Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

A REVIEW ON REPAIR OF FIRE-DAMAGED CONCRETE COLUMNS WITH FIBRE REINFORCED POLYMER

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ABSTRACT

This paper presents a review on repairing fire damaged reinforced concrete columns with externally bonded Fibre Reinforced Polymer (FRP) reinforcement. When a reinforced concrete is subjected to fire, even after the most severe fire, repairing the fire damaged reinforced concrete structures is the better choice rather than demolishing them. Several repairing methods have been extensively used in repairing damaged reinforced concrete columns such as concrete and steel jacketing, steel caging, steel encasement, steel plates with steel stiffeners etc., however this paper is focussed on repairing fire damaged RC columns with FRP fabric wraps. It highlighted the effect of strength, ductility, and stiffness of FRP repaired fire-damaged RC columns. Eventually, the paper also addressed some of the drawbacks of using FRP as repairing material.

Keywords: *Repair, Fire-damaged, FRP*

1. INTRODUCTION

Fire is recognised as one of the most severe environmental conditions that the structures might face during its lifetime [1], although the probability of the structures to be caught in fire is slim. However, all the codes and standards have a provision for fire to provide fire resistance that exceed or at least equal to severity imposed by fire [2]. The most notable fire incident that caught the eyes of the world is the WTC fire incident that occurred on September 11, 2001. Prior to WTC fire incident, researchers have focussed much attention on fire protection for steel structures however, on reinforced concrete structures have not significantly addressed. Cardington fire test has been conducted in the mid-1990s by British Steel and Building Research Establishment to investigate the behavior of eight storey steel framed building under fire. This fire test has been marked the climax of steel structures in the construction industry [3]. However, after these incidents, the attention has been focussed in the direction of preventing the collapse of steel and reinforced concrete structures rather than reducing the cost of fire protection [4].
In Malaysia, according to Fire and Rescue Department Malaysia (BOMBA), in 2009 alone, several fire incidents have been reported in motorised vehicles and structural fire as shown in Fig. 1. Among the 3898 incidents, more than 3800 incidents have been reported in structural fire. From Fig. 2, it can be seen that more than 50% of fire accident occurred in residential buildings and another 24% in factories and shops. However, other fire accidents such as office buildings, warehouses, etc are relatively less than the residential buildings and factories. Sometimes the fire damaged residential buildings are demolished whereas, as for shops and warehouses', they are economically repaired. According to [5], even after the most severe fire, the best choice is to repair and preserve the damaged structures rather than demolishing them.

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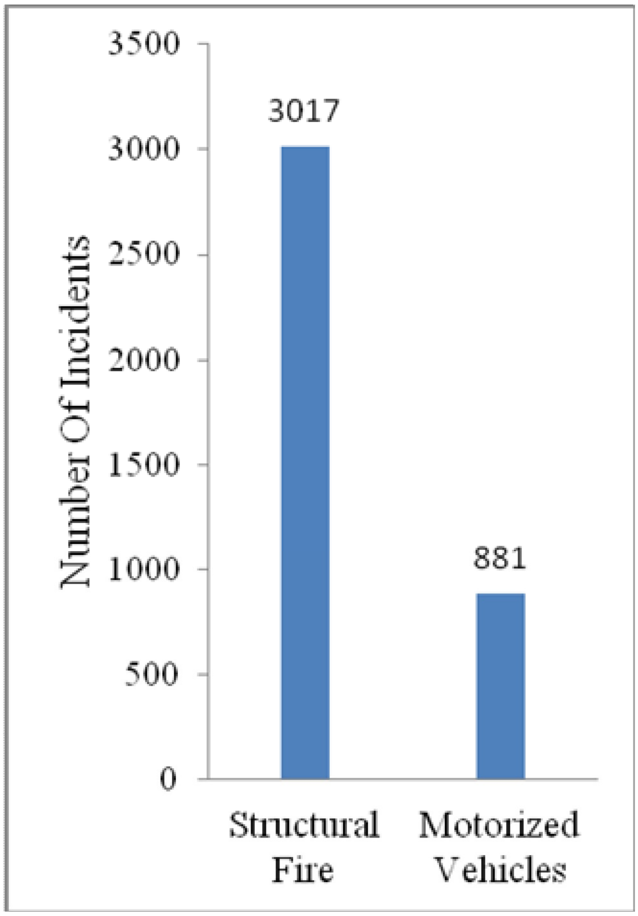

