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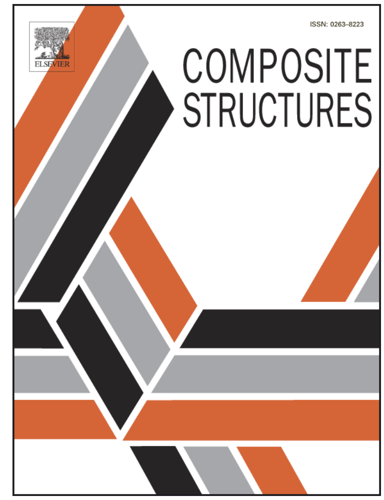

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Review article

Structural applications of Fibre Reinforced Polymer (FRP) composite tubes: a review of columns members

By

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Structural applications of Fibre Reinforced Polymer (FRP) composite tubes: a review of columns members

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Abstract

Use of fibre reinforced polymer (FRP) in column applications is increased because it can act as a confining material, a reinforcement and a structural column. The application of FRP tubes is correlated with the fibre orientation since tube stiffness is mainly attributed to the stiffness of fibres. Thus, for confinement, the fibres should align in the transverse direction of the tube while they should align in the axial direction when tubes are used as compression members. FRP tubes with fibres mainly in axial direction may reach failure because the stiffness in the perpendicular direction to fibres depends only on the stiffness of the matrix. In order to boost the stiffness in the secondary direction while supporting fibres in the main direction, fibres should be in multi-directions.

This paper reviews and identifies gaps in knowledge on the use of FRP materials in column applications in new or existing construction regimes.

Keywords: Confined concrete column; pultruded FRP tube; concrete strength; hybrid column; stress-strain models.

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1. Introduction

The use of Fibre Reinforced Polymer (FRP) materials in civil engineering applications gained increased popularity during the last three decades because they have better properties than the traditional construction materials such as steel. FRP materials have an ability to resist corrosion, and it is easy to use them either for strengthening existing concrete members or for building new composite members [1]. Reduced construction time and lower maintenance cost during the service life are some advantages of FRP members.

FRP profiles are mainly used in beam and column applications in a typical structure. Using FRP tubes in column applications can be classified into three categories; (a) FRP tube encased concrete to obtain strength and strain enhancements, (b) all FRP profiles and (c) hybrid columns that consist of steel, concrete and FRP tube. Main purpose of the first and the third categories is to utilize the strength of the FRP tube to produce confining pressure in the transverse direction of concrete columns or concrete –steel columns. On the other hand, the purpose of the second category of FRP profiles is to produce light weight structural column members. The use of pultruded FRP profiles which are similar to existing steel profiles has gained popularity because of the cost reduction in the fabrication process. [2].

This paper reviews the recent research on the axial behaviour of structural column members which are made by using FRP tubes and to point out the knowledge gaps for further studies. The review is presented using the three categories identified above.

2. Concrete columns with FRP confinement

Reinforced concrete column members fail when the lateral strain reaches a specific value and concrete cover starts spalling followed by the buckling of steel reinforcement [3]. Thus, a delay in reaching lateral strain in the concrete to its ultimate failure leads to performance enhancement of a concrete column. This goal can be met by providing lateral pressure around the column diameter through confinement by FRP materials. The concept of confinement depends on keeping fibre orientation in the transverse direction of the column [4-6]. This is because the concrete under axial load expands laterally. This expansion creates tensile stress in the confining material which turns into confining pressure on the lateral direction of concrete columns [7]. The following sections highlight the effect of FRP confinement on the compressive behaviour of concrete columns by considering the influences of different parameters on the degree of confinement and present a summary of the available stress-strain models for FRP confined concrete.

2.1 Advantages of FRP confinement in concrete columns

The confinement of concrete columns results in mitigating the possible failure due to unexpected load due to an earthquake since the confinement with FRP material increases the ultimate strength and strain. Additionally, FRP confined material protects the concrete column against aggressive environments, acts as non-corrosive reinforcement and as permanent formwork. Moreover, Qasrawi et al. [8] found out that the localised damage is decreased in FRP-confined concrete columns compared with conventional reinforced concrete columns under blast loading. This important feature provides the ability to save civilian and property against intentional or accidental explosions.

2.2 Effect of different parameters on the degree of confinement

The degree of improvement in the axial strength and strain capacities of concrete columns due to the confinement with FRP materials depends on many parameters such as slenderness ratio of columns, shape of cross–section, concrete strength, method used to manufacture the tube, fibre properties, fibre orientation and FRP thickness [9].

2.2.1 Slenderness ratio

The influence of slenderness on the axial performance of normal strength concrete filled [10] as well as high strength concrete filled [11] FRP circular tubes were studied in the past. Their studies concluded that the degree of enhancement of strength and strain capacities in concrete has been decreased when the slenderness ratio is increased. Similarly, it was found that FRP confinement of circular reinforced concrete columns was less significant for slender columns than short columns [12-14].

2.2.2 Shape of the concrete columns

Less effect of FRP confining material on the behaviour of columns with non-circular cross-sections was reported by Pessiki et al. [15], Hong and Kim [4] , Fam et al. [16] and Mirmiran et al. [17]. The results of their work verified that the confinement in non-circular sections is not as effective as circular columns due to the outward bending in the flat sides of the non-circular FRP tubes. The same view was reported by Ozbakkaloglu and Xie [18] after testing square and circular FRP tubes filled with geopolymer concrete under axial compression. Thus, researchers have followed two methods to overcome this problem to improve the confinement of square and rectangular concrete columns by modifying the cross section to circular and elliptical shapes respectively. In the first method, prefabricated FRP shells were placed around the existing concrete column to change the cross section and the gap between shells and original concrete column was filled with concrete (Figure 1a). A wet lay-up process of FRP sheets or strips were used to fix FRP shells [19]. The second method (Figure 1b) to modify the cross section was similar to the first one except the use of concrete segments without creating a gap with the original concrete section [20].

Beddiar et al. [9] improved the first method by assembling three GFRP sheets made from twill weave glass with structural bending to modify the cross section of square concrete columns and then, filled the gap with shrinkage compensating cement mortar (Figure 2). The test results confirmed that strength and ductility capacities of non-circular concrete sections can be improved through cross section modifications.

The second method has also been evolved for rectangular columns with large aspect ratio by Bhowmik et al. [21]. They used the concrete segments to form a capsule-shaped column instead of an elliptical shaped column. The concrete segments in shape of either semi-circular or circular were added at the short ends of the rectangular columns to change the cross section of rectangular columns. The results showed that the shape modification techniques enhanced the confinement effects on the structural response of the rectangular columns.

In addition to the circularization modification method of the conventional square concrete columns, Youssf et al. [22] followed two more methods; refined –corner section and rounded - corner angle section as shown in Figure 3. They used crumb rubber aggregate in three different percentages to replace the fine aggregate in the concrete cross-sections modifiers. The external confinement was achieved by using unidirectional carbon sheets with a nominal thickness of 0.128 mm. Their test results showed that crumb rubber concrete is useful to replace the normal concrete in modification approaches of the non-circular columns.

Recently Zeng et al. [23] studied circularized concrete square columns that were confined partially and comprehensively with fibre reinforced materials. They tested 33 concrete columns divided into three groups; one for square columns and two groups for the circularized square columns. The difference between circularized groups is the strength of the concrete segments that were used to circularize the square column. Concrete segments of one group was made identical to the concrete strength of the core while it was higher for the other group. The width of the FRP strips was set to 90 mm. The fully FRP confined strengthening technique was used for all square columns and some circularized square columns while the remaining columns were confined partially. The partial FRP confinement was performed by creating space between the adjacent FRP strips. Four spacings (0, 30, 45 and 90 mm) of FRP strips were considered. The results reported in this study showed that the partial FRP confinement of the modified square column is an economical and unconventional method compared to the fully FRP confinement. This is because the consumption of FRP material is decreased by about 50% without a huge compromise on the strength and strain capacities compared with fully FRP confined square columns.

