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Behaviour of FRP composite columns: Review and analysis of the section forms

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Abstract. As confining materials for concrete, steel and fibre-reinforced polymer (FRP) composites have important applications in both the seismic retrofit of existing reinforced concrete columns and in the new construction of composite structures. We present a comprehensive review of the axial stress-strain behaviour of the FRP-confined concrete column. Next, the mechanical performance of the hybrid FRP-confined concrete-steel composite columns are comprehensively reviewed. Furthermore, the results of FRP-confined concrete column experiments and FRP-confined circular concrete-filled steel tube experiments are presented to study the interaction relationship between various material sections. Finally, the combinations of material sections are discussed. Based on these observations, recommendations regarding future research directions for composite columns are also outlined.

Keywords: FRP-confined concrete; the hybrid FRP-confined concrete-steel composite columns; the mechanical performance; the interaction relationship

1. Introduction

In the past three decades, researches regarding the applications of fibre-reinforced polymer (FRP) composite materials in civil engineering have been rapidly developed (Adil *et al*. 2014, Ahmed 2014, Afifi *et al*. 2015, Sumathi and Arun 2017, Youssf *et al*. 2015,2016). Based on a large number of experimental and analytical researches (Farid and Adel 2015), it is now clearly understood that FRP is a useful constraining material for concrete structures and that the applications of FRP can significantly improve the mechanical performance, seismic performance and durability of a structure. In previous researches, multiple constitutive models of FRP-confined concrete were proposed to analyse and simulate the axial mechanical performance of concrete with FRP constraints. Most studies have been focused on the composite structure, which involves the combination of FRP, steel and concrete. As the composite can benefit from the characteristics of the constituent materials to improve the mechanical performance of the structure, the manner of combination is the most important aspect in the relevant researches; the composite structure should not only take full advantage of the combined effect of the three materials but also meet the practical demands in engineering practice.

New types of composite columns made of FRP, steel and concrete have been developed on the basis of the conventional FRP-confined concrete column to improve the fire resistance, seismic performance and durability of composite columns; these new types of composite columns can be classified as follows: (a) FRP-confined concrete-encased steel columns (FCCSCs), which consist of an FRP outer tube, an I-, H-, or cross-shaped steel section and concrete filling the intermediate spaces; (b) FRP-confined concrete-filled steel tubes (CCFTs), in which concrete-filled steel tubes (CFTs) are confined using FRP to improve mechanical performance and corrosion resistance; and (c) hybrid FRP-concrete-steel double-skin tubular columns (DSTCs), which are formed of a layer of concrete sandwiched between an outer tube consisting of FRP and an inner steel tube that provide the well mechanical performance, strong shear resistance performance and excellent corrosion resistance of these columns. However, few researches have analysed the combined characteristics of the three materials in depth to take full advantage of the section shape and effective combination of the various materials so that they complement each other in a manner that addresses their limitations.

The purpose of this study is to analyse FRP-steel composite columns of various cross sections considered in previous researches, it can be the foundation to study a design method for composite columns. In this study, the mechanical performance of traditional FRP-confined concrete columns are first reviewed and analysed. To this end, the mechanical performance of the various sectional forms are studied in detail. The characteristics of the three types of materials after being combined are obtained.

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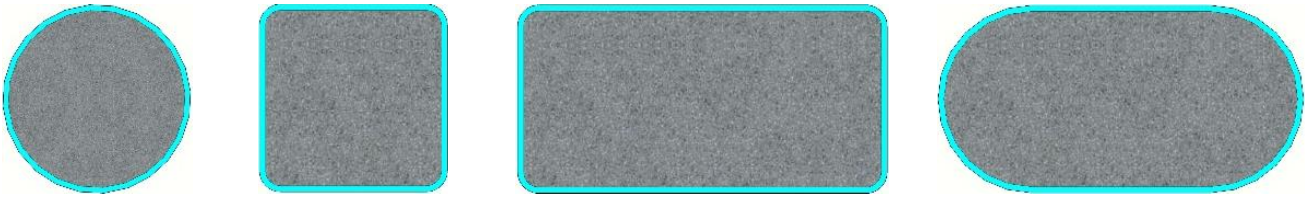


(a) Circle (b) Square (c) Rectangle (d) Capsule shape

Fig. 1 Sectional shapes of FCC

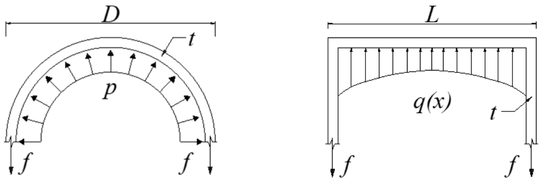
Moreover, the inadequacies of the proposed section forms are determined. In addition, two experiments are conducted to study the mechanical performance of confined concrete and the combination effect of the three materials. In the final part, we apply the three materials in a complementary manner and outline recommendations regarding future research directions for optimizing the section form.

