Performance Based Fire Design for Steel Reinforced Concrete Structures

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ABSTRACT
This study aims to investigate the behavior of large-scale steel reinforced concrete structures (SRC) in fire through a series research projects started from 2011 year. In order to achieve the goal to draft a performance based fire design code, four topics have been made. The material properties at elevated temperatures, behavior of structural elements in fire, assessment of fire-structure safety and design code are involved in the project. Among all of SRC structures, the Hollow structural steel sections or pipes that are filled with structural concrete are often used to enhance the column strength and stiffness. The structural steel used in the concrete-filled box columns possesses high strength and ductility, but with higher thermal conductivity, and the strength will be significantly decrease at elevated temperature. Therefore, the research of the large-scale concrete-filled box columns (CFBC) subjected to axial load at elevated temperatures has given precedence over all others.

Keywords: Concrete, Box column, Fire, Axial deformation

1. INTRODUCTION

In Taiwan, steel reinforced concrete (SRC) accounts for 20% of the total floor area for occupancy permits applied during 2002. However, Chapter 7, “Structure of SRC” wasn’t added to the building structure section of “Building Technical Regulations” until January 16, 2004. On April 26, “SRC structural design standards and instructions” was added to it. SRC combines the material characteristics and advantages of steel and reinforced concrete. The material, engineering approach and structural behavior during fire are more complicated than the traditional steel structures. The duration of this four-year study spans from 2011 to 2014. Studies completed so far include establishing local experimental data on thermal properties of SRC, fire response of encased concrete-filled box column (CFBC) and effects welding methods have on fire response. These initial studies will help establish regulations applicable for coated SRC columns and the minimum fire resistant coating required for CFBC to meet the fire resistant duration.

Hollow structural steel sections or pipes that are filled with structural concrete are often used to enhance the column strength and stiffness. The use of concrete-filled tube columns leads to several advantages such as possessing excellent strength and stiffness compared with steel or reinforced concrete columns, using steel tube to replace formwork and simplifying the construction process, and providing confinement for the concrete through the use of steel tube. However, to be used for medium and high-rise buildings, concrete-filled box columns are frequently designed instead of the concrete-filled tube columns because the concrete-filled box columns can provide greater strength than concrete-filled tube columns do. A steel box column is fabricated by welding four structural steel plates through the complete joint penetration weld or partial penetration weld.

In addition to analytical and numerical work(Lu, H., Zhao, X. L., and Han, L. H., 2009), experimental work on the behavior of the concrete-filled tube columns has been conducted by a number of researchers (Yang, H., Han, L. H., Wang, Y. C., 2007). The test specimens included various test variables such as size of the cross section, shape of the steel tube, thickness of the fire protection, load ratio, load eccentricity, concrete strength, type of the concrete material, and fire duration time, etc. Moreover, the specimens tested in the literature were mostly small scale. Although the behavior of the concrete-filled tube columns in fire has been extensively studied, experimental work carried out for large-scale concrete-filled box columns is very few due to the limitation of the test equipment. Furthermore, the behavior of the concrete-filled box columns at elevated temperature is not yet well established. The structural steel used in the concrete-filled box columns possesses high strength and ductility, but with higher thermal conductivity, and the strength will be significantly decrease at elevated temperature. Concrete has good compression strength, and low thermal conductivity, and has better fire resistance than the steel. The concrete-filled box columns must subject to axial compression, and the structural behavior and thermal response is complex at elevated temperature.

On the other hand, the use of fireproof coating would increase the construction cost by approximately 30%(Kim, D. K., Choi, S. M., Kim, J. H., Chung, K. S., and Park, S. H., 2005). In addition, it is a non-reusable building material and its fire resistance tends to be affected due to peelings caused by impact from external forces. Currently, the Eurocode and National Research Council of Canada (NRC) have established design standards that regulate the minimum fire resistance (1 to 2 hours) required for uncoated materials. In Taiwan, there are no similar design methods or standards. Under the premise of fire prevention and structural safety, it would be economical and environmental if the use of fire resistant coating can be minimized or even eliminated. The purpose of this study is to fully utilize the Fire Experiment Center at Architecture and Building Research Institute, which is one of the few institutions in the world that is equipped to conduct experiments on the loading, heating and fire resistance of structural components of beams and columns. The aim is to enhance the localization of SRC regulations in Taiwan with scientific research, establish proven techniques and design standards and develop sustainable and safe buildings.

