Review of Strengthened FRP-confined RC column with various aspect ratios under axial load and high-temperature

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Abstract. In civil and structural engineering, building structures with vigorous stability and strength utilizing economical materials is challenging. Stability of structures during their lifespan is a very demanding endeavor in civil engineering systems. Recent trends are highly focused on high strength materials, strong corrosion-resistance in structural elements, slender structure development, broad span provision, and load reduction, in order to achieve these conditions, composite materials have proved to be a successful aspirant. The fiber-reinforced polymer (FRP) possesses novel properties that encourage the researchers to strengthen or restore the structural degradation of the reinforced concrete (RC) columns via confinement. The present study highlighting the different aspects of (FRP) confined (RC) column having different aspect ratios, the axial load, and the high temperature under extensive literature review. The FRP confinement is much more effective in the case of circular columns than sharp-edged rectangular columns. The variation of the cross-sectional aspect ratio (section depth to width ratios) of RC columns plays a vital role in the evaluation of the efficiency of strengthening techniques. In spite of the clear and proven advantages of utilizing FRPs over conventional materials, awareness of the behavior of such composite materials after exposure to high temperature is noticeable and requires more research.

1. Introduction
In India, many existing structures do not reach its load-carrying capacity level due to the deterioration generated by a combination of decay, improper design, or unforeseen activity like earthquakes, storm, etc., and not capable to sustain cautiously the same [1,2]. Dismantling a structure and rebuilt it again is not a practical solution. Because of time and economic aspects, the most desirable choice is to immediately overhaul the damaged part of the structure. Confinement of RC columns using FRP sheets is considered to be a very effective technique. It improves both axial compressive load carrying capacity and structural ductility of RC columns [3–6]. The previous study has confirmed that the repairing of damaged concrete by means of external confinement is successful in restoring the original strength of RC columns [7–10]. The researchers noticed that confinement was a better option for refurbishing the ductility and strengthening of damaged concrete [11, 12]. The FRP is a combination of high strength fibres (glass, carbon, aramid or basalt) and polymer matrix (polyester, vinyl ester or epoxy)[13]. The FRP has excellent properties having outstanding corrosion resistance, low specific gravity at high mechanical strength, less effect of weather, good insulation qualities, high strength to weight ratio as compared to steel, and innate protection to decay [14]. The FRP confinement is more
effective in the circular columns due to uniformity in stress distribution than in the rectangular columns [6, 15–17]. The confining pressure is different in the corners and the flat side in the case of the rectangular column. Most research and evaluation work focused on characterizing the performance of FRP confined circular concrete columns [18–23]. Nevertheless, very few tests and research are performed on the rectangular column because of the complex distribution [8, 20, 24–27]. The efficacy of FRP confinement in RC columns depends on different influencing factors like the type of fiber, the thickness of jacketing, orientation of fiber, bond between core, concrete strength, and shape of cross-sectional, etc [6]. The cross-sectional aspect ratio affects the confinement efficiency of FRP composites and stress-strain behaviour. The maximum value of the cross-sectional aspect ratio was limited up to 1.5 [28, 29] and it was revised to the value of 2.0 [30].

The FRP has been widely used in a practice due to its various advantages. However, utilizing the FRP in the repair and retrofit of structures, it's poor performance under the effect of high temperature or fire exposure was noticeable [31]. Moreover, designing a structural element, it needs to design a satisfactory level of fire safety and minimized risk from heat and smoke. The utilization of FRP materials is a major challenge owing to the lack of standard codes and complex behaviour of FRP materials at various temperatures.

