Post-fire resistance of concrete filled steel tube columns

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Abstract. Basically, columns of CFST (Concrete-filled steel tube) are a common technique to increase the carried compressive forces in the frame. These columns are very effective method of composite building. The behaviors of these columns due to several various loading types have been well studied. This study investigated the CFST columns in order to advance their post-fire resistance. A standard fire exposure was used to examine columns without and with concrete. In order to study their performance after fire, fire exposed samples and specimens without fire exposure in total 6 samples were examined by concentric compressive load to the failure. Samples of CFST column were cast by high performance self-compacting concrete. The obtained results showed that concrete with steel tube provides very high post-fire resistances. Generally, certain configurations achieved post-fire resistances significantly higher than that CFST samples without fire exposure. The results of this work supply novel insights and suggest cost effective solutions to enhance the execution of concrete-filled steel tube columns that subjected to ambient temperature and due to fire exposure.

Keywords: Experiments; CFST columns; Post-fire resistance; Fire exposure.

1. Introduction

The greatest part of the design concerns related with projects that require challenging design can be eliminated using compression members of CFST. Combined actions and confinement effects provided by CFST members ensure that essential parts work properly when leveraging the strength of materials under very high static dynamic and compressive loads earthquakes [1,2]. The concept of CFST supports the utilize of ultra-high or high strength concrete by suppressing quite brittle kind of failure of such concretes that take place in columns of unguarded reinforced concrete [3,4]. Due to their proper properties, the compressive members of CFST columns was used widely different fields, they can be used in skyscrapers, tunnels, buildings and bridges of long spans.

Fire is considered as critical design aspect that should be earnestly treated, specifically in vast constructions. Exposure to fire temperatures can negatively influence the strength and durability of concrete [5-7], appearance and structural performance [8-11]. As this type of columns are commonly used in large and high performance constructions, the strength of these members when they exposed to elevated temperatures should be estimated for integrity. The external casing of CFST members has the ability to lessen the damage of concrete core due to the temperature raising by two aspects. Firstly, the concrete is covered by the steel casing and this minimizes the increasing of temperature rate [12]. Secondly, the concrete confinement by the used casing eliminates the concrete spalling that happens in uncovered columns [13-15].
Additionally, the useful effect of concrete core on the tube casing should be showed. The concrete core supplies the heat sink influence and leads the tube casing to be cooler than hollow steel tube underwent to the fire [14,16,17]. Furthermore, due to several previous experimental studies, one can conclude that CFST with circular shape show higher resistances of fire and post-fire as compared with that of counterparts of square section with the same area [18-20]. By using a proper design procedure, the requirement for outer fire protection of the steel casing in the columns of CFST can be eliminated [19,21]. There are several longitudinal investigations that underline the advantages of CFST stub column configuration and study the behavior of these columns when they are subjected to standard fire loadings.

2. Experimental program

2.1. Material properties

Mixtures of self-compacting concrete (SCC) of high strength, which is classified as high performance concrete (HPC), was used in this study to cast the circular casing. Basically, SCC fulfills the required strength, durability and strength due to the intensive loading. Nevertheless, there are rising worries related with the post-fire performance of such kind of concrete [22]. Furthermore, as aforementioned, also there are controversial illations related with the post-fire behavior of (HPC) according to variations in the procedures of the test and mixed ingredients. Table 1 shows the mix design of the used concrete. The confusing effect of the cementitious material, such as silica fume, in the post-fire behavior was eliminated as the used binder was cement. At the ambient temperature, the determined mean compressive strength of cylindrical samples with dimensions of 100x200 mm was (83.6 MPa). Samples pure concrete cannot be underwent to the fire exposure for determining the post fire characteristics. That is because, in presiding experiments, samples pure concrete, which subjected to severe temperature increasing, showed behavior of spalling and led to significant integrity worries. Just one type of casing was depended to identify the influence of steel on post-fire behavior of CFST samples. The diameter of steel cover is 114.3 mm, while its thicknesses was 2.68 mm. typically, this range represents most of the actual applications of CFST. In order to knowledge the mechanical performance of materials without and with fire exposure, tensile testing samples of steel casing were extracted according to [23,24].

