Performance of concrete-filled RHS columns exposed to fire on 3 sides

Shashank Bhardwaj , Ms Priyanka Dubey

Shashank Bhardwaj , M Tech (SE) APJ University Indore
Priyanka Dubey, Assistant Professor APJ University Indore

ABSTRACT

The behavior of concrete-filled steel tubular (CFST) columns subjected to uniform fires has been well studied over the past few decades. However, knowledge of the performance of concrete-filled rectangular hollow section (RHS)columns exposed to fire on 3sides, which is a common scenario in practice ,is limited. Hence, this paper presents an experimental and numerical study into the response of concrete-filled RHS columns subjected to3-sidedfire exposure. Three full-scale concrete-filled RHS columns, two of which were exposed to fire on 3sidesand the other on4sides, were tested to failure. The temperature distributions, axial displacements, lateral displacements and failure modes were all recorded and discussed. Following the experiments, a sequentially coupled thermal-stress numerical model was developed, featuring heat transfer analysis and stress analysis. The FE model was validated against the test results, and used to assist in the understanding of the observed failure mechanisms and to extend the investigated range of key parameters. The separameters included load ratio, load eccentricity, cross-sectional dimensions, slenderness ratio, steel ratio and strengths of the constituent materials. It was found that the load ratio, cross-sectional dimensions and load eccentricity have a significant influence on the fire resistance. Based on the results of the parametric studies, a simplified design formula was developed for predicting the fire resistance of concrete-filled RHS columns subjected to 3-sidedexposure. Furthermore, a reduction factor method was proposed for the design of concrete-filled RHS columns exposed to 3-sided fire, based on fire safety design methods for concrete-filled RHS columns in uniform fire, which may be more convenient for engineering applications.2

Key words: *Concrete-filled RHS columns ,finite element analysis, fire resistance, fire testing, 3-sided exposure.*

Introduction

Concrete-filled steel tubular (CFST) columns are gaining increasing usage in practice owing to their excellent structural performance and ease of construction. Since fire safety is one of the key aspects of structural design, it is essential to develop a full understanding of the fire performance of CFST columns.

Considerable experimental and numerical research has been carried out to investigate the fire performance of CFST columns in the past few decades. Hass[1],Lie and Chabot[2,3], Kodur and Lie[4]conducted experimental studies of the fire resistance of concrete-filled circular and square hollow section columns filled with plain concrete, reinforced concrete and steel-fibre -reinforced concrete. Wang[5]and Han[6]examined experimentally the behaviour of concrete-filled rectangular and square hollow section columns exposed to standard fire conditions. Kodur[7,8]and Romeroet al.[9]studied the fire resistance of steel tubular columns filled with unreinforced high strength concrete and reinforced high strength concrete with bars or steel fibres. Lu and Han[10]tested a series of CFST stub columns filled with high strength self-consolidating concrete. Although fire testing is expensive and time consuming, it remains the most direct and reliable method of evaluating the fire resistance of members and developing an understanding of their behaviour.

Meanwhile, numerical simulations are also gaining acceptance as a means of examining fire behaviour. Lie and Chabot[11], Lie and Kodur[12]and Han[13]developed fibre models to predict the fire resistance of CFST columns. Such models can provide accurate results, though local buckling and the interaction between the steel tube and core concrete cannot be precisely considered. Ding and Wang [14], Hong and Varma[15], Espinos and Romero[16]and Han et al.[17]developed three-dimensional finite element models for predicting the fire performance of CFST columns. The three-dimensional finite element method can account for various complexities of the thermal and mechanical behaviour of CFST columns,. Nevertheless, discrepancies between numerical simulations and the experimental response of members under fire loading tend to be larger than the seat ambient temperature, due to the greater number of variables and uncertainties.

Previous research has focused largely on the fire performance of CFST columns in uniform fire. However, in real structures, columns may be subjected to non-uniform exposure due to localized fires or the barrier effect of adjacent walls. For concrete-filled rectangular hollow section(RHS)columns, this means that, in different situations, only some sides will be exposed to fire, i.e., one side, two sides or three sides. It has been shown that the number of sides exposed to fire (hereafter referred to as the fire boundary)has a considerable influence on the thermal distribution and fire resistance of structural members[18-]. To date, no research has been reported on the fire performance of concrete-filled RHS columns subjected to 3-sided fire exposure,.
In this paper, the performance of concrete-filled RHS columns exposed to fire on 3sides is investigated experimentally and numerically. Three full-scale concrete-filled RHS columns, two of which were subjected to 3-sided fire exposure & the other one to 4-sided fire exposure, were tested to study their fundamental fire behaviour & obtain data for the validation of finite element (FE) models.
In the experiments, temperature distributions, axial displacements, lateral deflections and failure modes were all recorded and discussed. The FE models employed sequentially coupled thermal-stress analyses, with a heat transfer analysis followed by a stress analysis, using the program ABAQUS. Parametric studies were conducted to identify the influences of key parameters on the fire resistance of the column, including load ratio, cross-sectional dimensions, slenderness ratio and load eccentricity. Based on the parametric studies, a simplified design method was proposed for predicting the fire resistance of concrete-filled RHS columns subjected to 3-sided exposure. Furthermore, a reduction factor method, which is considered more convenient for practical applications, was devised to extend existing fire safety design methods for concrete-filled RHS columns in uniform fire to those columns in 3-sided fires.