2.2.3 Concrete strength and concrete types

In order to identify the influence of concrete strength on the behaviour of FRP–concrete columns under axial compression, Vincent and Ozbakkaloglu [24] used three different concrete strengths; 35 MPa, 65 MPa and 100 MPa. They tested 55 cylindrical specimens with 152 mm diameter and 305 mm height under axial loading. Carbon FRP (CFRP)-wrapping and CFRP tube–encased concrete were used. The research concluded that the ductility of the high and ultra-high strength concrete specimens can be improved when the FRP confinement is at adequate level. On the other hand, for the same confinement ratio, the strength and strain enhancements increase as the compressive strength of the concrete decreases. This is due to the increased brittleness in concrete with increased compressive strength which resulted in an increase in the hoop rupture strain of FRP confined material with a decrease in unconfined concrete strength. Hence, the capacity of concrete with low compressive strength confined by FRP material shows higher improvement compared to high and ultra high strength concrete confined by the same amount of confinement. It is noted that the strain reduction factor does not significantly change due to various ways of preparing FRP confinement (FRP-wrapped and FRP-tube), while it changes because of variation in the concrete strength. This view is supported by the study of Lim and Ozbakkloglu [25] which reveals that the hoop rupture strain reduction factor decreases when either unconfined compressive strength of concrete (Figure 4) or elastic modulus of FRP material increases.

The confinement of other types of concrete have been experimentally investigated by Yu et al. [26], Zhao et al. [27], Xie and Ozbakkaloglu [28], Zhou et al. [29], Lokuge and Karunasena [30] , Ozbakkaloglu and Xie [18] and Wang et al. [31]. In these studies, circular concrete specimens were made of self–compacted concrete, recycled aggregate concrete, lightweight aggregate concrete, geopolymer concrete and seawater coral aggregate concrete. Generally, the results confirmed that FRP confinement improved the axial performance of confined specimens compared with unconfined specimens.

2.2.4 Influence of fibre orientation

In addition to the previous studies by Hong and Kim [4], Kim et al. [5] and, Vincent and Ozbakkaloglu [6] examined the impact of fibre orientation in FRP tube on the axial behaviour of confined concrete specimens. They prepared different types of tubes using filament winding technique with carbon fibres oriented at various angles with respect to the axial direction. The study showed that the axial behaviour of confined specimens is influenced by the fibre orientation and the effect is maximized when the fibres are aligned towards the hoop direction (Figure 5). When there are more fibres in the hoop direction, they provide restraint to the lateral dilation of the concrete. This in fact is the confinement provided by the fibres which increases the compressive strength of the confined concrete and ultimately increase the axial capacity of the column.

2.2.5 Effect of other parameters

The effects of other factors such as manufacture methods of tubes, specimen size, amount and type of fibre on the behaviour of FRP-concrete circular column specimens were studied by Ozbakkaloglu [32] and Ozbakkaloglu and Zhang [33]. The results showed that the compressive strength of FRP confined concrete was significantly affected by properties of FRP tubes while both manufacture methods and specimen size had less effect (Figure 6).

2.3 Stress-strain models for FRP confined concrete columns

The axial stress-strain relationship of FRP confined concrete columns is needed in the structural analysis of the composite member. As the behaviour of FRP confined concrete columns has been conducted by researchers, many models to calculate confined compressive strength and strain of concrete have been suggested. Lam and Teng [34] classified these models into design oriented and analysis oriented models, and modified their previous models according to the collected data. The design oriented models are defined using simple closed-form equations to predict the confined compressive strength, the corresponding axial strain and the overall stress- strain relationship [7, 34]. The use of design oriented models for design purposes is suitable compared with the analysis oriented models[35]. Analysis oriented models predict the stress-strain curves of FRP confined concrete by considering the interaction between the FRP confinement material and concrete core [36, 37]. An incremental–iterative numerical procedure is followed to evaluate the axial stress and axial strain at a given confining pressure. This procedure makes the direct use of these models in design unsuitable. However, it is suitable for use in the finite element analysis [38]. Hong and Kim [4] summarized existing design oriented models and proposed a model that considers the winding angle of fibre orientation as a parameter and the model was modified later by Kim et al. [5]. Additional models were proposed by Teng et al. [38] and Teng et al. [35] for FRP confined concrete columns while Mohamed and Masmoudi [39] and Gao et al. [40]

proposed models for FRP confined concrete columns that are reinforced with steel bar and steel wire mesh respectively.

Thorough assessment of the models for FRP confined circular concrete columns was done by Ozbakkaloglu et al. [36] who reviewed 88 stress –strain models (both design and analysis oriented models). The number of test results collected by authors was 2038 from 202 experimental studies published from 1991 to 2011. These 730 data sets from 92 experimental studies included circular sections confined with unidirectional fibres oriented in the hoop direction, height-diameter ratio less than 3 with unconfined concrete strength less than 55 MPa. They stated that the accuracy of the model was improved when the value of the hoop rupture strain has been used instead of the ultimate tensile strain of fibres. Furthermore, the performance of design oriented model is better than that of the analysis oriented model because the former is calibrated with test database, while the latter is not.

2.4 Prestressing FRP confining material

It can be concluded from the available literature that the axial behaviour of confined concrete is similar to that of unconfined concrete during initial stages of loading. This is because the activation of confinement is delayed until the lateral strain of concrete reaches a specific value. One way to overcome this delay is prestressing FRP material where hoop strain of confining materials is increased thus confinement by FRP will be better. This increment leads to enhance the level of lateral confining pressure and as a result, the axial behaviour of FRP confined concrete specimens improves. Mortazavi et al. [3] and Yan et al. [19] had constituted initial prestress in the external FRP jacket or shell through inserting an expansive grout in the gap between original concrete specimens and external FRP Jacket. In order to minimise the axial expansion and allow the specimen expansion only in the hoop direction, steel plates and vertical weight had been used. Vincent and Ozbakkaloglu [41] could obtain this state for concrete filled FRP tube by adding an expansive agent to the concrete mix. They used prestressing rigs to restrain the axial extension of the concrete. The results showed that the prestressing of FRP material improves the axial behaviour of FRP-confined concrete columns.

2.5 Summary of FRP confined concrete columns

Originally FRP use in the civil engineering applications aims to increase the strength and strain capacities of concrete columns and to retrofit existing columns that are subjected to damage due to either aggressive environment condition or load increments. The establishment of tensile stress in the FRP confining material is necessary to ensure a high degree of confinement. This explains why most researchers have aimed to include most fibres in the transverse direction of the column member for creating tensile stress in the FRP material which provides lateral confining pressure. Table 1 is the summary of the reviewed studies of FRP confined concrete columns.

3. All FRP column members

This section discusses the axial members that are made out of FRP only. FRP members that are fabricated by pultrusion method have the majority of fibres in the axial direction. This property makes pultruded FRP having higher capability to resist tensile stress. On the other hand, pultruded FRP tubes have been used as compression members too [42]. The instability condition due to either local or global buckling is created because of the low longitudinal modulus and the wall slenderness of FRP profiles [43, 44] which prevents their maximum utilisation of the strength capacity. Below sections discuss the past research on all FRP column members with regards to the axial behaviour, models for predicting load carrying capacity and the ways to overcome the issues in the axial compressive behaviour.