| W/C  | Mix design proportions kg/m3 |  |  |  |  |  |
|------|-------------------------------|---|---|---|---|---|
| 0.3  |                               | C | W | HRWR| CA | NS | CS 0.3–2mm | CS <0.3mm |
| 590  | 177                           | 5.96 | 835.5 | 668.4 | 111.4 | 55.7 |

Table 1. Mix design of high strength SCC

| Tensile specimens | Without fire exposure | Fire exposed |
|-------------------|-----------------------|--------------|
|                   | 30 min (633 °C)       | 60 min (853 °C) |
| From steel tube (<2.68 mm) | 309/418 MPa | 275/357 MPa |
|                   | 222/294 MPa           |

Table 2. Yield strength of the steel tubes

Tensile coupon specimens that were cut from the steel tube with and without fire exposure are depicted in Figures 2 and 1, respectively. Fire subjected tensile samples were storied inside the furnace with CFST samples and underwent to a standard fire increasing. After the accomplishment of the fire exposures process, temperature of tensile samples were cooled till they reach the temperature of the room, then the tension experiments were carried out. Table 2 gives the yield strength of the steel casing. Figures 3 to 5 show the curves of stress-elongation that obtained from the conducted tensile experiments.
Figure 1. Tensile coupon samples that were cut from the steel casing without exposure of fire

Figure 2. Tensile coupon samples that were cut from the steel casing after exposure of fire

Figure 3. Stress-elongation curves of Coupon experiments for 114.3×2.68 mm prior exposure of fire

Figure 4. Stress-elongation curves of coupon experiments for 114.3×2.68 mm after fire exposure of 30 min
Figure 5. Stress-elongation curves of coupon experiments for 114.3×2.68 mm after fire exposure of 60 min

2.2. Column specimens
By using steel tubes of 270 mm length, all samples were prepared [25]. Six samples were prepared using 2.68 mm tube thickness. The characteristics of the used tubes are listed in Table 3. Basically, the characteristics of the used tube were selected to permit different types of failure behaviors to happen under compressive loads. Table 3 also presents the characteristics and details of the stub columns of CFST.

Employed column samples naming order in Table 3 shows the strength of concrete (fc) and the diameter of circular steel tube (D), respectively. The labeling order of sample involves the kind of the column and the total time of exposure to the fire. Additionally, for kind of samples, the utilized letters are H and C. C indicated the control columns of CFST, while H indicates hollow tube. As an example, C-F60 means the columns of CFST with core of concrete subjected to fire exposure extended to 60 min. prior to concrete pouring, the lower and upper faces of the used tubes were machined in order to ensure contact of ultimate uniformity with the loading heads of the testing apparatus [25,26]. To obtain quite reliable experimental results, providing the sample ends uniformity and flatness is an important stage in the testing procedure of tube sample [2]. The tubes machining process is showed in Figure 6. For leveling purposes of the samples before the test, the upper (10 mm) of used tubes were kept without concrete.

| Specimens | Fire dura. (min) | fy (MPa) | fc (MPa) | Nexp(kN) |
|-----------|-----------------|---------|---------|---------|
| 42.65-H   | –               | 309     | –       | 291.22  |
| 42.65-C   | –               | 309     | 83.7    | 1130.61 |
| 42.65-H-F30 | 30         | 309     | 83.7    | 258.13  |
| 42.65-C-F30 | 30       | 309     | 83.7    | 1133.99 |
| 42.65-H-F60 | 60        | 309     | –       | 209.60  |
| 42.65-C-F60 | 60        | 309     | 83.7    | 802.75  |
2.3. Heat treatment

By using a specific electrical furnace at the Structural Laboratory of Gaziantep University, Turkey, the prepared columns were heated in order to be dry, this took place after month of water curing. Couple of samples were dried for entire two days at 100 °C prior to the application of the high. It is important to remind here that the increment of the fine materials in the prepared mixture significantly minimizes the contact between the pores and minimize the porosity which in turn enhances the growth of pore water pressure. Thus, the preheating to hundred °C minimizes the free water in the pores of concrete but does not eliminate it all.