2. Background
In the 1930s, united states have shown interest in the utilization of FRP based confinement in concrete structures. Nevertheless, the actual practice to utilize these materials for retrofitting was stared in the 1980s after the initiative of the National Science Foundation (NSF) and Federal Highway Administration (FHWA). Retrofitting the concrete structures using FRP was testified in the year 1978 in Germany [32]. Similar kinds of investigations for the retrofitting of concrete structures were done in Japan and Europe in the 1980s. In the mid of 1980, externally bonded FRP systems were being used universally. Externally bonded FRP system was first utilized in Switzerland for the flexural strengthening of bridges [33]. In Europe, FRP method was being used as an alternative method to steel plate bonding. In Japan, the FRP system was being used in the 1980s to improve the confinement [34]. The utilization of FRP systems has been increased in the last decade from a few projects to several thousand projects around the world [14]. Europe, Japan, Canada, and the United States have developed the design rules and guidelines in the area of applications of externally bonded FRP systems. Preceding research and field applications for the rehabilitation and strengthening using FRP are described in (ACI 440.2R-17) [35]. Canadian Standard Association (CSA) has approved the code, "Design and construction of building a component with Fiber Reinforced Polymers” [36].

3. Type of confining method
Restoring, repairing and strengthening of RC columns is necessary for prolonging the structures life, to restore the degraded column, for enhancement in load carrying capacity over the design value, and to ensure the ductility, etc. Researchers and practitioner engineer have developed various RC column strengthening measures (Ref). Some of them are highlighting here under subsiding paragraphs.

3.1 Concrete Jacketing
Amongst several confining techniques, the first method of repairing damaged concrete is concrete jacketing. So many studies focused on strengthening and repairing of RC columns by using concrete jacketing to the original column [37–40]. From the past study, it was concluded that concrete jacketing enhancing the strength and ductility of damaged RC columns. However, high operating costs and the increased size of the repaired columns have definitely restricted its usage.

3.2 Steel Jacketing
One most effective ways of increasing the ductility of damaged concrete columns were the steel. Several researchers investigated the use of steel jackets in strengthening the RC columns [41]. However, the bonding between the steel plates will considerably affect the efficiency of the use of
jackets. For members with a right angle of cross-section (square or rectangular) efficiency was considerably low, as does not improve flexural stiffness effectively.

3.3 FRP Jacketing
The wrapping of RC columns by FRP is another technique for strengthening and ductility enhancement. Several researchers have examined the use of FRP jackets to reinforced RC columns [42-52]. As an alternative to above two methodologies, the FRP composites presented it as an attractive option.

4. Techniques of confinement
There are two types of confinement techniques, defined as an active confinement technique and passive confinement technique. Lateral confining pressure acting on the column is the main difference between active and passive confinement [53]. In the active confinement, the confining pressure is applied laterally on the elements prior to the loading. This employs a little lateral stress on the concrete resulting in an increase in load-carrying capacity of the element. Passive confinement method is used to gaining a higher strength and ductility. The passive confinement is generally done by wrapping the FRP to the circular or rectangular column. The passive confinement has been achieved through the application of circumferentially unidirectional fiber epoxy-bonded sheets [54]. Confinement effectiveness of RC columns depends on various factors; e.g. cross-sectional aspect ratio (length to width), the radius of the corner, type of confinement, type of column, etc. Up till now, research has mainly focused on describing the nature of circular and square cross-sectional columns but it's far less understood the efficiency of FRP confinement for the rectangular columns [6]. The efficiency of confinement is stronger in the circular RC columns due to equal nature of stress distribution than the prismatic columns which has limited to just a portion of a prismatic cross-section. From Figure 1 it is clear that axial load acting on FRP confined rectangular concrete columns, the confinement pressure concentrated at the corner of the section. The confining pressure concentrated at the corner of the section is very less or negligible.

Figure 1. Confine behaviour at the corner of the section (a) Mechanism of the tension force (b) distribution of confining stress (adapted from [24])

5. FRP confinement in rectangular RC Columns
Axial compressive load carrying capacity of rectangular column increases intensely with wrapping the FRP sheets. In non-circulars (square or rectangular) columns FRP wrapping is not as effective as circular column [55]. Due to the equal distribution of fiber on entire section, the effectiveness of FRP confinement in the circular column is very high, whereas in square or rectangular column, the corner confined properly but other part remains unconfined. This efficiency loss is usually shown with corner-defined parabola areas as shown in Figure 2. Also, this efficiency is highly dependent on the cross-section aspect ratio and the radius of the corner [54].
5.1 Confining models for rectangular RC columns [30]

