Experimental Thermal and Fluid Science 62 (2015) 52–57

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

A new hybrid heating method used in fire test

Jingsi Huo [a], Yan Xiao [a,b,*], Xiaohu Ren [a], Xiang Zeng [a,c]

[a] China Ministry of Education Key Laboratory of Building Safety and Energy Efficiency, College of Civil Engineering, Hunan University, Yuelu Mountain, Changsha 410082, China
[b] Department of Civil Engineering, University of Southern California, 3260 S. Vermont Ave., Los Angeles, CA 90089-2531, USA
[c] College of Civil Engineering and Architecture, Hainan University, No.58, Renmin Ave., Haikou 570228, China

ARTICLE INFO

Article history:
Received 28 June 2014
Received in revised form 25 November 2014
Accepted 25 November 2014
Available online 3 December 2014

Keywords:
Fire resistance test
Electric furnace
Liquefied gas burner
Hybrid heating

ABSTRACT

Based on a common electric furnace, a newly-developed built-up fire furnace equipped with liquefied gas burners is used to heat a structural column by electricity and blowing liquefied gas flame into the furnace simultaneously. Fire test results indicate that the hybrid heating method can be used to heat the test specimens closely following the ISO-834 standard fire curve, and can be used in fire test with excellent convenience and cost-effectiveness because it combines both merits of electric heating and liquefied gas fire heating. The proposed method provides a convenient way to simulate fire effects.

1. Introduction

Structural damage due to fire is a major concern in high-rise building design. Understanding the fire performance and post-fire behaviour of structures and structural components is an important task for structural designers. Fire furnaces have typically been used to carry out fire tests all over the world since the beginning of the last century. The International Standard Organization (or ISO) has established a fire test standard and a standard curve to simulate real fire attacks [1]. In the case of China, more than ten fire furnaces are in use to conduct tests on the fire resistances of various types of structural components, such as beams and columns. Due to the limitation of standard fire testing furnaces, custom-built furnaces and test set-ups have recently been used to conduct fire tests on restrained structural members at elevated temperatures or at non-uniform temperature exposure. Some researchers have used specially-built electric furnaces to heat the specimens owing to the advantages of safety, easy manipulation and reduced environmental pollution.

Spyrou and Davison [2] developed a purpose-built electric fan-assisted furnace which was designed with image acquisition and processing system in order to capture the deformations of the testing specimen. The fan can not only avoid the presence of flames within the field of view of the video cameras but also ensure a uniform distribution of surrounding temperature up to 1100 °C. Wang and Davies [3] developed a gas furnace which consists of six panels bolted at their junctions for easy assembly. A non-sway loaded steel column, rotationally restrained by two loaded steel beams, was exposed to fire to evaluate how bending moments in restrained columns would change and how these changes might affect the column failure temperatures. Al-Jabri et al. [4] present test results of twenty semi-rigid steel beam-to-column connections at ambient and elevated temperatures, with a series of elevated temperature tests conducted on moment–rotation–temperature curves of beam-to-column connections. Tests were performed in a gas-fired portable furnace lined with ceramic fibre specially designed for testing connections. An electric firebrick kiln was used by Bailey and Toh [5] to experimentally study the failure modes of horizontally unrestrained two-way spanning reinforced concrete slabs at elevated temperatures. Tan et al. [6] developed L-shaped electric furnaces in order to provide various heating schemes, such as three-face or four-face heating for different specimen lengths. Each furnace had four units of heating modules made of metallic spiral heating elements embedded in foamed ceramic fibre insulation. Gao et al. [7] and Yuan et al. [8] developed an oil-fired furnace to carry out experimental studies on fire resistance of unbonded pre-stressed concrete continuous slabs in fire. Wang et al. [9] carried out an experimental study on the fire-resistant capacity of extended end-plate joints. Tests were performed in an oil-fired furnace designed for testing joints. The furnace was specially built according to the shape of tested joints as well as

* Corresponding author at: China Ministry of Education Key Laboratory of Building Safety and Energy Efficiency, College of Civil Engineering, Hunan University, Yuelu Mountain, Changsha 410082, China. Tel./fax: +86 731 88821395.
E-mail address: yanxiao@hnu.edu.cn (Y. Xiao).

http://dx.doi.org/10.1016/j.expthermflusci.2014.11.015
0894-1777/

the requirements of gas burners and exhaust opening arrangements.

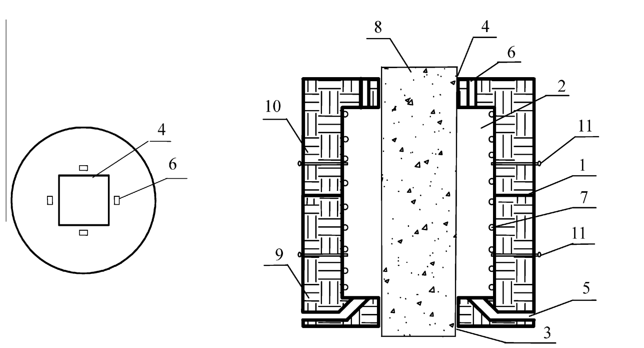
The literature above shows that researchers tend to assemble the built-up heating units into a fire chamber in order to flexibly enclose different types of testing specimens. It is also noted that most researchers prefer electric heating to gas or oil fire because of the merits of electric heating, such as safety, reliability, easy operation, high-accuracy control and reduced pollution. However, the heating rate of electricity is relatively low compared with that of gas or oil fire exposure. Gas or oil-fired furnaces can produce a speedy increase of temperature required to simulate real fire attacks, however they need complex temperature, air pressure and exhaust management systems which are generally difficult to control.