2. PROGRAM REVIEW

The purpose in the structural design of SRC is to effectively combine the structural advantages of steel and reinforced concrete. The structure of carefully designed SRC possesses the advantages of both steel and reinforced concrete. The two structural properties can also be complementary to reach the goals of safety and cost-effectiveness. Since the 921 Earthquake, residents in Taiwan are demanding buildings with higher seismic-resistant property and safety. The government is also concerned about these issues. Additionally, to address sustainable buildings and to combine fire resistant and green effects, this study will be conducted in conjunction with “Development and Applications for Sustainable Concrete Materials” to gradually achieve the goals of using pre-cast concrete components, reducing the amount of binder materials used and adopting reusable materials.

With adequate design, SRC effectively combines steel and reinforced concrete into a higher quality structure. SRC is considered a composite material made up of concrete and steel. The thermal conductive characteristics between the two materials are different. This study addresses how stress distribution between the two and the dislocation of joints affect fire resistance of SRC. The tendency for reinforced concrete to burst under high temperature is also one of the focuses. Fig. 1 shows how steel and reinforced concrete join together. Fig. 2 and Fig. 3 show the “combined” concrete-encased SRC and how SRC and steel columns are joined together. The SRC shown in Fig. 2 is cross-shaped encased SRC while Fig. 4 shows encased concrete-filled SRC column. Designers may also choose concrete-filled tubular column (CFTC) instead of encased SRC column. Fig. 4 and Fig. 5 show how square and round tubular columns connect with the steel beams. For side columns, designers may consider the T-shaped encased SRC as shown in Fig. 6.

There's also a difference in the study of fire resistant structures. The Fire Prevention Master Plan focuses on reinforced concrete or steel structures. This new plan, on the other hand, takes into consideration the seismic and windy characteristics in Taiwan. Buildings have to be seismic-resistant while offering comfortable living, avoiding building sway caused by strong wind. Structures built with SRC are the industry's response to these issues. This type of buildings encompasses the composite character-ristics of reinforced concrete and steel, which are mostly used in low to medium levels. According to Building Technical Regulations, higher fire resistance rating is required for the lower levels. Therefore, the building components and structural fire resistance technology should be further explored. The focus should be on the stability of SRC under high temperature caused by flashover during a fire in order to provide a set of performance-based design method and establish warning systems to ensure the safety of the public and firefighting personnel.

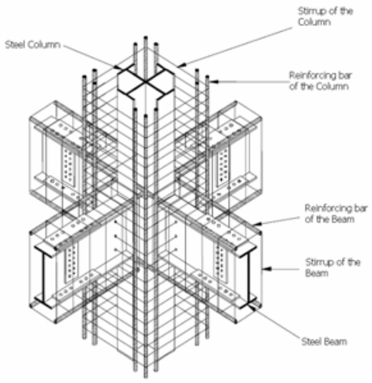


Fig. 1 The combination of steel and reinforced steel.

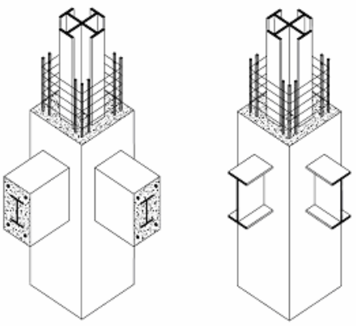


Fig. 2 The combination of cross-shaped encased SRC columns and SRC beams or steel beams.

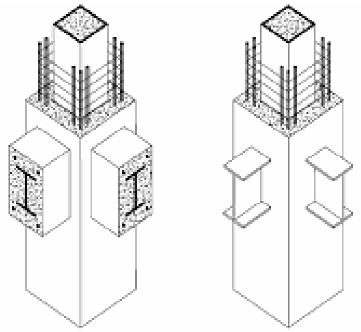


Fig. 3 Combination of encased concrete-filled SRC columns with SRC beams or steel beams.

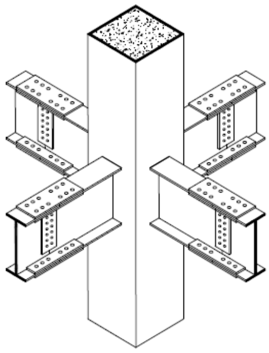


Fig. 4 Combination of square concrete-filled tubular column with steel beams.

