Behaviour of Post Heated Reinforced Concrete Columns

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Abstract. Fire represents one of the most severe environmental conditions experienced by the reinforced concrete (RC) structures. The aim of this study is to examine the behaviour of post-heated RC columns. There were two different geometries of RC columns were cast, i.e.: square and circular. Eight RC columns were heated at 600°C for two hours and tested under axial compression load. The main variables investigated were column’s geometry and heating temperature. The test results showed that the mechanical properties i.e.: load carrying capacity, elastic stiffness and ductility of RC columns significantly affected by heating temperature. Column’s geometry highly influenced the loss of water of post heated RC columns, however, less significant on the mechanical properties of post heated columns.

1.0 Introduction
Concrete is the most commonly used construction material worldwide. It is mandatory for concrete material to be used in construction of building and bridge structures to fullfill the fire safety requirement as specified by relevant code such as Eurocode 2 [1]. This is because fire represents one of the most severe environmental conditions experienced by the reinforced concrete (RC) structures such as buildings and bridges. Exposure of RC buildings and bridges to an accidental fire may result in cracking and loss of bearing capacity of their major components such as beams, columns and slabs. RC columns are critical elements in many structures as local member failure may lead to partial or complete collapse of the structures. There were lot of studies’ and literatures’ findings and discussion on the effect of high temperature on mechanical properties of plain concrete [2,3,4]. In general, it is well acknowledged that concrete posses the best fire resistance properties compared to other building construction material such as steel and wood. This excellent property is due to its constituent material, i.e.: cement and aggregate. When they were chemically combined, they will form an inert material that has low thermal conductivity, high heat capacity and slower strength degradation with temperature. However, under prolonged exposure to high temperatures, the mechanical strength of concrete and the properties of steel reinforcement bar embedded would be reduced. Chan et al. [5] reported that the compressive strength of concrete may decrease up to 50% when the concrete is exposed to more than 600 °C. At 800 °C, the residual compressive strength of the concrete is only 20% of its original value. Furthermore, normal-strength concrete experiences a sharper loss in tensile splitting strength than compressive strength at 600 °C. Exposure to high temperatures may also change the pore structure of concrete through pore structure coarsening, which leads to increased permeability and reduce its durability. Later, the cumulative pore volume in normal-strength concrete will increase twice. At temperatures higher than 600 °C, extreme C-S-H gel dehydration and pore structure will further coarsening and losing strength [5].
On the other hand, the experimental studies on the behaviour of post-heated RC members especially column were very limited. Yaqub and Bailey [6] found that the explosive spalling occurred in some of the circular columns and no spalling observed in square columns even though they were cast from exactly the same batch of concrete. All heated and non-heated columns failed at the top of the columns due to stress concentration in this region. In both square and circular un-heated columns, the failure was notably brittle, sudden and explosive in nature. The failure of both post-heated square and circular columns was more gradual showing ductile behaviour. In terms of strength, the square columns lost 44% of their compressive strength after heating and circular columns lost 42% of their compressive strength.

Note that, in experimental works done by Yaqub and Bailey [6], the samples were heated to 500°C and when the average temperature of furnace reached 500°C, the furnace temperature was kept constant until the measured temperature at the centre of each column reached 500°C. This unusual heating method does not represent the actual heating process of structural elements during fire event. In Eurocode 2 [1] there are temperature profile charts for designer or engineer to calculate the load bearing capacity of heated reinforced concrete member. These temperature profile charts be evidence for that the temperature inside the heated RC element is lower than outside temperature. Therefore, this study investigates the behaviour of post-heated RC columns under common heating process.

2.0 Experimental Works

In this experimental works, eight specimens of RC column were prepared with the height of 500 mm. Half of them were square with 150 mm cross section and another half of them were circular in cross section with 155 mm in diameter. The square and circular columns were reinforced with four and six 10 mm diameter longitudinal reinforcing deformed bars, respectively, having 1.40% and 2.50% of longitudinal reinforcement ratio. All bars were evenly distributed throughout the cross section of the columns with 25 mm cover to the main reinforcement. The columns use 6 mm diameter bars as link bars spaced at 100 mm centre to centre. In the circular columns a 60 mm overlap were provided to the link bars at the ends without any extension into the concrete cores. The measured yield strength of the longitudinal and transverse reinforcement used in all columns was 693 MPa and 476 MPa, respectively. The arrangement and fixing of reinforcing steel in square and circular columns is shown in Figure 1. The square and circular columns were cast vertically using wood and Polyvinyl Chloride (PVC) pipe as formwork, respectively, as shown in Figure 2. For compaction, a hammer was used. One column was cast at a time from one batch of concrete along with three cubes of 100 mm size to monitor the concrete strength. After cast, all column samples were covered with plastic sheet for 14 days and after that were left in laboratory environment until the day of testing [6].