Fig. 1 Structural and motorized vehicles fire investigations for year 2009 (Source: Fire and Rescue Department Malaysia (BOMBA))

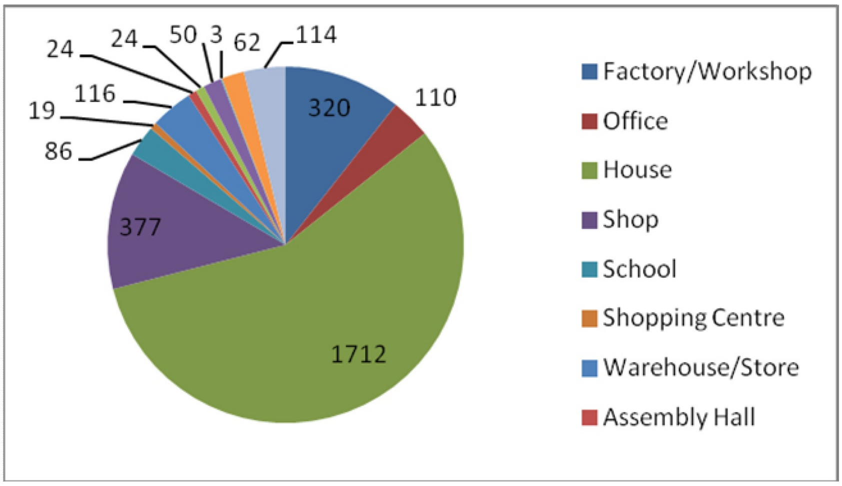

Fig. 2 Pie chart for structural fire incidents according to building categories for year 2009 (Source: Fire and Rescue Department Malaysia (BOMBA))

Over a few decades, several researchers have been focused much on repairing and retrofitting of fire damaged reinforced concrete and steel members. Repairing is required when a structure has been damaged by natural calamity and unexpected incidents such as earthquake and fire. However, retrofitting is a condition when a structure is modified or strengthened (usually for old structures) before it is damaged [6]. However, sometimes researcher [7] used retrofit that conveys the same meaning of repair. In this paper, the repair and retrofit refers to the definition given by [6], unless otherwise stated. Several investigations have focussed repairing and retrofiting of reinforced concrete structures, however limited experimental investigations on reinforced concrete members exposed to fire has been addressed [7-14]. Therefore the paper presents the performance of FRP repaired RC columns exposed to fire.

2. METHODS OF REPAIR

Several repairing methods have been extensively used in repairing fire damaged reinforced concrete columns such as concrete and steel jacketing (Fig. 3a, b), steel caging, steel encasement, steel plates with steel stiffeners, pre-stressed jacketing, and composite jacketing (Fig. 3c). However, the most commonly used methods are concrete jacketing, steel jacketing, and composite jacketing.