3.1 Effect of slenderness on the axial behaviour

Hassan and Mosallam [45] investigated the buckling behaviour of 30 box section columns and 40 I-section columns with slenderness ratio (L/r) ranging from 20 to 120. They reported that the box and I –shape FRP columns failed due to global buckling when its slenderness ratio was equal to or greater than 60 and 50 respectively. Otherwise, they failed in either local buckling or a combination of local and global buckling. Based on the results of testing 24 full-scale columns having universal and box sections, Hashem and Yuan [46] have established a distinguishing criterion for behaviours of short and long FRP composite columns. They stated that specimens with slenderness ratio (L/r) equal to or less than 50 fails by either local buckling of the flange plate or localised crushing of the composite material. In both situations, the composite material reached the inelastic range. The deciding factor about the type of failure is the length to thickness ratio of the flange and the web plates. On the other hand, a specimen with slenderness ratio (L/r) greater than 50 fails by global buckling. Moreover, they mentioned that using Euler's formula to predict critical buckling load provides very accurate results, and this accuracy becomes higher when the slenderness ratio of composite column increases. This is because the effect of the instability conditions due to global buckling will control ultimately the axial behaviour of the slender FRP columns without interaction with local buckling or material failure. Therefore, the lateral movement occurs causing the entire profile to move out of its vertical plane while the shape of the FRP columns remains undeformed [47, 48]. As a result, the accuracy of the Euler's buckling equation to predict the load carrying capacity of slender columns increases since the axial compressive behaviour of pultruded FRP columns is controlled by the elastic Euler buckling mode.

Qian et al. [49] tested five circular GFRP tubes with an external diameter of 41.2 mm, thickness of 3.6 mm and length of 120 mm to determine the basic mechanical properties and four groups of GFRP tubes with various slenderness ratios ranging from 35 to 90 under axial compression to investigate the instability. They reported that there was a little difference in the values of elastic properties (5.5%), and the lateral displacement of long tubes increased rapidly when the value of axial load had reached buckling load. Also they stated that the failure mode of GFRP tube changed from fracture to buckle and failed in oversize lateral deformation when the slenderness ratio of tubes was increased.

Godat et al. [50] investigated the axial behaviour of different FRP pultruded members to predict the failure mode. They tested angle and box sections (square and rectangular). The results show that if the global slenderness ratio is higher than local slenderness ratio, the global buckling failure dominates and vice versa while both types of failure may occur when the difference between slenderness ratios is not large enough. It further shows that the failure mode of box section is local plate buckling in all sides of the square section and in the wider side of the rectangular section.

Full–scale tests of the new type of pultruded GFRP square tube that has glass fibre plies at ± 45 ˚orientation were carried out by Guades et al. [51] in order to measure the compressive strength of the hollow tube, modulus of elasticity in the longitudinal direction and compared the results with coupon tests. The height of specimens was set to provide slenderness ratio (L/r) of about 2.6. The results showed that full-scale specimens exhibit linear elastic behaviour up to the failure and the maximum variation between results of full scale tests and coupon tests is 8 %.

3.2 Prediction models of axial load capacity

Developing a model to predict the axial strength of hollow FRP column member with buckling effects is more economical than conducting an extensive testing. Local and global buckling of pultruded FRP wide flange- I section (WF-I) was researched by Barbero and Tomblin [52]. Based on their experimental results, they proposed design equations which, in authors' opinion, do well to predict the critical loads of intermediate length of FRP–I section columns. Zureick and Scott [53] experimentally investigated 24 specimens made of E-glass and vinyl ester under concentric axial compressive load. They used two types of sections; pultruded wide flange sections and pultruded box sections. The slenderness ratio had a range from 36 to 103. As a result, they proposed design guidelines to consider effect of shear deformation in calculation the critical load of global buckling. Hassan and Mosallam [45] proposed a formula to predict the global buckling load for the box and I–shaped pultruded FRP columns and the predictions were in good agreement with the experimental results.

A new design method to predict the load at which the pultruded FRP columns will fail due to either local or global buckling was proposed by Puente et al. [54] by testing pultruded FRP circular columns. The results of their model showed an acceptable degree of accuracy, as they were close or below the experimental values. Another model to calculate the axial strength of pultruded GFRP square column was proposed by Cardoso et al. [55]. Five different sizes of the square tubes with 14 specimens in each size were tested to cover a range of global and section slenderness ratios. When either the material stress reached to the ultimate strength or the value of lateral deflections at mid-height exceeded L/50, the test was stopped. The researchers found that the proposed equations perform well for short and intermediate columns, but not for long columns because the restriction of the lateral deflection at mid-height. Gangarao and Blandford [56] used another approach to predict axial strength of FRP columns by using the strain energy density model which used the area under the axial stress-strain curve of the column. The main objective of their work was to investigate the effects of local and global buckling on the strength of pultruded GFRP compression member. They tested 46 hollow box columns. The results of hollow box sections show that the difference between predicted and experimental values vary from 8% to 19%. The possibility of having shear failure in the pultruded GFRP profiles before compressive failure due to low shear-to-compressive strength ratio was also studied by Bai and Keller [57] for rectangular tubes with different lengths. Based on that, a model was proposed to predict ultimate load based on shear failure and second order deformation. A number of researchers [58-63] have been dealing with the calculation of local bucking load as a plate buckling problem. They did an analytical study of FRP plate element under various loading conditions and different states of restrained edges to assess the local buckling load of FRP section through evolving closed form equations. Different types of pultruded FRP shapes such as I-section, channels, angles, box sections and Z-sections were included in their studies.

3.3 Enhancing the axial behaviour of all pultruded FRP profiles

Although pultruded FRP tubes have low self-weight and similar ultimate strength compared with steel, they have one-seventh of the modulus of steel. These features combined with thickness of the wall tube lead to buckling failure which prevents FRP pultruded member from reaching its ultimate strength. Thus, researchers have investigated on how to delay the buckling failure. Fam and Rizkalla [64] tested nine circular short columns cut from the ends of beams after testing to compare their behaviour under different degree of concrete fill. According to the stacking sequence of glass fibre layers, different tubes were used to investigate the influence of laminate structure. The results of the pultruded tube with fibres only in the axial direction and filled with concrete reveal low ability to carry axial load compared with specimens of filament wound tubes that contain fibres in transverse direction. This is because the pultruded tube has low stiffness in the hoop direction to resist the lateral deformation of the concrete and to apply confining pressure.

Han et al. [65] studied the crushing performance of GFRP pultruded tube and the effect of wrapping with carbon or glass braid. Two values of braid thicknesses were used 0.3 mm and 1 mm. They stated that the crushing behaviour had improved due to the restraint from braids to the crack propagation in the pultruded tube. In the same vein, Li et al. [42] confined hoop direction of the circular pultruded FRP tube with carbon fibre sheet . The numbers of carbon layers were limited between 2 and 8. The results revealed that the ultimate axial compressive stress increases when the number of CFRP sheets are increased for specimens of equal wall thickness.

Correia et al. [44] could increase the critical buckling load, the ultimate load and the axial stiffness of hybrid specimen by 14%, 13.5%, and 30% respectively than reference specimens of pultruded FRP I-section by adding carbon fibre sheet to the flanges as shown in Figure 7.