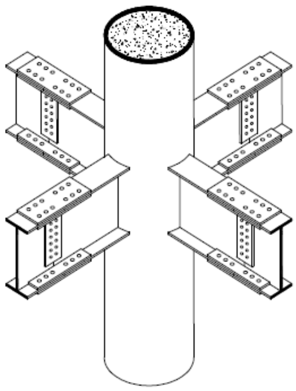


Fig. 5 Combination of round concrete-filled tubular column with steel beams.

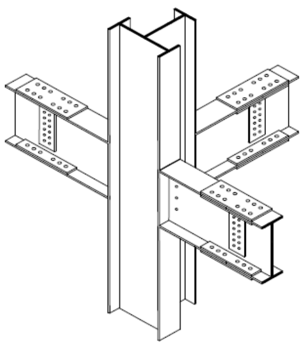


Fig 6. T-shaped encased SRC column.

3. PROJECT DETAIL

The goal of this study is to establish performance, design and verification standards for the structural fire resistance of SRC and to study current fire prevention regulations within Building Technical Regulations that are related to the fire proof qualities of SRC. Details are as follows:

3.1 Improve the fire safety of buildings with SRC

(1)Establish (Amend) the design and verify-cation standards for the fire resistance of SRC;
(2)SRC fire resistance design;
(3)Implement the standardization and localiz-ation of current construction techniques or performance-based fire prevention regu-lations;
(4)Establish safety evaluation and fire pre-vention design standards;
(5)Promote safety education and application of structural safety.

3.2 Research and develop technology or new materials that prevent structural destruction.

(1)Establish a databank for material properties of structural materials under high tem-perature;
(2)Improve structural loading during fire;
(3)Apply non-destruction evaluation in conducting post-fire structural safety monitoring;
(4)Research and improve on new materials for reused thermal conductive concrete.

In order to accomplish the goals listed above, the yearly program details to be implemented include:

I. Study on the high thermal conductivity and material property of SRC

When flashover occurs during a fire, the temperature could get higher than 600°C. The strength and stiffness of the beams and columns may be weakened due to high temperature. If the sub-assemblage cannot withhold any additional loading, it may cause a building to collapse completely or partially and therefore trap the rescue workers within or keep them from rescuing the victims. The material's dynamic characteristics are damaged by high temperatures. Therefore, the focus at this stage will be materialistic changes caused by high temperatures, such as fire response of thermal conductivity and distribution on SRC cross section, bolt pre-stress, shear resistance, weld pass, as well as RC and steel joints. In addition, after a fire occurs, data on the maximum temperature at the fire scene is often used as a reference to decide whether future structural reinforcement is required. Large-scale steel factories (such as China Steel) get their raw materials from a variety of sources. Some uses grit and some uses scrap metal. Therefore, the strength of steel of the same gauge also varies. To establish the databank for steel materials under fire and to establish design standards require the help and coordination of many agencies. The collaborative mechanism for establishing local databank is yet to be clarified. Current issues concerning this study are listed as follows:

(A) Study on thermal properties of SRC.

The purpose is to conduct experiments and analysis on SRC beams and columns with different cross sections heating options (two, three and four sides); types of concrete (regular, high-performance concrete such as filled concrete and high performance concrete); thermal distribution along the cross section of SRC, and establish concrete parameters as well as formulas for calculating the temperature for the cross-section when under high temperature to be applied toward fire prevention engineering and design. Thermal conduction rate of SRC cross-section would directly affect the structural fire response later on. With different surface heating (such as heating on two sides – corner column or heating on three sides – side beams and columns), the variation in the distribution of temperature field tends to cause asymmetrical structural deformation, even early deterioration. The experiment and analysis of modulus of elasticity, yield strength and ultimate strength will be conducted to establish quantitative graphs and figures to be included in the subsequent establishment of design and testing standards.