The total compressive load taken by an RC column is the combination of the compressive load taken by concrete and tensile load taken by longitudinal steel bars. They take reduction factors as per the codes. The nominal axial compression capacity (Pn) of non-slender, normal-weight concrete member confined with transverse fiber sheets can be calculated as below equation 1.

\[ P_n = \alpha [0.85 f'_{cc} (A_g - A_{st}) + f_y A_{st}] \]  

Equation 1

Where,
- \( P_n \) = nominal axial compression capacity of column
- \( \alpha \) = Coefficient to cater for minimum eccentricity
  - 0.85 for non-prestressed members with existing spiral steel reinforcement
  - 0.80 for non-prestressed members with existing steel-tie reinforcement
- \( f'_{cc} \) = Maximum compressive strength of concrete
- \( A_g \) = Gross cross-sectional area of column
- \( A_{st} \) = Total area of reinforcement
- \( f_y \) = Yield strength of reinforcement

Figure 2. Confinement pressure in a rectangular column (a) axial loading on column (b) confined behaviour of rectangular column (adapted from [30])

Figure 3. (a) Circular column with FRP confinement (b) Rectangular section without FRP confinement (c) (d) (e) FRP confined Rectangular columns with different corner radius (adapted from [58])
Hoop stress is also depending on the corner edges. It directly affects the behaviour of FRP confined RC column. The stress level at rectangular corners is the main reason for the untimely failure of FRP [56]. At the time of FRP confinement in rectangular RC columns, FRP laminates bent first when wrapped around the column. The effectiveness of FRP laminate reduces due to bending, this action depends on the edges of the corner. The radius of the corner greatly affects the efficiency of confinement. For achieving the better result of confinement the corner radius must be large [57].

Different from the circular cross-section, when the square cross-section is subjected to axial compression the lateral stress is not uniform over the perimeter of the section [58]. Cross-section change from circular to a square, the lateral (circumferential) stress over the section perimeter is not uniform for axial compression. From Figure 3 it should be noted that corner radius plays a very important role in confinement.

5.2 Effect of aspect ratios on the confinement

As discussed earlier, the confinement efficiency is directly related to the shape of a section. Figure 4 shows the loading scheme of a rectangular column in a multi-storey building. The compressive pressure gets distributed unequally if the square and rectangular sections are not uniformly confined with FRP. From the previous research, the shape of a section directly marks the efficiency of the FRP confinement due to the difference of stress-strain relationship [4]. When the cross-sectional aspect ratio increases, the ultimate strength of a column is decreased. Moreover, it can be observed that the strengthening ratio decreases with an increase in the aspect ratio [59]. Figure 5 shows various values of the cross-sectional aspect ratio generally adopted in structural design [59]. For analysing the effect of aspect ratio on RC column, a parametric study was conducted by researcher and it was concluding that increasing in aspect ratio from 1:1 to 1:6 strengthening value decreased up to 10%. [60]. In order to find out the effect of aspect ratio and confined behaviour of RC column an experimental study was conducted by and concluded that increasing in aspect ratio, the ultimate strength of CFRP confined RC columns get reduce [61]. The maximum value of the cross-sectional aspect ratio was limited up to 1.5 [28], and it was revised to the value of 2.0 [30]. When the aspect ratio reaches more than 2.0 the strength improvement in RC confined column become insignificant [4].