Based on the relative merits of electric furnace and gas or oil-fired furnaces, herein a hybrid heating method is newly developed to heat test specimens by a stackable electric furnace, in which a liquefied petroleum gas flame is introduced into the furnace simultaneously in order to increase the heating rate to simulate the prescribed fire-temperature curve. The furnace heating can be controlled easily and safely in such a hybrid system using gas and electricity, such that the average temperature in the furnace closely follows the ISO-834 standard fire curve.

2. Hybrid furnace structure, heating control method and heating efficiency

2.1. Electric furnace

A stackable electric furnace was built first in order to conduct fire tests on structural columns. The shape and structure of the furnace was determined according to the geometrical dimensions of test specimens in order to be installed conveniently and flexibly. Fig. 1 shows a schematic view of the stackable furnace, which is composed of six semi-cylindrical shells with an inner diameter of 590 mm and a height of 630 mm. The furnace was built with small segments in order to flexibly provide different heights of testing in the chamber. Thus, the furnace can be used to heat columns with heights of 630 mm, 1260 mm and 1890 mm. The furnace wall is made of an exterior steel shell, a thick layer of insulation fibre and interior honeycomb ceramic wall. Each semi-cylindrical shell has a unit of heating module made of metallic spiral heating elements embedded in foamed ceramic fibre insulation. The furnace rating is 60 kW/380 V/3 phase, with a maximum operating temperature of 1200 °C and a maximum heating rate of 100 °C/min. Three Type K thermocouples (chromel–alumel) are fixed to the upper, middle and lower interior furnace wall at the middle section of each segment (as shown in Fig. 1), and used to monitor the furnace temperature so that the stackable electric furnace can be used to provide a uniform heating condition. Three units of heating module of the upper, middle and lower segments, i.e., two semi-cylindrical heating elements, can be automatically controlled independently or share one heating control signal. The heating control system is mainly composed of a XMT2100 intelligent temperature controller, voltage control triggering switch, silicon-controlled switch. The XMT2100 intelligent temperature controller is made by Changzhou Nuohai Electronics Co., Ltd., China. The furnace heating can be close-loop controlled by comparing and processing the temperature difference between the fire furnace temperature and the pre-determined value in real time, as well as by transmitting the control signals to continuously adjust the output power rates. Fig. 2(a) shows the heating control system.



1-fire wall; 2-furnace chamber; 3-lower fire hole; 4-upper fire hole; 5-gas vent; 6-exhaust hole; 7-heating cord; 8-Specimen; 9-lower segment; 10-upper segment; 11-thermocouple

Fig. 1. Schematics of electric furnace (left – plan view; right – elevation view).

In order to know the maximum heating capacity and the heating control accuracy, trial fire tests without a test specimen were carried out. Fig. 3 shows a typical temperature versus time curve labelled as "Electric heating", which was obtained with the heating rate at the highest setting. Obviously, the electric furnace's heating rate is too lower as it took about 20 min to reach the ISO-834 fire standard curve. There is a remarkable difference between the measured temperature curve and the ISO-834 standard fire curve before the two joins. However, the electric heating can easily and closely follow the ISO-834 fire standard curve during the temperature increase and during the cooling phases, as shown in Figs. 4 and 6.

2.2. Gas fire burner

Since the heating capacity of the electric furnace is not sufficient to follow the ISO-834 fire standard during the initial 20 min of the ISO-834 fire exposure, a liquefied gas fired facility was developed with the intent to accelerate the initial heating process. This facility was achieved by installing gas fired burners in two fire holes at the bottom of the furnace, thereby allowing for additional energy to be introduced while the furnace is being heated by electricity. The liquefied gas facility, as shown in Fig. 2(b), includes the temperature control unit, proportional valve, gas fire burner and flame igniter, liquefied gas conducts and air-blower. The liquefied gas facility is equipped with four gas fire burners. The furnace heating can also be controlled in a close-loop fashion by regulating the gas pressure valve in real time to change the ratio of air to liquefied gas according to the predetermined temperature versus time history.

In order to know the maximum heating capacity and the heating control accuracy, trial tests without a test specimen were also carried out using the gas fired facility. Fig. 3 shows the comparison of different fire heating modes with the ISO standard curve. Obviously, the heating capacity of the gas fired facility is a little higher than that of electric heating during the initial 5 min, but sharply lower thereafter. Apparently, it would take much more time to intersect with the ISO-834 fire standard curve. The comparison between temperature versus time histories for electric heating and the gas fired heating demonstrates that the gas fire heating, compared with the electric heating, can result in rapid temperature rise in the initial several minutes but lower heating capacity at later stages.

3. Hybrid heating control method and validity of application in fire tests

Although the heating rates of the electric furnace and the gas fired burners have their limitations as shown in Fig. 3, gas fired heating can provide the required rapid temperature rise during