The partial replacement of glass fibre with carbon fibre for pultruded FRP I-section to improve its axial performance was investigated by Nunes et al. [66]. Specimens were divided into four series in addition to the reference group. Each series includes short, intermediate and long columns. Specimens were prepared by using unidirectional and bidirectional carbon mats.The results showed the replacement method increases the axial stiffness of columns up to 17% and the load of global buckling rises in a range from 10% to 17%. In contrast, the load carrying capacity of the short and intermediate columns that fail by buckling was reduced by (1-13%) than reference columns due to delamination in the carbon mats. Further study needs to be conducted to enhance the axial behaviour of all FRP columns. This enhancement can be obtained by overcoming the deficiency of the low axial stiffness and high wall slenderness ratio. Furthermore the stacking sequence of the fibre layers, their orientation, dimensions of the FRP profile together with the type of fibre type can be varied to investigate the effect of them on the axial behaviour of all FRP columns.

3.4 Summary of all FRP column members

Pultruded FRP profiles have fibres oriented either totally or mostly towards axial direction compared to the other directions. This feature makes these sections behave better as column members. The main drawback that affects adversely in its axial behaviour is low axial stiffness and length-thickness ratio of the wall plate (b/t). Both of these issues prevent FRP columns to reach their ultimate strengths. Studies in this area have focused on two objectives. The first one is increasing the accuracy of the predictive models and looking for the new methods to improve the load carrying capacity of FRP column profiles. The general frame of the calculated models is to determine the load values of local and global buckling and then, compare the results with ultimate compressive load of the section. The lower value among them is the safe load that should be considered in the design. The second objective is strengthening the low axial stiffness of FRP profiles. In order to do that, researchers either replace the fibre of low stiffness with fibre of high stiffness or confine the transverse direction of the FRP profile with FRP material to delay the delamination in the FRP column section. Summary of past studies on all FRP columns are shown in Table 2.

4. Hybrid FRP column members

The hybrid FRP column member is a combination of FRP profile with traditional structural materials such as steel and/or concrete. The purpose of this type of FRP column is to achieve improved performance due to composite action. The action of FRP material is generating a confining pressure on the concrete which it supports the steel profile against buckling. A variety of innovative, cost-effective and high-performance hybrid FRP column members have been studied by researchers. The following sections focus on these studies together with the numerical methods to evaluate the axial performances

4.1 Columns with circular FRP and steel tubes

The first type of columns (Figure 8) with a diameter of 152.5 mm and height of 305 mm consists of outer FRP tube, inner steel tube and the space between them filled by concrete were tested by Teng et al. [67]. The FRP tubes were fabricated by wrapping process of fibres oriented mainly in the hoop direction. They reported that the test results confirmed the positive influence of confinement on the concrete which it supports by the inner steel tube against buckling.

Fanggi and Ozbakkaloglu [68] examined the effect of inner steel tube diameter, concrete infill and loading pattern on the axial behaviour of FRP-concrete-steel composite columns. They tested 32 specimens with concrete filled FRP tubes and two types of double-skin tubular columns (DSTCs). The inner steel tube in the first type was filled with concrete while it was kept unfilled in the second one. The dimensions of FRP tubes were 152.5 mm in diameter and 305 mm in height, and they were formed by layup process of S-glass fibre in the hoop direction. The unconfined concrete strength of the filler was ranging from 82.4 to 96.2 MPa. The results of filled specimens that were confined by both FRP and steel tubes show a high level of improvement than others that were confined by FRP tube only due to the dual effects of FRP and steel confinements on the concrete. DSTCs specimens exhibit higher strength under cyclic loading as well. According to the study, the axial behaviour was improved for filled compared to that of the hollow DSTCs especially when the diameter of inner steel tube increases (Figure 9).

Ozbakkaloglu [69] investigated the effect of filling DSTCs with different concrete grades. Depending on the fill conditions of the inner steel tube, three series of specimens were set; hollow, filled with the same concrete that was used to fill annular section between tubes and filled with concrete of higher strength than that used to fill annular section. The research showed that specimens with dual grade concrete exhibit superior compressive behaviour than those with single grade concrete.

Zhang et al. [70] tested FRP-concrete-steel double skin tubular columns (DSTCs) under seismic loading. In order to simulate seismic condition, columns were subjected to the axial compressive load and cyclic lateral loads. The dimensions of columns were 300 mm in diameter and 1350 mm in unsupported height. The point of applying lateral load lays at 175 mm from the upper end of the column. The space between FRP and steel tubes was filled with concrete at values of compressive strength ranging from 37 MPa to 117 MPa. The research concluded that the axial behaviour of columns showed excellent ductility and seismic resistance even for those that were made out of high strength concrete. Also, they stated that filling the lower inner part of the steel tube with concrete resulted in better behaviour.

Different types of concrete were used to cast hybrid FRP columns by Cao et al. [71], Zhou et al. [72] and Zhang et al. [73]. Cao et al. [71] prepared and tested three types of hybrid FRP columns; FRP-concrete steel double skin column, FRP confined solid concrete column and FRP confined concrete filled steel column. Self-consolidating concrete (SCC) and expansive self-consolidating concrete (ESCC) were used as the filler. They reported that creating prestress in the FRP tube influenced positively on the compressive behaviour of all types of columns except those in the form of FRP–

concrete steel double skin column. The reason for this behavior is due to the prestress in the FRP confined material related to the concrete expansion is not as high as that for other types of columns because the prestress in concrete close to the inner steel tube is much less than that close to FRP. Furthermore, the buckling of the hollow inner steel tube may influence adversely so that the effects of the prestress is not clearly visible in these columns. Use light weight concrete to fill the void between steel and FRP tubes to form the hybrid double skin columns was researched recently by Zhou et al. [72]. The results revealed that the light weight concrete was confined by FRP tubes effectively resulting in enhancements in the ductility and compressive strength. Zhang et al. [73] performed similar tests on double skin hybrid columns to examine the influence of using high strength concrete to fill the gap between FRP and steel tubes. The research concluded that the ductility of hybrid columns were not compromised even with high strength concrete filler.

4.2 Columns with circular FRP tube and different types of steel sections

A new form of a hybrid column was proposed by Xue and Gong [74]. Their columns consist of GFRP tube filled with concrete and reinforced with steel I- section. They investigated effects of concrete strength by using two types of both concrete (39.5 MPa, 51.6 MPa), and reinforcement ratio and three values of FRP wall thickness. Three types of GFRP tubes with same inner diameter and different wall thickness (4, 5, 6 mm) were fabricated using filament winding of fibres at an angle of 55˚ with the transverse direction and two different sizes of I-steel section. The reference specimen was a concrete filled GFRP tube. The research concluded that rupture of the GFRP tubes is the dominant failure mode, and the proposed hybrid column has higher strength and deformation (due to the steel I section reinforcement) than the concrete filled FRP tube.

The same type of hybrid FRP-steel column section was used by Zhang et al. [75] to strengthen the axial behaviour of steel members (Figure 10). They tested different cross sections of the steel core that were surrounded by pultruded FRP tube. The space between steel section and FRP tube was filled with mortar. The results reported in this study showed that both the bearing capacity and the capacity of axial deformation had been enhanced.

4.3 Other types of hybrid FRP columns

Hu et al. [76] , Xie and Ozbakkaloglu [77] and Gao et al. [40] tested another type of hybrid FRP columns to examine the axial behaviour of circular FRP tubes that were reinforced with either steel tube (no gap between FRP tube and steel tube), steel fibre or steel wire mesh and filled with concrete. FRP tubes were fabricated via wet lay-up procedure of unidirectional fibre sheet in the hoop direction. Hu et al. [76] tested three series of specimens with various diameters to thickness ratios of the steel tube and each series consisted of three confined specimens and one unconfined. The thickness of the FRP jacket was ranging from 0.17 to 0.68 mm. In this combination, steel tube is prevented to buckle inward and outward by the concrete and FRP jacket respectively. The research pointed out that the compressive behaviour of concrete filled steel tube is improved because firstly, the buckling failure of steel tube is delayed by the FRP wrap, and secondly, additional confining pressure is created by FRP wrapping.