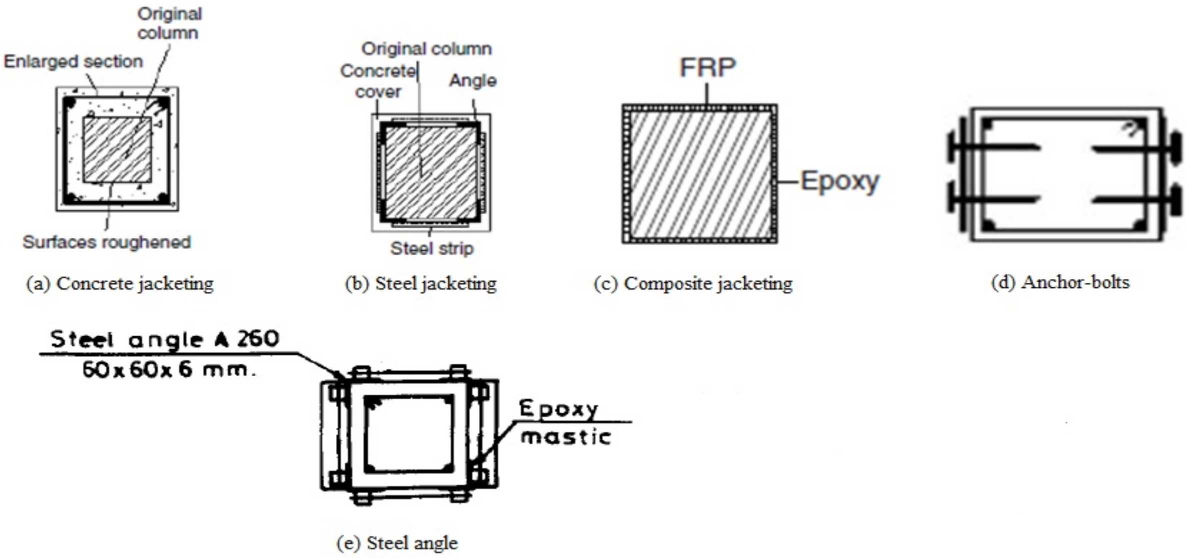

Fig. 3 (a) Concrete jacketing; (b) Steel jacketing; (c) Composite jacketing; (d) Anchor-bolt method [5]; and (e) Steel angle method [15]

Concrete jacketing generally can be made by adding a layer of concrete, on top of damaged surface with additional longitudinal and transverse reinforcements [6, 15]. Using this method, the load bearing capacity [15] and stiffness [6] of the column can be significantly increased, however the self-weight and size of column is extensively increased. This method is very effective and labour intensive as well. The concrete jacketing can also be made using ferrocement jacketing method. This is carried out by applying a wire mesh wrapped around the perimeter of columns followed by spraying concrete on to the column surfaces [6]. Another method that can be adopted in column has been described by [9] is fiber reinforced concrete (FRC) jacketing method. The concrete mix used by [9] is high strength concrete with additional fibers (i.e., brass-coated steel, hooked steel, high performance polypropylene and glass fiber). The FRC is applied on the surfaces of the damaged reinforced concrete columns.

The second method used in repair and rehabilitation of a reinforced concrete column is steel jacketing. As compared to concrete jacketing, the increase of column size after repairing is relatively smaller in steel jacketing method [6]. Different types of steel jacketing are steel caging, steel encasement, and corrugated steel jackets [6]. Ramirez [16] conducted a study to determine the most effective repair methods for reinforced concrete column. It is concluded that steel angle method (Fig. 3e), (one of steel jacketing techniques) and concrete jacketing method are the most efficient and cost effective method used to repair the column over its entire length.

At last, the most recent and effective method used in repairing work is FRP composite jacketing. This method has been used to replace steel jacketing because of its advantages over other exiting repairing methods. The potential advantages of usng FRP reinforcement are easy to install thus saving more time, reduce maintenance, high strength, light weight, and more durable [6]. The application of FRP reinforcement is explained in section 4.

3. FIBER REINFORCED POLYMER

The first application of FRP as external reinforcement is reported in 1984. Three different types of FRP reinforcement are glass FRP (GFRP), carbon FRP (CFRP), and aramid FRP (AFRP). Table 1 shows the typical mechanical properties of glass, carbon, and aramid FRP reinforcement. These fibres have highly beneficial properties such as high strength-to-weight ratio, resistance to corrosion, durability, ease of application, and low maintenance. According to Darby, 1999 [17], FRP plates weight are only 20% of steel plates, however it can be achieved up to 10 times the strength of steel plates.