Figure 7 shows the used furnace, its dimensions were 620×1300×1360 mm, its capacity reaches to 1200 °C. In order to guarantee a homogenous application of the heat over the tested columns, heaters are fixed on five sides of the furnace except its floor. Type-K thermocouples was used to measure the temperature of the furnace. In order to minimize the heat transfer to the interface of steel-concrete from the ends of columns, the end faces of the tested columns were enveloped by a mineral wool layer prior to the fire exposure as displayed in Figure 8.

The temperature rising of the used furnace was controlled to be approximately compatible with the smouldering fire curve, typically as displayed in Figure 9. For the fire proceeding steps, the curves get closer. As an example, after 1 hour, the temperatures were 885, 945 and 927 °C for EC smouldering fire curves, ISO 834 fire curves and ASTM E119, respectively [27, 28]. The EC smouldering fire curve was previously depended for study purposes [29], they also depended in CFST fire studies [30]. In this study, samples were underwent to different two levels of (30 and 60 min). By using thermocouples type K, temperatures at midlevel of core concrete and of the external face of the steel casing were measured constantly. After the exposure of fire, the furnace was shut down, the temperature of samples was reduced naturally due to opening of the furnace ventilation door. When room temperature was obtained, the upper face of columns was leveled by epoxy of high strength. A scheme of slow rate loading of displacement-controlled was depended up to the experiments end. By using of very sensitive LVDT-based displacement transducers, samples end shortenings were recorded constantly.

2.4. Test setup and instrumentation

A hydraulic compression device with capacity of 2500 kN was used to perform the experiments. The sample was placed in the device with a vertical position. A steel block, which has a cross section greater than that of the sample, was placed between the upper platen of the device and the sample. Figure 10 shows a testing device, which operated with a loading rate of 0.5 mm/min for all the tested samples. Additionally, LVDT 1 and 2, which were used to observe end shortening of steel tube, are shown in the same figure.
3. Compression loading vs. end shortening behavior

Compressive strengths of the prepared samples are listed Table 3. The curves of end shortening of the prepared columns of CFST against the applied loading are showed in Figures 11 and 12. One can notice that sample of H-F3, which is subjected to 30 min fire exposure, maintained approximately 88.6% of its compressive strength. Sample of H-F60 maintained about 72% of the compressive strength. This is attributed to the steel casing capability to recover great part of the compressive resistance after the exposure of fire. Moreover, it is essential to mention that is no great variation in initial stiffness performances for the hollow steel tubes sections. After the exposure of fire, the stiffness of sample without exposure of fire is quite close to that of the hollow tube, as shown in Figure 11.

Figure 7. The used furnace

Figure 8. Sample covering by a layer of mineral wool

Figure 9. Measured temperatures and Fire curve

Figure 10. The tested sample

Figure 11. Compression loading curve and end shortening curve of hollow casing
Samples of CFST showed quite interesting compression performances. As shown in Figure 12, sample after half hour of fire exposure exhibited compressive strength higher than that of samples without exposure of fire. This enhancement after the exposure of fire is quite important, it can be attributed to several factors. Basically, steel with 30 min fire exposure mainly encounters 11.4% strength degradation, as shown in Figure 11.

According to the sink effect, in members of CFST, the interior face of tube remains cooler than interior face of hollow member. Thus, the degradation degree in the steel tube strength is small in member of CFST. Actually, this does not illustrate individually the strength enhancement of the column. Basically, the concrete behavior can be considered as the essential source of improvement like that. For fire exposure of half hour, the concrete core temperature reached to (334 °C). A concrete fire study emphasizes that unlike the concrete of normal strength, fire insulting influence on remaining resistance of HPC does not affect up to 400 °C; therefore, the enhancement in HPC remaining compressive strength is obtained after exposure of fire up to 400 °C [31, 32]. In previous studies, compressive strength enhancements for HPC reach to 47% can be achieved after exposure to the fire [33]. Such kind of compressive strength enhancement is mainly depended on tobermorite gel generation, it is major factor of the HPC mechanical characteristics [32, 33]. Additionally, free water evaporation leads paste of cement to consolidate, this increases the forces of surface between particles of cement gel, providing most consolidated structure [32]. Such conclusion is very important for members of CFST, it provides extra time for extinguishing of fire and the required evacuation before collapse of building. Moreover, it is noticed that the initial stiffness decrement of the columns after half hour of fire exposure is slight, as displayed in Figure 12.