Xie and Ozbakkaloglu [77] used steel fibre to reinforce concrete filled FRP tubes. They studied the effect of fibre volume fraction, fibre aspect ratio and fibre shape on the axial behaviour of specimens with dimensions 152.5 mm in diameter and 305 mm in height. The results indicate that the axial behaviour is influenced significantly by the presence and the amount of steel fibre, whereas the fibre shape and its aspect ratio have less influence. Gao et al. [40] used wire mesh as a reinforcement to make hybrid FRP column. They reinforced their specimens that confined with FRP tubes by using a steel wire mesh and compared its results with unreinforced specimens. The thickness of GFRP tube and wire mesh volumetric ratio were chosen as research parameters. The test results show that the strength and ductility of reinforced specimens are improved.

4.4 Assessment of the axial behaviour of the FRP hybrid columns

The confined concrete strength of FRP hybrid specimens (inner steel is empty) is calculated after subtracting the axial load resisted by the steel tube from the total load. Then, the concrete load at failure was divided by the cross sectional area of the concrete. The contribution of steel tube was assumed to be equal to the load carrying capacity of hollow steel tube. This procedure was followed by Teng et al. [67], Fanggi and Ozbakkaloglu [68] and Ozbakkaloglu [69]. A simple model of FRP hybrid columns was proposed by Yu et al. [78]. They modified the design oriented stress-strain model proposed by Teng et al. [35] to consider the influence of the hollow inner steel tube. This model was used to model the stress-strain curve of concrete in hybrid FRP columns subjected to cyclic axial compression and of high strength concrete in hybrid filament-wound FRP columns by Yu and Teng [79] and Zhang et al. [73] respectively. Another model was proposed by Yu and Teng [79] for the square FRP hybrid columns. The model of the FRP hybrid columns filled with light weight concrete was suggested by Zhou et al. [72]. In cases of filled inner steel tube , the concrete core will be confined by both FRP and steel tubes [76]. As a result, models of FRP confined concrete should be adjusted before using to shape stress-strain curves by considering the confinement effects of FRP and steel tubes. Gao et al. [40] investigated confinement effect of steel wire mesh and proposed model to predict the ultimate compressive behaviour while a theoretical model had been proposed by Deng et al. [80] for FRP- steel concrete column.

4.5 Summary of hybrid FRP columns

The use of traditional construction material (steel and concrete) and the FRP tube to form hybrid FRP columns is similar to the first one because the orientation of fibres sets towards transverse direction of the column in order to create confining pressure. Furthermore, most studies were conducted on short column specimens. Although the main reason to innovate hybrid FRP columns is to provide the light weight property, the hybrid FRP columns are ever evolving by the use of fillers, steel tubes or steel I sections. This process provides hybrid FRP–steel concrete column which can be researched in two ways. The first one is the axial behaviour of hybrid column and the second one is the improvement in the axial behaviour of steel section due to strengthening with concrete filled FRP tube. Table 3 gives a summary of research on FRP hybrid columns.

5. Gaps in knowledge

Factors that influence the degree of confinement are studied extensively in the past. Majority of the research used circular concrete specimens with height-to-diameter ratio equal to 2. These short columns will not fail due to local or global buckling. The combined effect of the slenderness ratio and effects of other factors that influence the degree of confinement are not investigated for columns at height-to-diameter ratio greater than 5 to specify how the axial strength and ductility of slender columns can be improved. Furthermore, it is important to study FRP confined lightweight concrete intensively because most previous studies examined the axial behaviour of FRP confined normal concrete or high strength concrete columns. The confinement of the light weight concrete columns results in improvements in its ability to resist the axial load [29]. Consequently, the applicability to use FRP confined light weight concrete columns instead of unconfined normal concrete columns in construction industry will be increased. This will be an economical application because the dead load of the structural column members will drop.

A general study to describe the effect of potential variables in the behaviour of pultruded FRP profiles having fibres in multiple directions is not done into greater depth in the past. Moreover, using a filler material with the pultruded FRP tubes to increase the stiffness of FRP tubes is not reported for short and slender columns.

The application and potential opportunities of FRP closed sections in civil and structural engineering will be improved due to further investigations into overcome the barriers that prevent them to be included in construction. Although extensive research have been done, significant and potential gaps in knowledge are still there. The combined effect of the slenderness ratio of the column and other factors such as strength of infill concrete, thickness and diameter of inner steel are not studied in depth. Particularly in the area of slenderness effects on the degree of confinement for concrete columns, the axial behaviour of the hollow and filled pultruded FRP tubes that having fibre in multiple-directions and the different shapes of the hybrid FRP columns. Moreover, the use of lightweight concrete will provide an opportunity not to compromise much of the light weight feature of the FRP profiles. These areas will contribute to fill the gaps in knowledge which will improve the use of FRP tube in construction industry.

6. Conclusions

This paper reviewed three broad areas of FRP tubes in column applications in either new or existing construction; concrete columns confined by FRP, all FRP columns and hybrid FRP columns. Based on comprehensive review in this research area, the authors identify the following key findings.

- Research on FRP as a confinement has been well established over the last three decades which resulted in their enhanced structural applications.
- While research has been conducted on all FRP profiles, one of the major challenge is the adverse effect of buckling on overall axial performance. As a

result there is a need to modify the cross sections in order to effectively utilise the capacity.

Research into the use of hybrid FRP columns is another area which will enhance the applications of these lightweight tubes. The following further investigations are recommended in order to address major challenges related to broader utilisation of FRP profiles in structural applications.

- Investigate the effect of the properties of filler material (light-weight, stiffness and creep) and properties of FRP (prestressed) on the behaviour of FRP confined concrete columns under concentric and eccentric loads.
- Investigate the axial behaviour of pultruded FRP profiles having fibres in the multiple directions under both concentric and eccentric loads for various cross section and support conditions.
- Comprehensive research work on FRP confined concrete column with larger length/ least dimension ratio to study the combined effect of slenderness ratio and other factors.
- Examine the improvement in the strength and strain capacities of the non-circular concrete columns. This improvement can be created through confining the core of the concrete column with circular FRP tube that has fibres only in the hoop direction. This gives an opportunity to keep the original shape of the column and increase its capacity to resist loading.

Once these further studies are completed, there will be improved knowledge on the use of filled FRP tubes as column members which will enhance their applications in civil infrastructure.

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All Figures

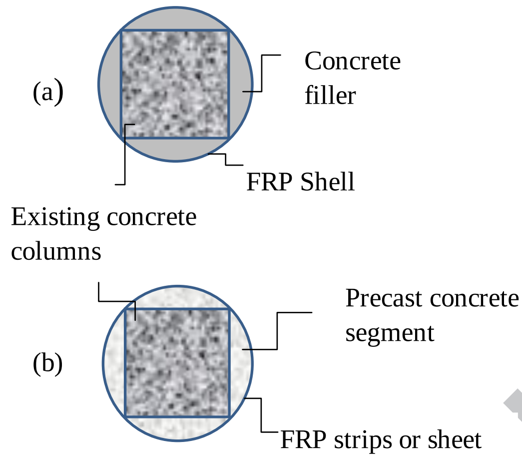


Figure 1. Modification methods of non-circular sections (a) using prefabricated FRP shell and (b) using precast concrete segment.