Experimental study

Following previous experiments on square shaped CFST columns exposed to non-uniform fire experiments are conducted herein to study the fire behaviour of concrete-filled RHS columns under 3-sided exposure, in order to develop an understanding of the fire response of these columns and to obtain test results to verify FE models,

Specimens

Three full-scale concrete-filled RHS columns were tested to failure, two of which(R1 and R2)were subjected to 3-sided fire exposure and the third(R3) was in uniform fire. The edge width, edge depth and total length of the specimens are 200mm, 300mm and 3810 mm respectively. Two enlarged end plates with a cross-section of 660 mm×460mm and a thickness of 30mm were welded to the top and bottom of the column. The centre of the end plates coincided with the geometric centre of the steel tubes to attain concentric loading.
The effect of load ratio on the fire resistance of concrete-filled RHS columns was investigated in addition to the fire boundary.

Test conditions and procedure

The fire tests were conducted in a purpose-built furnace specially built for testing structural columns, which can provide combined actions of elevated temperature and structural load. The furnace is a rectangular box with a plan area of 3m × 2m and a height of 3.3m. The maximum load capacity is 400 tonnes. The interior surfaces of the furnace chamber are lined with ceramic fibre materials that efficiently transfer heat to the test specimens. The furnace temperature can be controlled by programmed fire curves ,and air pressure can be also adjusted. Specimens were installed in the furnace by bolting their end plates to cast steel support plates . The upper cast steel plate was fully restrained except for movement in the vertical direction and rotation about the major axis of the cross-section of the column. The lower cast steel plate was fully restrained except for rotation about the major axis. The boundary conditions of the columns were considered to be pinned-pinned. Load was applied approximately 30mins before the start of the test, until no further increase of transient axial displacement was measured. The load was held constant with a servo controlled hydraulic jack throughout the test.

Test results

It was observed that the specimens under 3-sided fire exposure failed by global buckling accompanied with local buckling on the exposed surfaces, which is similar to the failure modes observed for square shaped CFST columns with1-sided or3-sided fire exposure. For the specimen in uniform fire, failure was by material yielding and local buckling with no significant lateral deformation of the column, similar to the failure mode described in [2,6]. A general view and close-up view showing local buckling of the specimens after testing are shown in Fig.

 

The measured time-temperature curves of the furnace in the tests were in good agreement with the standard ISO-834 time-temperature curve. The temperatures along the longitudinal direction of the R2 specimen, which was typical of all specimens, are shown in Fig., and confirm the uniformity of the temperature along the member length. Hereafter, the temperature of the cross-section at mid-height is considered to be the temperature of the specimen. If the corresponding thermocouple was damaged during the test, the temperature near the end isused instead. Fig.9shows the measured temperature curves of the three test specimens ;as expected, the temperature of the outer steel tube is much higher than that of the concrete core. For the specimens exposed on 3 sides, the temperature near the unexposed side is much lower than that near the exposed sides, with the difference reaching around 200-300°Cat the time of failure.

Finite element modelling

There are two types of coupled thermal-stress analysis methods: sequentially coupled thermal-stress analysis and fully coupled thermal-stress analysis. Fully coupled thermal-stress analysis solves for the stress/strain and the temperature fields simultaneously, and is used when thermal and mechanical solutions affect one an other strongly. For most conventional structures, it is reasonable to assume their structural behaviour in fire depends on the thermal field but that there is no interdependency. Romero et al.[9] have shown that load and corresponding deformation typically have insignificant influence on the thermal distribution. There fore the sequentially coupled approach was used in this study. It was performed by firstly solving the pure heat transfer problem, then reading the temperature solution into the stress analysis as a predefined field.

.**Heat transfer analysis**

Heat transfer analyses were conducted to simulate the heat transferred from the fire to the structural members. Heat is transferred from the fire to the outer surfaces of the specimens via radiation and convection. In this study, the convective heat transfer coefficient and resultant emissivity were taken as 25W/(m2K) and 0.5 respectively for the exposed sides. Heat is transferred within the specimens through conduction. It was assumed that the steel tube and the concrete core were in perfect contact such that there was no heat loss at the interface. Fire conditions followed the ISO-834 standard fire curve or the ASTM-E119 fire curve], depending on the specific conditions of the test members. Unless otherwise specified, the ISO-834 standard fire was employed.