![Figure 1. Reinforcement arrangement in square and circular columns](image)

The concrete mix comprises of sand, coarse aggregate (maximum size 10 mm) and Ordinary Portland Cement (OPC). The mix proportion was designed to achieve a target compressive strength of 30 MPa at 28 day as in accordance to Building Research Establishment Method [7]. The concrete mix comprised of 550 kg/m³ cement, 250 kg/m³ water, 745 kg/m³ sand and 805 kg/m³ limestone aggregate. The maximum size of aggregate was 10 mm.
In this study, the reinforced concrete column specimens were heated at 600°C inside the gas furnace with internal dimension of 1 m x 1 m x 1 m. The furnace was programmed to heat the specimen with heating rate of 150°C/h to the desired temperature of 600°C and then to hold that temperature for the required duration of total heating of two hours. The furnace was then switched off and allowed to cool slowly to ambient. Typical heating profiles for the thermal exposures are shown in Figure 3. Then the samples will be loaded under concentric loading using a hydraulic jack with capacity of 1000 kN. The load will be applied using load control at a rate of 1kN/s as used by Yaqub and Bailey [6]. During the loading process, the axial load, vertical and lateral displacement as well as strain were measured at mid height of the samples. For that purpose, two 20 mm linear variable differential transducer (LVDT) and two 120mm strain gauge were installed in vertical and horizontal direction. From the measurement, the load-displacement curve in vertical and horizontal direction was plotted and three important mechanical properties of reinforced concrete column i.e. peak and ultimate load, stiffness and ductility were obtained.

![Figure 2](image)

**Figure 2.** (a) Formwork (b) Sample during casting (c) Experimental setup

![Figure 3](image)

**Figure 3.** Heating profiles

### 3.0 Result and Discussion

Compression test on unheated and post-heated cube samples showed that the residual strength of the post-heated concrete cube sample is about 53% of its pre-heated strength in which the compressive strength of pre heated and post heated samples were 37.1 MPa and 19.7 MPa, respectively. This finding is parallel with Chang et al (2006) [8] who reported that the residual strength of concrete heated at 600°C was 55% of its pre-heated strength. The unheated and post-heated reinforced concrete columns were weighed and it indicated that the lost of weight were about 5.93% and 8.41% which represent the loss of water about 1.65 and 1.93 kg for square and circular column, respectively, after they were heated at 600°C for the duration of two hours. During the heating process, it can be observed the water flow out from the furnace. Despite of higher surface area for square column which
is about 0.35 m$^2$ compared to 0.27 m$^2$ for circular column, square columns experienced less of water lost compared to circular columns. This is because the farthest point from the surface in square column (distance from the center point of column to the corner of the column) is farther than circular column. This make the water at center point of square column requires longer time to reach the surface of the column.

Both circular and square columns were tested under axial compression load in a similar manner. A typical crushing failure mode was observed in all columns. All unheated and post-heated columns failed at the top of the columns due to stress concentration at this part as shown in Figure 4. In both unheated circular and square column, the failure was brittle, sudden and explosive. The failure of both post-heated square and circular columns was more gradual indicating ductile behaviour. These observations are parallel with the load-displacement curves and stress-strain curves obtained from the compression test as shown in Figure 5 and Figure 6, respectively. Note that, USC, HSC, UCC and HCC are abbreviation for unheated square column, heated square column, unheated circular column and heated circular column, respectively. Number 1 and 2 represents first and second specimens. For example, UCC 1 is first unheated circular column specimen.