![Figure 4. Loading scheme of a rectangular column](image1)

![Figure 5. Aspect ratios of column](image2)

Wu and Wei 2010 experimental study, RC short column was strengthened with CFRP wrapping, and the axial load was applied afterwards up to the failure of an RC column. Different values of aspect ratio and a various number of CFRP layers were used for the strengthening of short RC columns. They have examined the behaviour of a specimen in the axial and transverse directions. From the test results, it indicates that the strength gaining in confined column relative to the unconfined column, mean compressive strength (fcc/fco) decreases as the aspect ratio increases. Table 1 defines the mean value of the compressive strength and the corresponding strength gained in the confined columns.
Table 1. Mean compressive strength and corresponding fcc/fco (adapted from [4])

| Aspect ratio h/b | Without Wrapping (MPa) | (1-layer CFRP wrapping) (MPa) | Mean Compressive Strength (fcc/fco) | (2-layer CFRP wrapping) (MPa) | Mean Compressive Strength (fcc/fco) |
|-----------------|------------------------|-------------------------------|------------------------------------|-----------------------------|------------------------------------|
| 1.0             | 35.30                  | 41.23                         | 1.17                               | 60.37                       | 1.71                               |
| 1.25            | 35.30                  | 38.77                         | 1.10                               | 51.36                       | 1.45                               |
| 1.5             | 35.30                  | 38.39                         | 1.09                               | 43.87                       | 1.24                               |
| 1.75            | 35.30                  | 37.68                         | 1.07                               | 40.51                       | 1.15                               |
| 2.0             | 35.30                  | 37.44                         | 1.06                               | 38.97                       | 1.10                               |

5.3 High temperature or fire effect on FRP wrapping a concrete column

In civil engineering area, utilization of FRP materials is a major challenge owing to the lack of standard codes and complex behaviour of FRP materials at various temperatures. The main disadvantage of utilizing FRP in the repair and retrofit of structures is its poor performance under the effect of high temperature or fire exposure [62]. While designing a structural element, it needs to be designed so as to offer a satisfactory level of fire safety and minimized risk from heat and smoke. Fire is characterized as a period of resistance to structural integrity, stability and transmission under fire condition by structural components [63]. With the use of [64, 65] standards, the fire resistance of a structural component can be obtained by conducting full-scale fire tests on a representative sample of a structural member in the furnace. This test is expensive and needs a long time to be performed [66]. In context to the cost-effectiveness, the performance-based method is upright for the calculations and numerical simulations. Variation in temperature produces high thermal stresses in RC structures. Thermal stresses are produced due to the restraining of free expansion, contraction or rotation. When the temperature increases more than 100°–150 °C, it directly affects the mechanical and physical properties of FRP [62]. The polymer resins in FRP improves strength when they are placed in the transverse direction. When the temperature exceeds the transition temperature ($T_g$), the bond between FRP and concrete gets affected.

The polymer resin is a type of epoxy material, which works as a binding agent and transmits the stresses between fibres in FRP. Epoxy can be utilized as a bonding agent between composites and structural elements. Polymer resins of FRP get deteriorated rapidly when their temperature reaches 200-250 °C above the glass transition temperature ($T_g$), [28]. Under the effect of fire on FRP, polymer resins in it change their state to the flexible/ rubbery state from the stiff/ solid-state [62]. When the temperature reaches the disintegration temperature, resins get deteriorated thermally and the fire spreads along the surface of the material. As the fire spreads extensively, the smoke is generated from the burning of FRP. Burning of this polymer resin directly affects the mechanical and bonding properties of FRP and this would be totally worsening [62].

6. Conclusions

The present study has assessed the various databases related to FRP confinement, the effect of cross-sectional aspect ratio and corner radius on rectangular columns, the effect of high temperature on FRP confined columns etc. and the following conclusions are drawn from the literature.

FRP confinement is more effective as compare to other confinement for strengthening and repairing of RC columns.

The passive protection provided by FRP wrapping can significantly improve the load-carrying capacity and ductility.
FRP confinement is less effective in rectangular columns due to its corner edges and uneven stress distribution. Corner roundness is an essential parameter for changing stress concentration in rectangular columns. FRP wrapping improves the performance of rectangular RC columns under an axial loading but enhancement level decrease with increase in aspect ratio. Axial and lateral stresses at the corner are significantly higher than in the middle of the sides in rectangular columns. With an increase in temperature, the load-carrying capacity of FRP confined RC column decrease continuously. The FRP wrap system was loss of effectiveness at temperatures below the Tg of epoxy adhesive used. The tensile strength of the FRP wrap at such temperatures is thought to decrease.

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