Table 1 Mechanical properties of GFRP, CFRP and AFRP [17]

Unidirectional advanced composite materials	Fiber content (% by weight)	Density (kg/m^3)	Longitudinal tensile modulus (GPa)	Tensile strength (MPa)
Glass fiber/polyester GFRP laminates	50-80	1600-2000	20-55	400-1800
Carbon/epoxy CFRP laminate	65-75	1600-1900	120-250	1200-2250
Aramid/epoxy AFRP laminate	60-70	1050-1250	40-125	1000-1800

4. REPAIR WORK USING FRP

4.1. Fire Exposure of RC Columns

Raut and Kodur, [18] conducted a study on 203 × 203 mm, 3350 mm long normal strength concrete (HSC) column exposed to ASTM E119 standard fire curve in order to gain better understanding of the behaviour of this type of concrete columns when exposed to fire. During the application of heating, the column is loaded with 0.4% load ratio (ratio of applied test load to calculated column capacity from ACI 318) and the load is maintained heating process. The column is considered to be failed when the hydraulic jack could not sustain any further load. The result gained by [18] can be classified into two categories which are (1) thermal response, and (2) structural response.

In terms of thermal response, both steel and concrete reached a plateau at 100°C. This can be attributed to evaporation of the surfaces water in concrete. After the plateau, the temperature in concrete increased with exposure time. Raut and Kodur [18] measured the steel and concrete core during heating process and it was observed that the steel temperature is much higher than temperature in concrete core. This happen since concrete possessed low thermal conductivity and high thermal capacity, thus lead slower heat dispersion into the inner part of concrete.

As for structural response, the reinforced concrete (RC) columns are expanded in the early stages of heating as a result of thermal expansion of both concrete and steel reinforcement. As the temperature and duration of exposure increased, the columns initiated contraction as a result of loss of strength in steel reinforcement. This is due to the increase of cross-sectional temperatures and load redistribution to concrete from reinforcement. Moreover the temperature in steel reinforcement rises at faster rate than the inner core concrete because the steel reinforcement is close to the outer core of the column section. As the temperature increased, the steel reinforcement undergoes yielding however the concrete carries more loads. Eventually, the column failure occurred when concrete no longer can sustain load imposed on them due to deterioration of concrete as the exposure time and and temperature increased [18].

4.2. Application of FRP

As exposed to fire, the strength of reinforced concrete column is decreased. Researchers have proved that the strength of the fire damaged RC columns could be greatly improved by confining the RC columns with FRP reinforcement [6]. Different FRP jacketing methods used for reparing RC columns such as prefabricated FRP shells, FRP straps, and FRP wraps [19]. However, in this paper, only FRP wraps method is discussed since it is the most widely used method in the construction industry.

The hand lay-up method is the simplest and most commonly used method for application of FRP reinforcement. The FRP reinforcement is wrapped around the perimeter of reinforced concrete column. Prior to application of FRP reinforcement, the surface of the concrete column/member is grinded to expose aggregate and cleaned using high pressure air blower. The sharp edges or corners of the columns are rounded to radius of at least 10-25 mm. The prepared concrete surface is free from dust and other dust integrated materials. A coat of primer is applied on the surfaces to fill the micro-cavities. After curing, the irregularities or uneven surfaces are to be levelled by the application of layer of putty. This layer is to fill the uneven spots and surface cavities. The putty is allowed to cure for 30 minutes until it become tack-free as well. The prepared epoxy is then applied in the form of thin layer using a roller. Subsequently, the fibre sheet is cut into desired length and width and wrapped around the perimeter of reinforced concrete column. The rubber roller must be rolled in fibre direction to remove the entrapped air between the fibres and resin. After the FRP reinforcement, a second layer of epoxy is applied. The same procedure is repeated to increase the thickness of FRP plies or layers.

Moreover, the applied FRP reinforcement using epoxy resin can be mechanically fastened with anchor bolts or FRP spikes. Previously, this method is used to fasten steel plates onto concrete surface using anchor bolts. However, since this FRP did not have sufficient bearing strength to withhold anchor bolts, the applied FRP reinforcement may split at the mechanical [20].