Ⅱ. Fire response of SRC components:

Structural behavior within a building is a complex issue. To conduct an overall study on the fire response of a composite framework may involve too many factors, which makes it difficult to narrow down the scope of research and reach the goals. Experiments conducted on composite structural behavior of beams, columns and floors require a longer period of time to thoroughly investigate and collect data on all aspects of the structural fire resistance. Therefore, it would be appropriate to experiment on the fire response of single component beams or columns with the CNS12514 standards to identify any fire influencing factors or destruction models of the component. Experiments on beam-column joints will be conducted after studies on fire response of components are completed for vertical integration and application to highlight the results of the study. During construction, SRC column system can be welded with full penetration and partial penetration welding. However, it is unclear whether the expected performance of partial penetration welding can be fully realized when the fire occurs. The structural component of SRC combines both reinforced concrete and steel. During a fire, the difference in thermal expansion coefficient and conductivity may cause cross-influence in the column deformity. Therefore, the placement of shear studs may influence the stress distribution and loading of the cross-section in a fire. The difference between the fire responses of reinforced concrete and steel will also be explored in this study to clarify the difference between fire prevention design in SRC and the previously mentioned two components. In addition, deformity test for structural components in a fire can serve as an important monitoring tool in the collapse of structures for rescue workers to understand the overall structure and safety prior to entering the fire scene. The equipment that is often used currently is non-contact thermal testing system. However, the flame, high temperature and smoke often affect the accuracy of this type of equipment or prevent it from getting a reading. Therefore, enhancing thermal testing equipments for structural deformity in a fire is essential. Related topics are as follows:

(A) The effects of welding methods and placement of shear studs on the fire response of SRC columns.

(B) Fire response of encased concrete-filled box columns.

Ⅲ. Evaluation on fire safety of SRC structure

As the number of aging structures increases, countries around the world are recognizing that structural health monitoring is an essential part of civil engineering, especially for structures that remain after composite disasters such as earthquakes and fire. Their seismic resistance may affect the planning and proceeding of post-disaster work such as relocation and rehabilitation of the victims. In the past 20 years, the concept of structural health monitoring is gradually being implemented and applied. Large amount of structural data has been collected through sensors placed throughout the structure. However, the dynamic behavior and seismic resistance of structures under fire have largely been ignored. In the past, structural safety for structures exposed to fire has mostly been focusing on static loading. A quantitative approach for evaluating future seismic resistance, however, has not been determined. Nor was one established for the evaluation of post-fire structural safety. Non-destructive testing (NRC) is a matured approach and has been widely applied in the field of architecture and civil engineering. It has been rendering good results on the evaluation of structural crack propagation, residual strength and structural integrity. NRC should also be used for establishing qualitative and quantitative safety evaluations on the strength and stiffness of structural materials such as steel concrete and reinforced concrete and serve as a reference for future reinforcement. It could be considered as part of the qualitative and quantitative safety evaluations on post-fire structural system as well. In addition, automated equipment will be adopted to enhance the convenience and consistency of the testing and to plan for data analysis, parametric studies and equipment building needed to highlight the overall results. To coordinate with the experiment on full scale simulator, the study will focus on the installation of physical structure with SRC, fire scenarios and experiment planning (including the establishment of testing system) to extend the results of the experiments from the current stage. Directions for data analysis and parametric studies needed are as follows:

(A) Boxed steel column - Fire response of composite materials in reduced steel beams.
(B) Encased concrete-filled boxed column – Fire response of composite materials in H-shaped steel beams.
(C) Evaluation of the structural fire safety of SRC with applied system identification.
(D) Study of post-fire seismic resistance of concrete-filled box column.
(E) The use of non-destruction evaluation in post-fire structural safety of CFT.
(F) Study on the verification techniques of fire prevention performance of concrete-filled box column.
(G) Evaluation of post-fire mechanical properties of steel joint bolt and weld pass.

Ⅳ. Design Standards

The research results from the early stages of the study will be implemented in construction regulations or standards with a focus on performance-based fire prevention regulation and the analysis of issues associated with current regulations and standards. The overall goals are as follows.

(A) Study on technical manual for performance verification of concrete-filled boxed steel column.
(B) Study on design standards for SRC fire resistance design – Fire prevention chapter.

4. EXPERIMENTAL STUDIES

The experimental program was conducted to study the fire resistance of three concrete-filled steel box columns. Specimens were axially loaded and subjected to fire to explore the axial deformation, axial stiffness, and mode of failure.