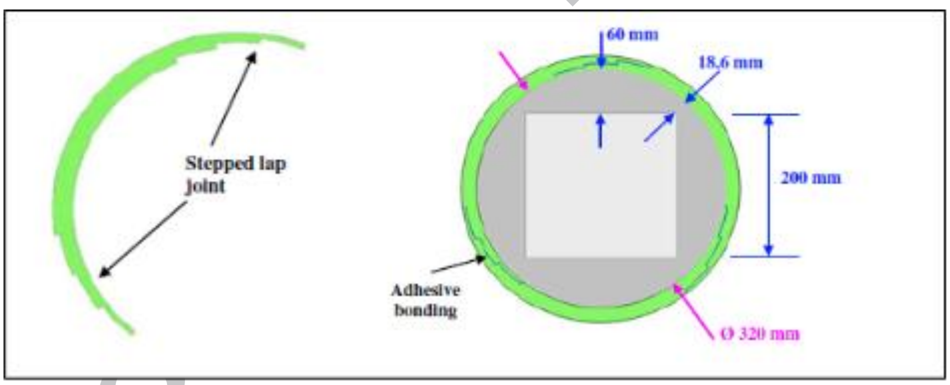


Figure 2. Stepped lap joint of GFRP shell to modify the square concrete columns [9].

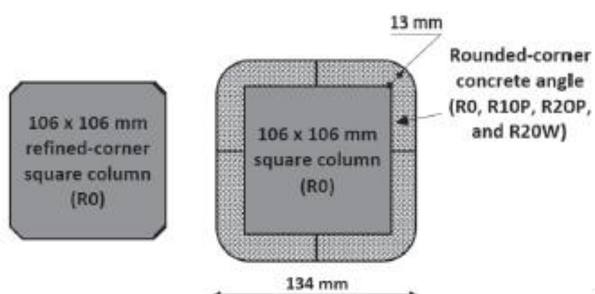
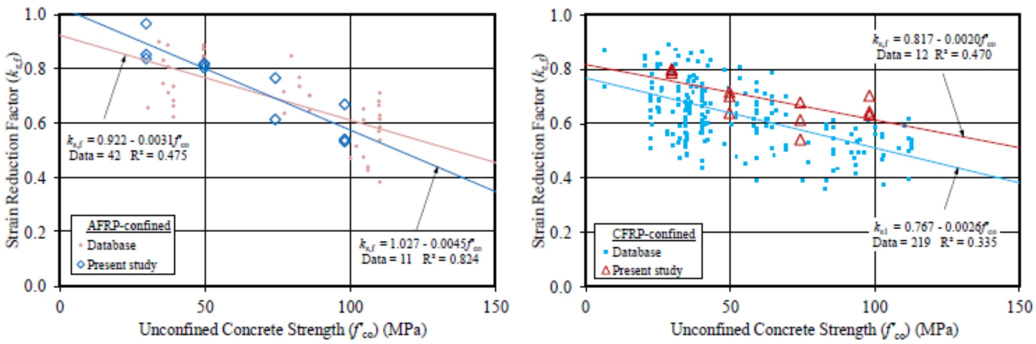


Figure 3. Refined –corner and rounded-corner methods to modify the shape of the square columns [22].



(b)

Figure 4. Effect of unconfined compressive strength on the hoop strain reduction factor: (a) Aramid FRP confinement (b) Carbon FRP confinement [25].

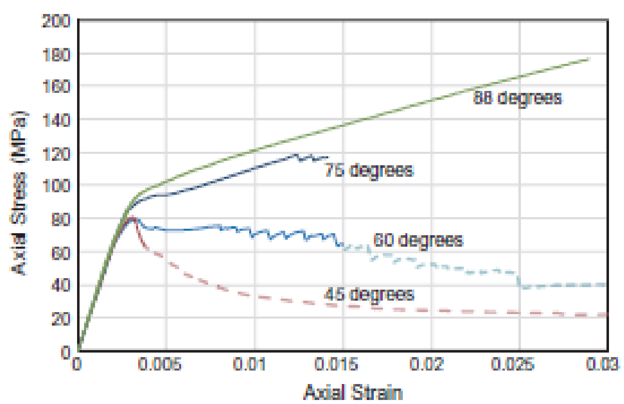


Figure 5. Effects of fibre orientation on the performance of confined concrete specimens [6].

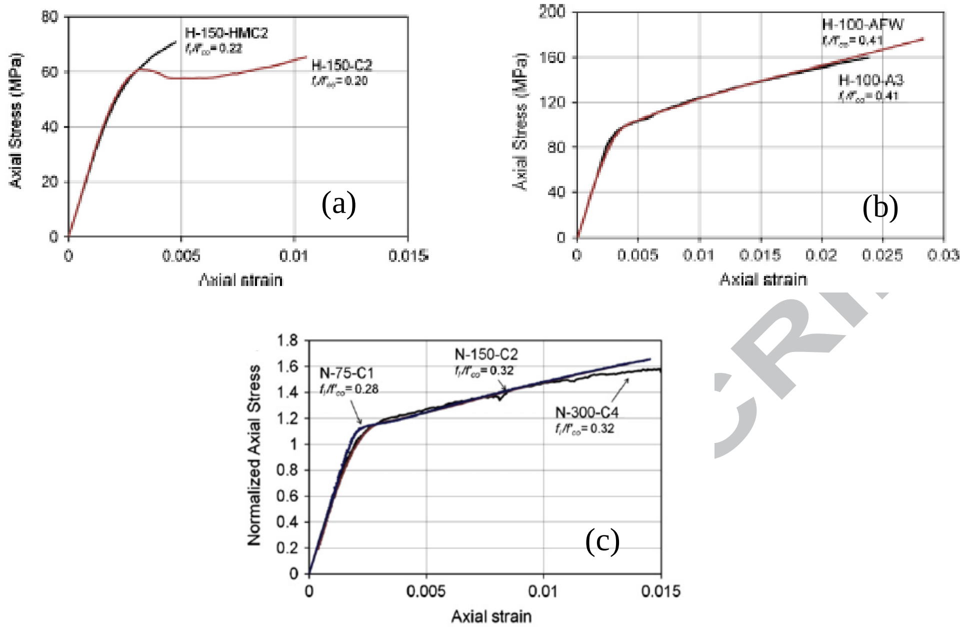


Figure 6. Effects of different parameters on the compressive behaviour of circular samples (a) FRP tubes with different modulus [32], (b) Manufacturing methods of tubes (lay-up and filament winding) [32] and (c) Diameter of specimens [33].

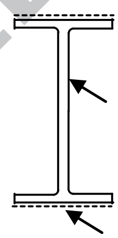


Figure 7. Improving the behaviour of pultruded I- section.

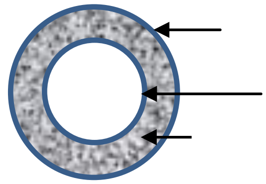


Figure 8. Hybrid columns.