5. EFFECT OF FRP WRAPS ON FIRE-DAMAGED COLUMNS

5.1. Strength

After exposure to high temperature, the reinforced concrete column experienced significant degradation in strength. It is reported by [13, 14, 21], when the square and circular columns exposed to 500°C, the reduction in strength is 44% for square columns and 42% for circular columns. These damaged columns are repaired with one layer of GFRP or CFRP using hand lay-up method. The effect of FRP confinement of repaired square and circular columns is significantly increased as compared with the post-heated column. As the axial load applied, the concrete expands laterally and initiates tensile stresses in FRP wraps. Due to the initiation of tensile stresses, the FRP reinforcement limits the dilation of concrete, inducing the concrete in tri-axial state of stress field, which results in enhancing the axial strength of columns [13, 14, 21]. However, the increase in strength is more significant in circular columns whereby the observed axial strength of column is restored up to or greater than its original strength. As for square column, there is an increase in axial strength; however the increment is not as high as in the case of circular cross section. The confinement effects of FRP are more effective in circular cross-section due to its membrane action, where the stresses are uniform in all directions. Whereas in square cross-section, the stresses are concentrated more at the corners and the area between the corners are not effectively confined [14] thus the effect of FRP confinement is not fully achieved. Moreover, the strength enhancement of FRP wrapped column is influenced by modulus of elasticity and its ultimate tensile strength of FRP reinforcement. Higher value of modulus elasticity and ultimate tensile strength of FRP leads to higher confining pressure thus resulted in greater strength enhancement [13, 14, 21]. However, for square or non-circular cross section, the strength enhancement provided by FRP is also influenced by the corner radius of the section [14].

5.2. Stiffness

The stiffness of reinforced concrete columns is also considerably reduced when exposed to high temperature [10]. This is due to the increase of porosity in concrete and development of internal cracking as exposed to high temperature [13]. When repaired with FRP wraps, the enhancement in stiffness of FRP wrapped columns is insignificant as compared to the strength enhancement in FRP wrapped columns. The stiffness of FRP wrapped columns is very minimal in the earlier stages of loading which is similar to the unrepaired columns. However, the stiffness of FRP wrapped column is became active when it attains the ultimate strength of FRP reinforcement. Moreover, the reduction in stiffness is greater than the reduction in strength [13, 14, 21]. This phenomenon is applied for both circular and non-circular cross-sections.

5.3. Ductility

According to [13, 14, 21], the ductility is related to the ability of a structural member to sustain inelastic deformation without loss of load carrying capacity. Wrapping the fire-damaged concrete column with FRP has significantly improved the ductility of the reinforced concrete columns [10, 13, 14, 21]. This is because of the confinement effect of FRP, where FRP confines the cracks that occurred during heating process. The enhancement in ductility is more pronounced in circular column compared to non-circular column due to the stress distribution in circular column. Stress distribution in circular column is more uniform, hence the confinement effect is more effective [13].

6. FAILURE PATTERN

As reinforced concrete columns are exposed to fire, spalling of concrete will almost certainly occur. Spalling of concrete is a complex phenomenon and the nature of spalling is still debatable [13].

Factors that contribute to spalling of concrete are; (1) rate of temperature rise, (2) permeability, (3) geometry of the column, (4) type of aggregates, and (5) moisture content [18]. According to Raut and Kodur [18], spalling can be categorised into three different levels (1) minor, when only a small mass of concrete usually from outer surface fall off from the RC column; (2) moderate, when the fall off pieces is bigger than that of minor spall, however still not exposing the reinforcement, and (3) severe, when the steel reinforcement is exposed.

Raut and Kodur [18] heated the RC columns in accordance with ASTM E119 fire curve and loaded with 0.4% load ratio simultaneously. It is observed that the concrete spall, however, it is being classified as minor by [18]. Moreover, it is expected that the moderate and severe spalling possibly occur with high strength or high performance concrete.

