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Elevated temperature behaviour and fire resistance of cast iron columns

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ABSTRACT

Cast iron columns were used in many 19th century structures. Many such structures are still in use today and it is important that they fulfill the current requirements on fire resistance. This paper presents the results of a comprehensive study of the behavior and fire resistance of cast iron columns based on extensive numerical simulations using ABAQUS. The ABAQUS simulation model was validated against six fire tests performed in the USA in 1917. The validated model was then used to investigate the effects of several parameters (column slenderness, load factor, load eccentricity, imperfections of column and cross section, axial restraint) on the behaviour of cast iron columns in fire. The parametric study results indicate that the fire resistance is governed by the applied load and these columns are sensitive to load eccentricity. Based on a comparison between the numerical simulation results and predictions of the EN 1993-1-2 method which is for modern steel structures, it has been found that the EN 1993-1-2 method can give safe and reasonably accurate estimate of the strength and fire resistance of cast iron columns.

1. Introduction

Cast iron possesses high strength in compression and was ideal for use as columns [1]. Cast iron columns were used for more than 100 years [2] before being replaced by steel as supports to timber, cast iron, wrought iron and steel girders in numerous 19th century historical structures. The ambient temperature behaviour of cast iron columns has been investigated by several researchers [3–7]. However, the behavior in fire of cast iron columns has been based on general observations of fire accident investigations [8–17] and standard fire resistance tests [18,19,20]. However, many such historical reports are not available today and the available fire accident investigation and standard fire test reports do not give detailed data and explanations to allow development of thorough understanding of their behavior in fire. Furthermore, there was no reported follow-up detailed research after these investigations and fire tests.

Many such structures are still in use today and there is a need to quantify their fire resistance. Yet a reliable method for assessing the fire resistance of cast iron columns is lacking. Without carrying out detailed research studies, some researchers [21,22] have proposed to use the Eurocode method for steel structures [23] to assess the fire resistance of cast iron columns. However, there are significant differences between cast iron columns and steel columns, because (1) their mechanical properties are different; and (2) cast iron columns have varying cross-sections due to 19th century casting methods. Therefore, extrapolating the steel column design method to cast iron columns may not be appropriate and further systematic investigations are clearly necessary.

The objective of this paper is to carry out detailed numerical investigations of cast iron columns and to use the simulation results to develop an analytical method that may be adopted in assessment of fire resistance of cast iron columns. Validation of the numerical simulation model, developed using the general finite element software ABAQUS, is established by comparison against available fire test reports. The mechanical properties are based on the model developed by the authors following a comprehensive review of the available test data [24] as well as the authors' new test data [25].

The numerical model considers the effects of imperfections in the cast iron cross-sections and initial imperfections. The parametric study, using the validated numerical simulation model, examines the effects of changing load ratio, load eccentricity, axial restraint, cross-section and member imperfections and column slenderness on cast iron column behavior and fire resistance. The results of this parametric study are then used to assess applicability of EN 1993-1-2 [23], which is for modern steel structures, to historic cast iron columns.