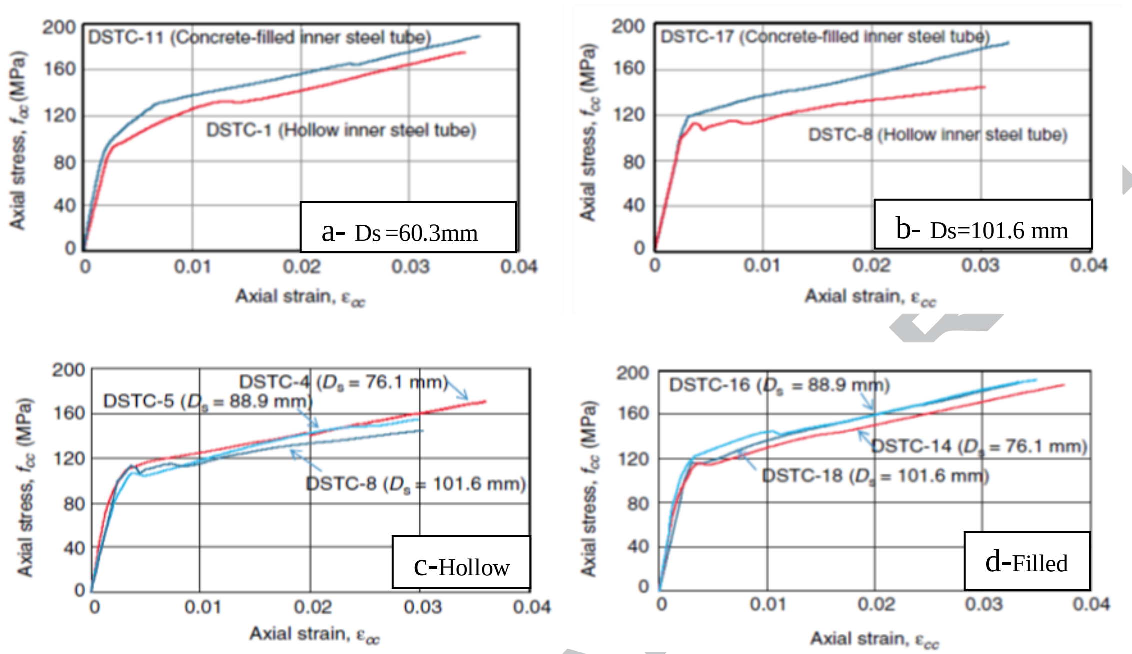


Figure 9. Influence of the size and the filling of inner steel tube with concrete on the axial behaviour of DSTCs [65].

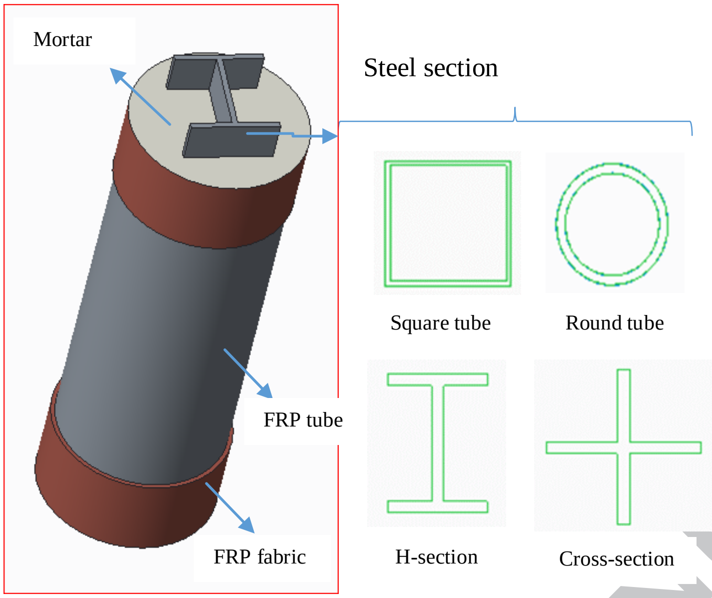


Figure 10. Different steel sections in hybrid FRP-steel column.

All Tables

Table 1 Summary for concrete columns with FRP confinement

Reference	Cross section	Fibre type	Stacking sequence(respect to the axial direction of the tube)	$f`_{co}$ (MPa)	$\frac{f'_{cc}}{f'_{co}}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}$
Mirmiran et al. [10]	Circular	Glass	Unidirectional E-glass fibres (±75˚), (t=3.68 mm)	22.4	-	-
Pessiki et al. [15]	Circular+ Rectangular	Glass Carbon	1- Multidirectional E- glass (0˚/±45˚)* 2- Woven unidirectional E-glass (0˚)* 3- Unidirectional carbon sheet (0˚)*	26-32	1.12-2	1.4-8
Mortazavi et al. [3]	Circular	Carbon Glass	Pre-formed confining jackets	32	1-4	-
Hong and Kim [4]	Circular+ Square	Carbon	Filament wound (t=3 mm) 90˚/90˚ - 90˚/±60˚ - 90˚/±45˚- 90˚/±30˚	17-19	1.2-5	11.2-23
Fam et al. [16]	Rectangular	Glass	Filament wound $(90˚/(\pm45˚)_2/(0˚)_2/90˚/(0˚)_2/(\pm45˚)_2/90˚)$	52	-	-
Yan et al. [19]	Square, circular rectangular	Carbon, Glass	Unidirectional prefabricated shell	10-15	-	-
Mohamed and Masmoudi [39]	Circular	Carbon, Glass	Confine reinforced concrete column. $\pm60_{3,4}˚$, ($\pm65_3˚$, ±45˚, $\pm65_3˚$), (60˚, $90_4˚$, 60˚), (±60˚, $90_2˚$, ±60˚, $90_6˚$)	30,45	1.6-4.2	-
Fitzwilliam and Bisby [12]	Circular	Carbon	Unidirectional CFRP sheet towards hoop and longitudinal directions of RC columns	30.5	1.1-1.7	-
Kim et al. [5]	Circular	Carbon	CFRP sheet wrapping (t=1.8 mm) 90˚/90˚ - 90˚/±75˚- 90˚/±60˚- 90˚/±45˚ - 90˚/±30˚	17.5	2.2-4.17	4.5-12.3
Hadi et al. [20]	Square	Carbon	Horizontal wrapping with CFRP layers	32	-	-
Ozbakkaloglu and Zhang [33]	Circular, Square, Rectangular	Carbon, HM carbon, Aramid	Wrapping fibre sheet by wet-layup	55-100	-	-
Ozbakkaloglu [32]	Circular	Carbon HM-carbon Aramid	The majority of FRP tubes that their results were considered made with wet lay-up process.(fibre sheet in the hoop direction)	36-110	1.13-2.77	1.7-14.1
Vincent and Ozbakkaloglu [24]	Circular	Carbon	Unidirectional carbon sheet is used to confine specimens either by wrapped concrete cylinder or precast CFRP tube.	35-65,100	1.01-1.68	1.6-7.16
Vincent and Ozbakkaloglu [6]	Circular	Aramid	1- Filament winding tube with angles (45, 60, 75 and 88) degrees. 2- Wet lay-up process at 90 degree. 3- wrapped cylinder via wet lay-up process (90)	50 - 85	1.0-2.23	1.5-14.8
Lim and Ozbakkloglu [25]	Circular	Aramid Carbon	FRP single continuous sheets wrapped by using manual Lay –up method around polystyrene forms in the hoop direction.	25-100	-	-
Yu et al. [26]	Circular	Glass Carbon	FRP Jackets (wet lay-up process)	30-105	1.1-2.09	2-7.89
Zhao et al. [27]	Circular	Glass	Wrapped in the hoop direction with unidirectional glass fibre sheet.	34-45	1-1.8	3-6.3
Siddiqui et al. [14]	Circular	Carbon	Unidirectional CFRP sheet towards hoop and longitudinal directions of RC columns.	35	-	-
Vincent and Ozbakkaloglu	Circular	Aramid	Wrapping unidirectional aramid fibre sheet around Styrofoam templates in the	100-110	1.2-2.11	5.4-7.97