Yaqub et al., [13] and Yaqub and Bailey [14 & 21] have conducted a fire exposure test on square and circular reinforced concrete columns exposed to constant temperature. The temperature rate is increased slowly (150°C/h) until it reached 500°C and left constant until the thermocouples reading (embedded in concrete core) is similar to the surface temperature. Subsequently, the columns are allowed cool down naturally in the furnace. After cooling down from the furnace, the columns are removed and allowed to cool at room temperature. Heated RC columns are divided into two groups; (1) heated & unrepaired and (2) heated & repaired with FRP wrapped. Both groups are tested under axial compression.

Heated and unrepaired columns observed a crushing of concrete failure at the top due to the stress concentration in this region, as seen in Fig. 4a and Fig. 4b. Failure of fire damaged column is more gradual as compared to the explosive, sudden and brittle nature of unheated column, indicating a ductile behaviour of fire damaged column [13, 14, 21]. Apart from the crushing of concrete at the top part of the column, it is also observed that, the link bar at the overlapped position was opened. This might due to the inadequate anchor of transverse reinforcement.

The heated and FRP repaired RC columns are failed in crushing of concrete with rupture of FRP (Fig. 4c and Fig. 4d). According to [21], this failure initiated gradually and ended with explosive noise as a result of rupture of FRP. Prior to failure, cracking noise is observed indicating the effect of FRP confinement and the rupture of FRP occurred outside the overlapped region of FRP wrapped [21]. This mean that, the overlapping of 200 mm provided by the researcher is sufficient to provide effective confinement.

Fig. 4 Failure pattern for (a) heated circular RC column; (b) heated square RC column; (c) FRP wrapped circular RC column; and (d) FRP wrapped square RC column [21]

7. LIMITATION OF FRP

The use of FRP has been extensively recognized as a strengthening and repairing method for civil engineering infrastructures. Extensive research investigations have been conducted on repairing RC columns with FRP reinforcement. However, there is still some improvement needed to be carried out in order to fully utilize this material. Some limitations of using FRP wraps as repair material are as follows:

- After repairing the fire damaged reinforced concrete column, the possibility of fire occurrence must be taken into account. FRP reinforcement is applied using epoxy resin. The glass transition temperature T_g of adhesive is very less, therefore the epoxy will melt as exposed to fire. The most common method that being applied when using FRP wraps is to protect them with fire protection layer, however, these layers may failed to prevent the T_g from being exceeded [22].

- Research investigation by [13] showed that the FRP wraps are effective in increasing axial strength of circular cross-section. As for non-circular (i.e., square and rectangular) with one layer of FRP wraps, the increase in axial strength did not even reach the original pre-heated column. Therefore [13], for non-circular cross section, more than one layers of FRP should be used or with other alternative method.
- Wrapping with FRP could increase the strength and ductility of fire damaged column. However, the effect on stiffness is insignificant when single layer of FRP is applied [13]. The increase in stiffness can be observed when using concrete jacketing as repaired method [6].

8. CONCLUSION AND RECOMMENDATIONS

The conclusions and recommendation can be drawn as follows:

- Wrapping the fire-damaged concrete column with one layer of FRP could increase its strength and ductility. However, there is no improvement in stiffness of FRP wrapped RC columns. Increasing the layers of FRP may not be significantly increase the strength however the ductility and stiffness of the FRP wrapped columns can be increased.
- The confinement effects of FRP are more effective in circular cross-section as compared to non-circular square or rectangular sections. Moreover, the strength enhancement of FRP wrapped column is influenced by modulus of elasticity and its ultimate tensile strength of FRP reinforcement.
- Use of more than one layer of FRP wrap to repair the fire damaged column probably increase the stiffness of fire exposed RC columns.
- Instead of using one type of FRP, the hybrid FRP wrapping technique (i.e. combination of more than one type of FRP) can used to study the efficacy of fire damaged RC columns.
- Use mechanical fastener as described by [20] however, some modification needed to be done in order to avoid complication in the process of erecting the fasteners.

ACKNOWLEDGEMENT

The authors are grateful for the financial support provided by USM-RU research university grant (Ref. No. 1001/PAWAM) from Universiti Sains Malaysia and Ministry of Higher Education Malaysia.

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