Furthermore, it can be seen from Figure 5 that the square columns lost 51\% of their strength after heating to 600°C for two hours and the circular columns lost 49\% of their strength. It exhibits that the lost of strength for circular and square columns almost similar even though the exposure area of square column is 30\% greater than circular columns. The lost of strength obtained in this study was slightly higher than result obtained by Yaqub and Bailey [6] due to higher heat temperature applied in this study. Moreover, the lost of strength for both columns also nearly similar with compressive strength reduction of concrete cube as shown in Table 1. Therefore, the residual strength of post-heated RC columns can be estimated using numerical or finite element method provided the compressive strength of concrete is known.

![Figure 4](image1.png) **Figure 4.** Axial compression failure of un-heated square and circular columns

![Figure 5](image2.png) **Figure 5.** Load-displacement curve for circular and square column
Figure 6. Axial stress versus axial strain and axial stress versus hoop strain

Figure 6 shows the axial and lateral or hoop strains (lateral strains in case of square columns or hoop strains in case of circular columns) of unheated and post-heated square and circular columns. It can be seen from Figure 6, that the axial strains and lateral or hoop strains in post-heated square and circular columns were significantly higher compared to unheated square and circular columns at the same stress level. This is due to the micro-cracking and greater porosity in post heated concrete as shown in Figure 7. Figures 5 and 6 depict the ductility of post-heated square and circular columns greater than unheated columns. This is due to the enhancement in the ductility of reinforcing steel upon heating and cooling [9].

Figure 7. Post-heated square column

Table 1. Secant Stiffness

| Sample        | Average Secant Stiffness (kN/mm) | Loss of Stiffness (%) |
|---------------|---------------------------------|-----------------------|
| Square Column |                                 |                       |
| USC           | 58                              | 45.24                 |
| HSC           | 32                              |                       |
| Circular Column |                                |                       |
| UCC           | 46                              | 57.44                 |
| HCC           | 19                              |                       |

Table 1 shows the average stiffness and percentage of stiffness loss of square and circular columns. The secant stiffness of all columns was calculated by dividing the ultimate failure of axial load ($P_u$) by the maximum vertical displacement ($\Delta_u$) measured during testing as shown in Figure 8. This value of secant stiffness may not be considered the overall actual stiffness of all columns, but it does provide a useful measure to compare the stiffness of unheated and post-heated RC columns. Table 1 demonstrates that the stiffness of square and circular columns significantly reduced when exposed to $600{\circ}C$ for two hours. This is attributable to development of micro-cracking and reduction in stiffness of concrete after heating. Voids in micro-structure of the concrete define its porosity and have significant influence on its stiffness. The porosity of concrete depends on factors related to the water-
cement ratio and on the level of internal micro-cracking. On heating, the porosity of concrete is increased due to loss of moisture and due to the development of internal micro-cracking, which results in stiffness loss [6].

Figure 8. Secant stiffness

Since the reduction of stiffness is quite significant as shown in Table 1, it is suggested that prior to repairing the fire damaged concrete structures, it is very important to consider deformations and stress redistribution in undamaged and fire damaged of reinforced concrete structures. In order to improve the stiffness of fire damaged columns it is proposed to use high strength concrete as repair material [9]. However, further study is required as there was no literature proved that the high strength concrete may restore the stiffness as well as compressive strength of fire damaged reinforced concrete columns. Based on numerical study conducted by Leonardi et al., [10] high strength fiber reinforced concrete jacket may improve the compressive strength of fire damaged reinforced concrete columns, but, no results on stiffness were revealed. Another findings have shown that the stiffness improvement can be made by recurred the fire damaged reinforced concrete members using water [9].

4.0 Conclusion

Based on the results and observation of this experimental works, the following conclusion can be drawn:

i) The strength of the square and circular columns was reduced by the 51% and 49% respectively after heating up to 600°C for two hours this is mainly due to the dramatic loss of compressive strength of concrete cube at about 53% of its original value.

ii) The ductility of post-heated square and circular columns greater than unheated columns. This is due to the enhancement in the ductility of reinforcing steel upon heating and cooling (Haddad et al, 2011).

iii) The reduction of stiffness is significant, therefore, it is suggested that prior to repairing the fire damaged concrete structures, it is very important to consider deformations and stress redistribution in un-damaged and fire damaged parts of reinforced concrete structures

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