4.1 Test specimens

The experiment consisted of fire tests on three large-scale concrete-filled box column (CFBC) specimens, filled with high-strength self-compacting concrete which the thermal properties has been studied as presented in the literature (Kodur, V. K. R., and Sultan, M. A., 2003). The cross section of the specimens was 500 mm square and the length was 4350 mm. The structural steel box column was 500 mm square and 22 mm thick. As depicted in figure 7, the box column was fabricated by welding four steel plates through completely joint penetration weld and ultrasonic test was performed to confirm the welding quality. The average tensile strength of the steel plate was 372 MPa. Self-compacting concrete was used to fill the box column. The average concrete compressive strength was 59.7 MPa (for specimen CFBC-1) and 66.0 MPa (for specimens CFBC-2 and CFBC-3) when the specimens were tested. Two of the specimens, CFBC-1 and CFBC-2, had been sprayed with fire protection for two hours fire resistance rating. The average thickness of the fire protection was 15.3 and 14.3 mm for specimens CFBC-1 and CFBC-2, respectively.

4.2 Instrumentations and test apparatus

In order to measure the temperature distribution of the specimens, type-K thermocouples were installed at four sections of the columns as indicated in figure 8 which also depicts the numbering of the thermocouples. The fire test was carried out on a fire test furnace as shown in figure 9. The furnace was programmed to execute the specified fire time-temperature curve.

4.3 Test procedure

ISO-834 standard fire time-temperature curve was followed for the fire test. During the ISO standard fire test, axial compression force, corresponding to 64%, 63.6% and 35.8% of the calculated compression strength of the specimens based on the material strengths, was applied to three specimens CFBC-1 to CFBC-3, respectively, to study their behaviour and failure in fire. The axial compression force was 15,190, 15,680 and 8,820 kN for three specimens, respectively.

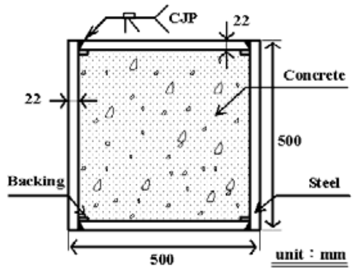


Fig. 7 Cross section of the specimens.

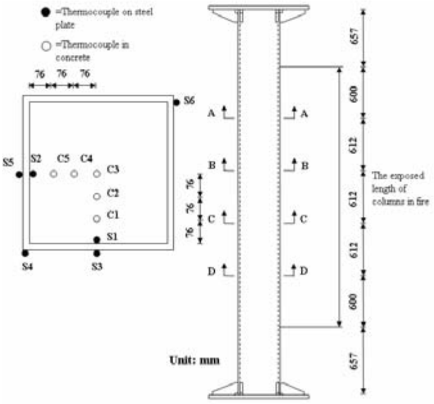


Fig. 8 Location and numbering of thermocouples.

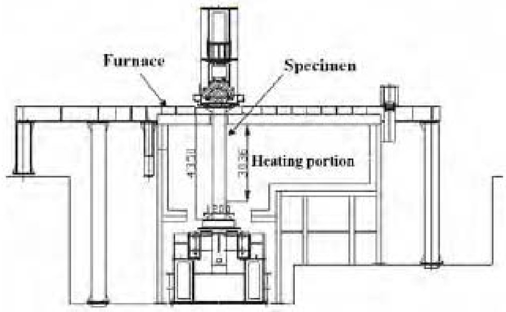


Fig. 9 Sketch of the furnace and test setup.

4.3 Specimen behaviour

Test results indicated that two specimens with two hours fire protection, specimens CFBC-1 and CFBC-2, can reach two hours fire resistance rating. During the specimen tested at elevated temperature, sound of the concrete bursting was continued heard which did not cause immediate failure of the specimen.

