probabilities in fire, consider building Consequence Class 2 (CC2) according to EN1990 [12] for general building design. This building class is required to achieve a target reliability index of 3.8, corresponding to a probability of failure of 7.23×10^{-5}. This can be taken as the total probability of failure acceptable to the society. When determining the acceptable probability of failure of structures in fire, it is necessary to include the probability of ignition and the probability of flashover given fire occurrence.

i. Probability of ignition

Several equations have been proposed to quantify the probability of fire occurrence in buildings [13–15]. An example is Poisson distribution of the probability of ignition of x fires during a time interval t, as follows [13]:

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

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

The probability of fire occurrence in building is a function of many parameters (the size of the compartment, the number of compartment etc). Values for λ are given in [16] for several cases. For a 50-year period, considered to be the typical life-time of a building, the probability of fire occurrence in a compartment of 500 m^2 in size ranges from 10^{-2} to 0.2.

ii. Probability of flashover

Structural resistance is rarely fatally affected before flashover. Therefore, it is usually assumed that structural failure occurs only after flashover. The probability of flashover may be calculated using the following conditional probability equation [10]:

Table 1
Conditional probability of flashover given ignition P(flashover | ignition) [17].

Fire protection method	P (flashover | ignition)
Public fire brigade	10^{-1}
Sprinkler	10^{-2}
High standard fire brigade on site combined with alarm system	10^{-3}–10^{-2}
Both sprinkler and high standard residential fire brigade	10^{-4}

$$P(fo) = P(fo\,|\,ignition)xP(ignition) \tag{2}$$

where P(fo) is the probability of flashover, P(fo | ignition) is the conditional probability of flashover given ignition and P(ignition) is the probability of ignition.

Table 1 gives typical values of conditional probability of flashover given ignition.

Combining with typical values of probability of ignition, 10^{-2} to 0.2 as given in (i), the probability of a flashover fire occurring in a typical building of 50-year life time is between $2{\cdot}10^{-2}$ and 10^{-6}.

iii. Probability of structural failure

Combining the above different probability terms, the probability of structural failure in fire is defined as [10]:

$$P(fail) = P(failfo)xP(fo) \tag{3}$$

where P(fail) is the probability of structural failure in fire and P(fail | fo) is the conditional probability of structural failure in a post-flashover fire.

Therefore, to achieve a target probability of structural failure in fire of 7.23×10^{-5} (corresponding to a reliability index of 3.8), the acceptable conditional probability of structural failure, given a flashover fire, is between 10^{-3} and 1. Clearly a failure probability of 1.0 is not permissible so a minimum safety factor for failure probability of 0.1 is recommended. This paper will estimate the required material partial safety factors for cast iron to achieve conditional probabilities of structural failure of 10^{-3}, 10^{-2} and 10^{-1} in flashover fires.

3. Fire curves

In this paper the standard fire curve [17] has been considered as well as two parametric fire curves [17] for slow (O=0.02 $m^{1/2}$, b=1120 J/m^2 $s^{1/2}$ K and $q_{t,d}$=200 MJ/m^2) and fast burning (O=0.1 $m^{1/2}$, b=1120 J/m^2 $s^{1/2}$ K and $q_{t,d}$=200 MJ/m^2). The range of difference between the parametric fires from the standard fire is large so that it enables an assessment of whether the findings of the paper would be generally applicable. The considered fire curves, using the parametric fire curve equations in EN 1991-1-2 [17], are shown in Fig. 2.

4. Material model

The stress-strain temperature relationships for cast iron are as proposed by the authors in [8] and are illustrated in Fig. 3. The stress-strain diagram parameters in tension are:

- Young's modulus,
- the 0.2% proof stress,
- the maximum stress and the corresponding strain.

For temperatures higher than 400 °C, there is also a descending part in the stress-strain diagram. Therefore, two extra parameters are needed: stress and strain at failure.

Under compression, the stress-strain relationship is simpler than