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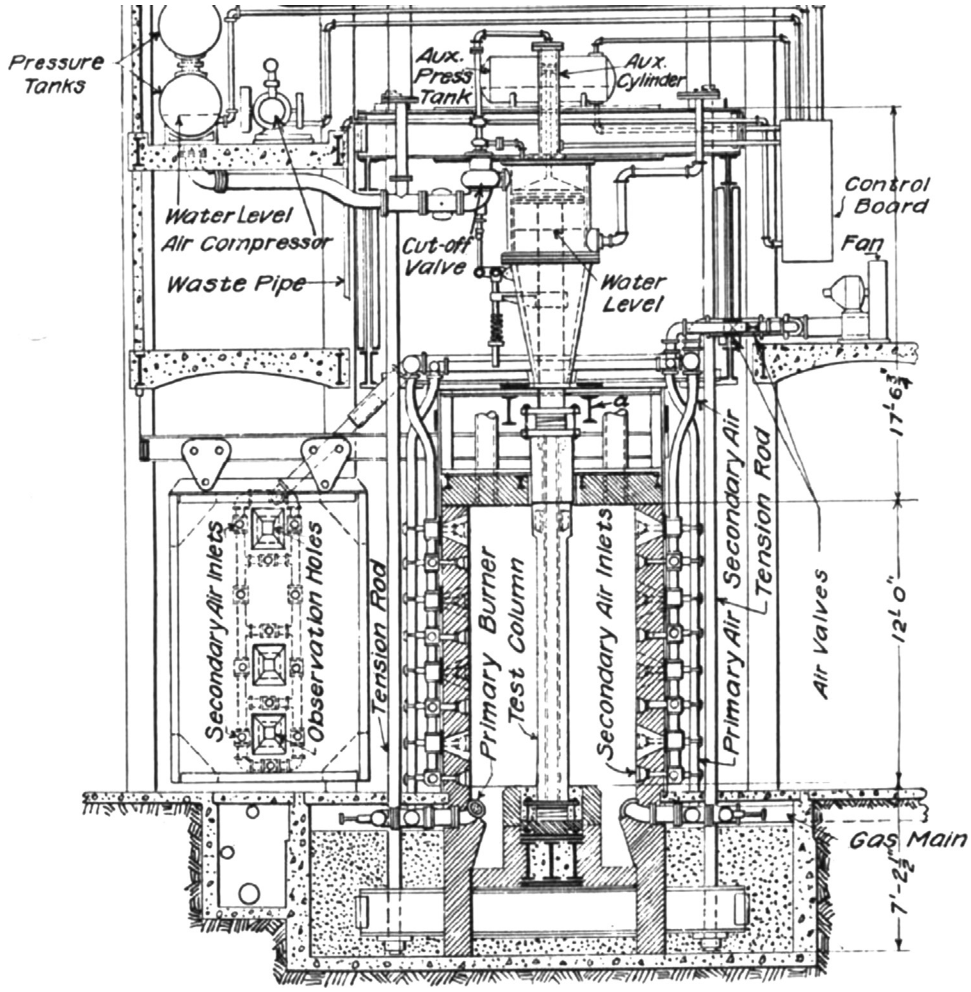

Fig. 1. Elevation of fire testing facility [19].

2. Fire tests

Between 1917 and 1919, 106 steel, cast iron, reinforced concrete and timber column fire tests were conducted at the Underwriters' Laboratories in Chicago, Illinois, USA [19]. Amongst these fire tests, some had unprotected cast iron columns and some had protected cast iron columns. Three of the unprotected cast iron columns, No. 9, 10 and No 10a, and four of the protected cast iron columns (No. 27, 47, 62 and 63), were fully instrumented and the test report has provided detailed information on the temperature and deflection histories of the columns. These fire tests will be used for validation of the simulation model of this paper.

The fire tests [19] were performed in a gas furnace as illustrated in Fig. 1. Fig. 2a shows the column geometry for columns No. 9 and 10. The columns had a nominal external diameter of 7 in (177.8 mm) and internal diameter of 5½ in (139.7 mm). However, there were imperfections in the cross-sections and the wall thickness varied by as large as 1/4 in (6.35 mm). The cross section imperfection has been assumed as uniform along the length of the columns as further information are not provided in [29]. Fig. 3a shows the actual recorded column cross-section dimensions. The vertical imperfection (at the middle of the column) was 1/8 in (3.18 mm). The length of the tested columns was 4.78 m. Table 1 summarises the cross-sectional and length imperfections of the columns.

All test columns had insulated heads as shown in Fig. 2b, so the fire exposed length of the columns was 3.76 m.

Both column ends in fire test No. 9 were assumed to be rotationally fixed because the bolted end plates were considered to offer a substantial amount of rotational restraint. Because the fixing bolts and end plates were cast in and, therefore insulated by, concrete as indicated in Fig. 1, the rotationally fixed condition was considered to have been maintained during the fire test. The top end in fire tests Nos. 10 and 10a was rotationally fixed but the bottom was considered to be simply supported (Fig. 2d). The assumed boundary conditions to other columns, based on the test report, are listed in Table 1.

The protected columns (Nos. 27, 47, 62 and 63) had the same nominal dimensions and test arrangement as the unprotected column No. 9. The fire protection provisions for the columns were:

- No. 27 (Fig. 4a): 1½ in (38.1 mm) thick Portland cement plaster in ribbed expanded metal lath with 1/2 in (12.7 mm) of broken air space (Fig. 3b);
- No. 47 (Fig. 4b): 2 in (50.8 mm) Portland cement, Long Island sand and Hard coal cinders (mixture 1:3:5) (Fig. 3c);
- Nos. 62 and 63 (Fig. 4c): porous semi-fired clay (52.3 mm) on 3/4 in (19 mm) of mortar (Fig. 3d).

The applied load was 95,500 lb (approximately 425 kN) for all columns except 10a on which the applied load was 98,500 lb (approximately 438 kN). These loads gave an average stress of 45 MPa, which was the maximum permitted stress according to the then US specifications (10,000–60*l/r, where l/r is slenderness ratio). This stress is similar to the maximum permitted value by the 1909 London Act [26].