Specimen CFBC-1, with two hours fire protection, was subjected to two hours standard fire test and the highest temperature in the concrete was only 93°C while that in the structural steel was 287°C. The average temperature in the steel was 256°C. Figure 10 shows the measured temperatures as a function of time at cross section A. The elongation of this specimen was 3.8 mm. Figure 11 presents the specimen appearance after the test. Further, in order to explore the effect of the temperature on the specimen's structural behaviour, axial compression test was carried out again after the specimen had been cooled down. The axial load-axial deformation curve illustrated that the axial stiffness of the specimen was recovered and the specimen behaved linearly elastic within the range of the design load, as indicated in figure 12

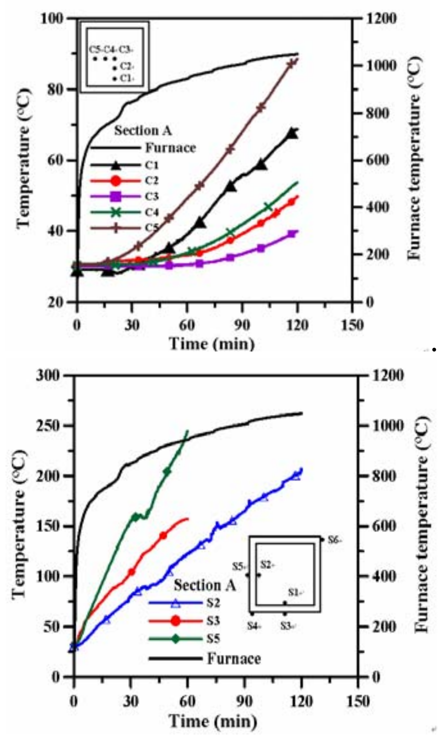


Fig. 10 Measured temperatures at cross section A of Spec. CFBC-1

Fig. 11 Spec. CFBC-1 at conclusion of the test.

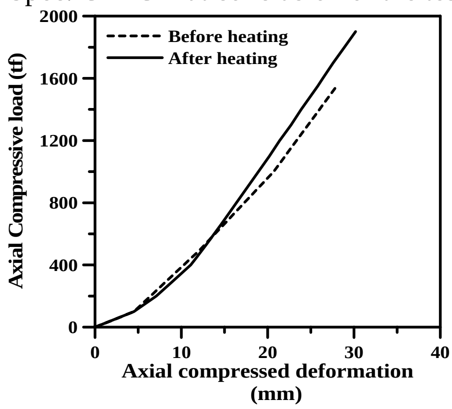
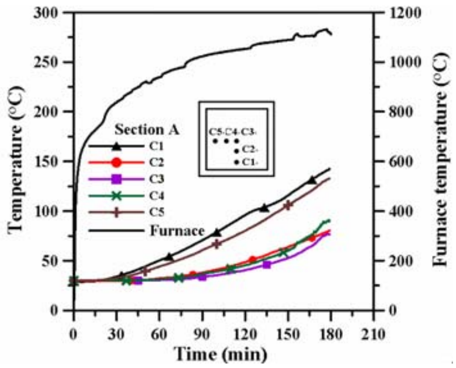


Fig. 12 Axial deformation of Spec. CFBC-1 before and after fire.

Test results of specimen CFBC-2 demonstrated typical column behaviour that the column elongated, reached maximum elongation, compressed and finally failed while subjected to elevated temperature. Specimen CFBC-2 failed at 179 minutes and the highest temperature in the concrete reached 146°C while that in the steel was 512°C. Figure 13 presents the measured temperatures for specimen CFBC-2. Specimen CFBC-2 reached to the maximum elongation of 4.0 mm. The final failure mode was the bulge of the column steel plate and concrete crushing, as shown in figure 14. Specimen CFBC-3 was tested without fire protection. As presented in figure 15, the highest concrete temperature was 470°C. The highest steel temperature reached 847°C and the average temperature in the steel was 758°C. The axial compressive load applied to this specimen was only 35.8% of the compression strength of the column which was even less than concrete strength in the ambient temperature. However, owing to the concrete bursting, specimen CFBC-3 failed at 43 minutes with maximum elongation of 17.3 mm. As demonstrated in figure 16, the bulge of the column steel plate occurred at several locations were also observed. After the specimen cooled down, the steel plate was flame cut, and the crushed concrete inside the steel plate was noticed.

Figure 17 presents the axial deformation versus fire time relations for three specimens and the distinct behaviour of specimen CFBC-3 was indicated. It is noted that the load ratio is a major variable affecting the axial deformation for the column. Structural steel plates provided the confinement for concrete exposure and prevented immediate failure of the column. Acceptable fire resistance of the concrete-filled box columns was also observed.