As shown in Figure 12, hour of fire exposure grows prejudicial effects on the stiffness and compressive strength of the samples. Basically, the after fire properties of both concrete and steel are responsible for the deterioration of compressive resistance for the samples. It is so clear that the steel yield strength considerably minimizes when it is subjected to fire of one hour, as listed in Table 2. Furthermore, the concrete midlevel approached to about (749 °C) after exposure to the fire of one hour. When the temperature becomes higher than 400 °C, calcium hydroxide decomposition happens inside the concrete [31]. The bond between the paste and aggregate reduces, as the evaporation of water contracts the paste and the increasing of temperature expands the aggregate [32].

4. Failure modes
The failure modes for the tubes and the CFST samples are displayed in Figures 13 and 14, respectively. Generally, the mode of failure mode for the hollow tubes can be considered as local buckling associated with yielding of material. As shown in Figures 13 and 14, the local buckling in hollow casing is higher than that of CFST samples. This local buckling dominant mode of failure in hollow casing prevented the compression loading against end shortening of these samples to exhibit hardening manner, as shown in Figure 11. Steel casing with concrete (CFST) showed hardening.
manner in the curves of compressive load and end shortening, as the failure for these casings is majorly governed by yielding instead the early buckling, as shown in Figure 12. Samples of CFST that prepared using steel casing exhibited concrete crushing failure modes that associated with local buckling of the casings. Notwithstanding, the concrete crushing was in the form of diagonal shear failure as displayed in Figure 14. Such performance emphasizes that casings cannot supply sufficient lateral restrain for concrete. Consequently, the concrete failure governs the mode of failure for CFST samples.

5. Conclusion
Actually, studies that investigate the performance of CFST columns has continued throughout the previous four decades, and the resistances these members under different static and dynamic forces have been studied precisely. Nevertheless, the perception of the performance of CFST columns after the exposure of fire remains undetermined as there are few researches about this aspect. Basically, rebuilding expenses of a burnt out building are significantly higher than that of any rehabilitation. The post-fire strength of the members should be determined when the process of rebuilding is neglected. The main aim of this study is to assess the effect of the concrete that cast in steel casing on both static and post-fire strengths of CFST columns. For this purpose, self-compacted high performance concrete was used in order to study the performance of efficient CFST columns rather than standard applications. The following points are the main conclusions:

- After half and one hour of fire exposure, hollow casings exhibited superior in the recovering of compressive resistance.
- For the samples of CFST, fire exposure of 30 min increased the compression resistance increments, this is due to the appropriate performance of HPC under 400 °C. However, fire exposure of one hour decreased the compression resistance for the tested samples. Less deterioration and greater confinement effect of the CFST played an essential role in this behavior and gave to smaller resistance loses.
- Cold-galvanized steel casings were subjected to stress relieving throughout the exposure of fire, this relieving provided the tested columns a higher ductility as compared with that of the samples without exposure of fire. Moreover, the results of straining displayed that exposure to the fire has a negative effect on longitudinal stiffness of samples. On the other hand, it has approximately no impact on the lateral stiffness, the lateral strain recordings suggest that the lateral stiffness of the specimens are not influenced from fire exposure.
- All the obtained conclusions of this work are depended on the experimental results that majorly represented specific limits of material characteristics, geometrical details and one way of exposure to the fire. Basically, it is necessary to provide more experimental data about the CFST columns with various characteristics to cover this knowledge and also to address the
generalized performance. When the specimens are exposed to ASTM E119 and ISO 834 fire curves, different results can be obtained.

6. References

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