For the unexposed side, the convective heat transfer coefficient was set to be 9W/(m2K), which also makes an allowance for heat transferred by radiation[29]. The ambient temperature was defined to be 10 °C for the simulation of the tests, and 20°Cforthelatter parametric studies. The concrete core and the steel tube were modelled with 8-node continuum solid elements(DC3D8) and 4-node shell elements(DS4),respectively.

Stress analysis

Nonlinear stress analyses were carried out subsequently to investigate the structural response of the specimens under combined constant axial load and non-uniform fire loading. A three-dimensional finite element model was developed. The concrete core and the steel tube were modelled with linear reduced-integration 8-node continuum element(C3D8R) and linear reduced-integration 4-node shell elements (S4R) respectively. In order to read the temperature data for each node efficiently, the finite element meshes of the stress analysis model were the same as those of the corresponding heat transfer analysis model.

Validation of the FE model

The measured temperatures and displacements from the tests on the concrete-filled RHS columns subjected to 3-sided fire performed in this study, as well as square shaped CFST columns exposed to non-uniform fire and uniform fire [2] and rectangular shaped CFST columns exposed to uniform fire [6]were employed to verify the FE model.

Comparisons between the predicted and measured temperatures are shown in Fig. , in which the unexposed side was modelled using the real exposure conditions .Layouts of thermocouples are shown in Fig. The predicted temperatures generally accord well with the temperatures measured in the fire tests.

Parametric studies

The validated FE model was used to study the influence of key parameters on the fire resistance of concrete-filled RHS columns exposed to 3-sidedfire, including load ratio, cross-sectional area, slenderness ratio, steel ratio, strength of steel and concrete, load eccentricity ratio and depth to width ratio. Values of these studied parameters are listed. The key parameters were varied individually while the other parameters were held constant.

An RHS section has a major and minor axis; hence, the location of the unexposed side and the direction of applied moment create four possible conditions, shown in Fig.18. Compared to condition B, condition A is much more detrimental because the effect of additional eccentricity induced by the asymmetric thermal field is superimposed on to that of the moment. A similar situation occurs for conditions C and D. Therefore conditions A and D were studied, and the more adverse of the two defined the fire resistance of the column.

Methods for predicting fire resistance

Simplified method

Based on the results of the parametric studies, it was found that the load ratio and cross-sectional dimensions have pronounced influences on the fire resistance of concrete-filled RHS columns subjected to 3-sided fire exposure. A formula was established to relate fire resistance time and the two principal parameters determining it.

Reduction factor method

Differences in fire resistance between concrete-filled RHS columns with 3-sided exposure and 4-sided exposure were studied to extend fire safety design methods for those columns in 4-sidedfiresto those in 3-sided fires. The parameters influencing the fire resistance design of CFST columns in uniform fire(load ratio, cross-sectional dimensions and slenderness ratio), were considered. The fire resistances of concrete-filled RHS columns in 3-sided and 4-sided fires, as derived from the FE models,.It may be seen that concrete-filled RHS columns subjected to 3-sided fire exposes lower fire resistance than those columns subjected to 4-sided fires when the slenderness ratio is less than about 30, whereas the reverse situation occurs at higher slenderness ratios. The results show again that slenderness ratio has a much larger influence on the fire resistance of columns in 4-sided fires than that of columns in 3-sided fires.

Conclusions

An experimental and numerical investigation in to the fire performance of concrete-filled RHS columns subjected to3-sided exposure was conducted. Three-full scale concrete-filled RHS columns were tested to failure to explore the fundamental behaviour of these columns and provide data for the validation of FE models. A three-dimensional finite element model was developed . Following validation of the models, parametric studies were carried out and two design methods were proposed for predicting the fire resistance of concrete-filled RHS columns exposed to 3-sidedfires. The following conclusions can be drawn based on the studies performed:

(1) The shift of the centre of stiffness, together with thermal bowing, which are particular phenomena associated with columns exposed to asymmetric fire conditions, promote global buckling. The collated numerical analyses

revealed that the effective centroid of the cross-section under 3-sided fire exposure typically shifted between 0.025 times and 0.125times the depth towards the unexposed side.
(2) Parametric studies revealed that load ratio, cross-sectional dimensions and load eccentricity ratio have significant influences on the fire resistance of concrete-filled RHS columns exposed to 3-sided fires, while slenderness ratio, steel ratio, material strength and depth to width ratio are less important.

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