[41]			hoop direction.			
Qasrawi et al. [8]	Circular	Glass	Continuous glass fibre wound (± 55˚)	34	-	-
Beddiar et al. [9]	Square	Glass	Twill weave glass	38.2	1.31	1.76
Vincent and Ozbakkaloglu [11]	Circular	Aramid	Unidirectional aramid fibre sheet wrapped in the hoop direction	55-110	1-1.73	3-11
Gao et al. [40]	Circular	Glass	GFRP sheets	29.7	-	-
Zhou et al. [29]	Circular	Carbon	CFRP sheets	19-48	1.4-5.17	3.9-32
Lokuge and Karunasena [30]	Circular	Carbon Glass	Wrapping fibre sheet by wet-layup	19-45	1.1-2.7	1-1.8
Ozbakkaloglu and Xie [18]	Circular Square	Carbon S- glass Basalt	Wrapping fibre sheet by wet-layup	25	1.1-2.48	5.2-13.5
Xie and Ozbakkaloglu [28]	Circular Square	Carbon Basalt	Manual wet layup with unidirectional carbon and basalt fibre sheet	37-66	1.1-1.4	5.8-11.6
Zeng et al. [23]	Square	Carbon	Wrapping unidirectional CFRP sheet by wet-layup	24.3	0.9-2.91	1.58-8.33
Youssf et al. [22]	Square	Carbon	Wrapping unidirectional CFRP sheet by wet-layup	48.8-51.5	1-1.69	1-4.21
Bhowmik et al. [21]	Rectangular	Car-bon	Wrapping unidirectional CFRP sheet by wet-layup	24-27.2	-	-
Wang et al. [31]	circular	E-glass	Filament –wound process (± 85˚)*	61-64	1.3-3.4	9.3-13.8
Lam and Teng [34]	Collected 76 results from others and present new model to anticipate the strength and strain capacities of FRP confined circular concrete specimens.			-	-	-
Teng and Lam [7]	Review paper	-	-	-	-	-
Teng et al. [38]	Collected results from others and present new model to anticipate the strength and strain capacities of FRP confined circular concrete specimens.			-	-	-
Teng et al. [35]	Make refinement to the previous Lam- Teng model			-	-	-
Jiang and Teng [13]	Circular	-	This paper present a theoretical model for FRP confined slender RC columns.	-	-	-
Ozbakkaloglu et al. [36]	Review paper	-	-	-	-	-

Notes: $f`_{co}$, ε_{co} = Unconfined compressive and strain of concrete values.

f'_{cc}, ε_{cu} =Confined compressive and strain values.

* Respect to the circumferential direction of the column.

Table 2 Summary on all FRP columns.

Reference	Cross section	FRP type	Stacking sequence(respect to the axial direction of the tube)	Enhancement methods	Critical load (kN)	Failure mode
Barbero and Raftoyiannis [43]	Box I- section	-	Pultruded	Analytical model.	-	LB
Barbero and Tomblin [52]	I –sction	-	Pultruded	-	79.2-174	LB+GB
Zureick and Scott [53]	I -section square	E-glass	Vinyl ester matrix reinforced with E-glass roving and nonwoven mats was used to made sections	-	33-494 54-334	GB
Fam and Rizkalla [64]	Circular	Glass	1-(+8˚/-86˚/(-86˚/+8˚)3/-86˚) 2-(-88˚/-88˚/+4˚/-88˚/(-88˚/+4˚)2/-88˚) 3-(0˚) pultruded 4-(-87˚/+3˚)4/-87˚) 5- (+15˚/-82˚/(-82˚/+15˚)3/-82˚)	Filled with concrete	350	Tube splits
Hashem and Yuan [46]	Universal square	E-glass	Specimens were made by using continuous filament at (o˚), continuous mat and woven roving (o˚/90˚)	-	468-1361 185-663	LB,GB,CE
Puente et al. [54]	Circular	Glass	Pultruded	-	-	LB,GB
Qian et al. [49]	circular	Glass	Short Pultruded tube. Long pultruded tube	- -	71-92 10-60	LC GB
Bai and Keller [57]	Rectangular	Glass	Pultruded	-	25-148	Delamination (shear failure)
Han et al. [65]	Circular	Carbon Glass	Pultruded	Insert FRP tube into glass or carbon braid		-
Correia et al. [44]	I -sections	Glass	Pultruded (layers of unidirectional roving and strand mat)	Adding carbon sheet in the outer face of flanges	533-625	LB
Godat et al. [50]	angle Rectangular Square I- section	Glass	Pultruded	-	32.6 339 716 18.6-67	LB
Li et al. [42]	Circular	Glass	Pultrusion method (fibres lay in the axial direction)	Wrapping with CFRP sheet	Rupture CFRP sheet and splitting GFRP tube	
Gangarao and Blandford [56]	Square Wide flange	Glass	Pultruded	-	44.5 44.5	GB GB,LB, CM
Guades et al. [51]	Square	Glass	Pultruded	-	540-590	LB,CE
Cardoso et al. [55]	Square	Glass	Pultruded	-	13.2-957	GB,LB,CM,CE, LB+GB
Nunes et al.	I-section	Glass	Pultruded	Partial	133-690	LB, web-

[66]	replacing of GF mats with CF mats	flange split, GB+LB, GB

Notes: GB=Global buckling, LB=Local buckling, CE=Crushing at end, CM=crushing at mid, GB+LB= buckling interaction, LC=longitudinal crack.

Table 3 Summary of hybrid FRP columns

Reference	Components of hybrid FRP columns	Cross section	FRP type	Stacking sequence*	Dimensions of steel tube (mm) d	t	Gap between tubes (mm)	f'_c (MPa)
Teng et al. [67]	FRP tube, concrete, steel tube	Circular	Glass	Wrapping FRP sheet in the hoop direction	76.1	3.2	38.2	39
Fanggi and Ozbakkaloglu [68]	FRP tube, concrete, steel tube	Circular	S-Glass	Wet layup process of fibre sheet in the hoop direction	60-114	3.2,6	-	82.4-96.2
Ozbakkaloglu [69]	FRP tube, concrete, steel tube	Circular Square	Aramid	(lay –up process)Unidirectional aramid fibre sheet	88.9,114.3	3.2, 6	31.8,19.1	49-113
Zhang et al. [70]	FRP tube, concrete, steel tube	Circular	Glass	Filament winding (± 80˚)	219	6	40.5	37-114
Zhang et al. [75]	FRP tube, concrete, steel section	Circular	Glass	Pultruded GFRP tube	Cross, H, circle and square sections		-	36
Xue and Gong [74]	FRP tube, concrete, steel section	Circular	Glass	Filament winding (55˚)*	I -section		-	39-51
Hu et al. [76]	FRP wraps, steel tube, concrete	Circular	Glass	Wet –layup with fibres in the hoop direction	202-204	1-2	0	35-42
Cao et al. [71]	FRP tube, concrete, steel tube	Circular	Carbon	(lay –up process) fibre sheet	150 114 89 60	3.5 4.5 4 4	-	26-32
Zhou et al. [72]	FRP tube, concrete, steel tube	Circular	Carbon	Alternate and orthogonal arrangement of unidirectional carbon fibre sheet.	42 55 71	2 2 2	55.4 49.15 41.1	39.8
Zhang et al. [73]	FRP tube, concrete, steel tube	Circular	Glass	Filament winding (± 80˚)	159 120 219	5 4.5 6	-	40-104
Xie and Ozbakkaloglu [77]	FRP tube, concrete, steel fibre	Circular	Aramid	(lay –up process)Unidirectional aramid fibre sheet	Hooked end , crimped steel fibre		-	116-125
Gao et al. [40]	FRP tube, concrete, steel wire mesh	Circular	glass	(lay –up process) fibre sheet	reinforcement ratio of steel mesh (0.31,0.6,0.89)%		-	29.7

* Respect to the hoop direction of the column.