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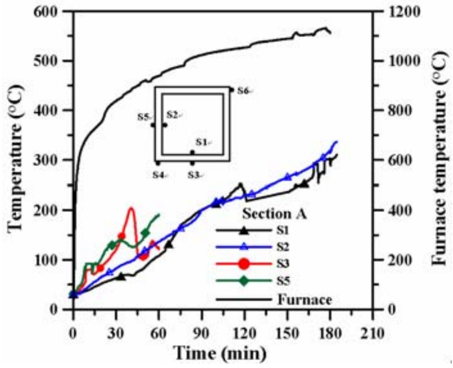
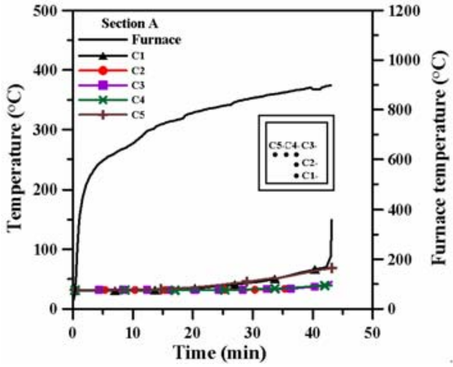


(b)

Fig. 13 Measured temperatures at cross section A of Spec. CFBC-2

Fig. 14 Appearance of Spec. CFBC-2 at conclusion of the test.



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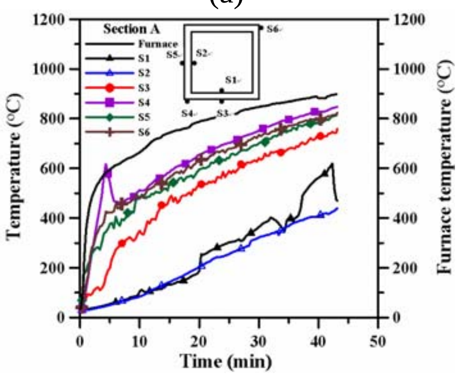

(b)

Fig. 15 Measured temperatures at cross section A of Spec. CFBC-3


(a)

(b)
Fig. 16 Appearance of Spec. CFBC-3 at conclusion of the test.

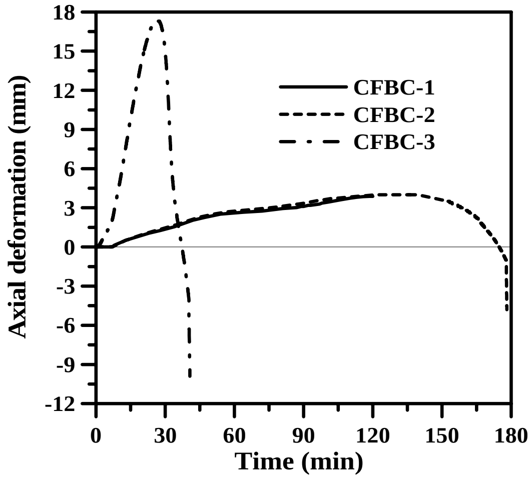

Fig. 17 Axial deformation versus fire time.

5. SUMMARY

1. Three research programs had been executed till now. “Material behavior of steel reinforced concrete in elevated temperature” conducted the basic material properties such as thermal conduction, specific heat and thermal expansion. “Behavior of concrete encased composite columns in fire” tested four CTBC under different loading ration and stud arrangement. “Effect of welding method on the fire behavior of concrete filled box columns” tested two CFBC with complete and partial penetration welded.
2. The following conclusions can be drawn from the results of the above test result.
   (1)For specimen CFBC-1 with fire protection did not fail within two hour fire exposure, axial compression test was performed after the specimen had been cooled down. The axial stiffness of the specimen was recovered and the specimen behaved linearly elastic within the range of the design load.
   (2)The failure mode of the concrete-filled box columns was the bulge of the steel plate and crushing of the outer concrete. Structural steel plates provided the confinement for concrete fire induced sapling and prevented immediate failure of the column.
   (3)No distinct temperature plateau around 100°C in concrete due to the evaporation of water in concrete was observed in these tests owing to the fact that the concrete was fully confined by the structural steel plates.
3. In 2013, more than 12 full scale CFBC specimens are going to be tested in fire. The variables have been considered with slender ration and optimized steel section for fire resistance. The 1 hour fire resistance of the CFBC without fire proof will be the research goal trying to achieve.

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