2. FRP-confined concrete column (FCC)

The concrete is the most complex material in composite structures, due to the confining effect. The mechanical performance of confined concrete should be further studied based on FRP-confined concrete. An FRP-confined concrete column (FCC) consists of an FRP outer tube filled with concrete. Similar to CFTs, the lateral confining pressure (p) provided by the FRP shell distributed around the core concrete is assumed to greatly increase the compressive strength and ductility of the concrete. The differences between FCC and CFT are summarized as follows: 1) the concrete in FCC is passively confined because FRP is a linear elastic material (i.e., the lateral pressure increases as a result of the lateral expansion of concrete under axial compression), whereas the concrete in CFT is actively confined because the steel stress shows no significant variation after yield stress (i.e., the lateral pressure tends to be constant after the first stage in the stress-strain curves); 2) the ultimate failure modes of FCC are accompanied by sudden stress reductions when the FRP shell ruptures, whereas the ultimate failure of CFT is due to the local buckling of the steel tube, and failure does not correspond to a significant change in the stress-strain curve; 3) the vertical bearing capacity of the FRP tube in FCC can be neglected, whereas the steel tube provides part of the vertical bearing capacity in CFT. In this section, the researches of FCCs are reviewed and analysed.

2.1 Axial compressive properties of FRP-confined concrete columns

The force mechanism of the FCC is simple: the FRP provides lateral pressure to restrict the lateral expansion of the concrete. Previous experimental researches (Lim and Ozbakkaloglu 2015a, Piekarczyk *et al*. 2011, Realfonzo and Napoli 2011, Soheil and Javad 2017, Xie and Ozbakkaloglu 2015) have indicated that FRP can provide an efficient confining effect that improves the strength and ductility of the core concrete. Moreover, the main factors of the mechanical performance are the unconfined concrete



(a) Circle (b) Square and rectangle

Fig. 2 Force sketch of FCC sections

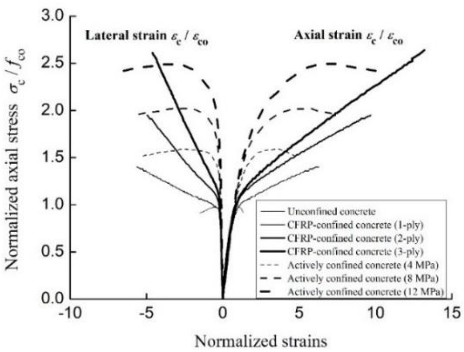


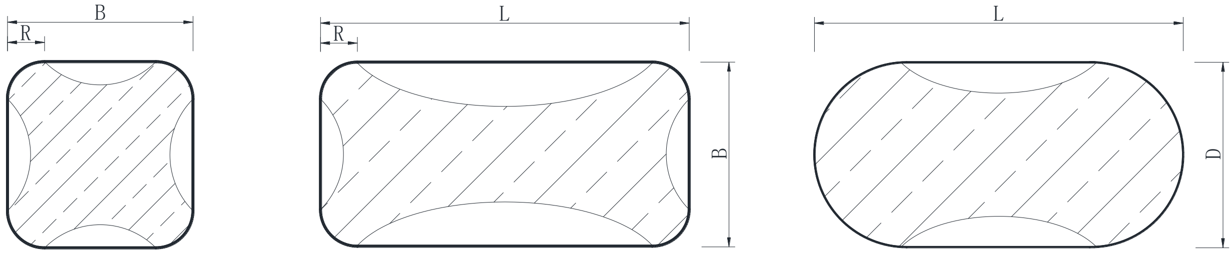
Fig. 3 Axial stress versus axial and lateral strains of FRP-confined and actively confined concrete (Candappa *et al*. 2001, Lam and Teng 2004, 2006)

properties, the FRP properties, the sectional shape and the sectional size. The lateral pressure provides a beneficial confining effect on low-strength concrete, and the high elasticity modulus and large thickness of the FRP tube can provide additional confining pressure. Moreover, the sectional shape, e.g., circular (Fig. 1(a)), square (Fig. 1(b)), rectangular (Fig. 1(c)) and capsule shape (Fig. 1(d)), influences the distribution of the lateral pressure.

In consideration of different 10m height wind speed v10 and the power law exponent index α results shown in Table 2, the representative upstream typhoon wind fields at different directions used as the input data for training ANN model are determined, which is shown in Tables 1-2.

2.1.1 Circular sections

In FRP-confined circular concrete sections, the lateral confining pressure (p) provided by the FRP shell is uniformly distributed around the circumference, as shown in Fig. 2(a). The lateral confining pressure can be computed by $p=f_{\mathrm{frp}}/D$, where f_{frp} is the pulling force provided by the FRP tube. FPR-confined concrete is passively confined, and its mechanical performance are different from those of actively confined concrete. The axial stress versus axial and lateral strain curves of various types of concrete are shown in Fig. 3, and the data is collected from the experimental



(a) Circle (b) Rectangle (c) Capsule shape

Fig. 4 Confining area of FCCs

researches (Candappa *et al*. 2001, Lam and Teng 2004, 2006). The trend of the stress-strain curves of actively confined concrete is similar to that of unconfined concrete; however, the constant confining pressure plays an important role in the process. Generally, the stress-strain curve of FCC shows a bilinear trend: the first stage is almost the same as that of unconfined concrete, the second stage is controlled by FRP, and the intersection point between the two stages is slightly higher than the peak point of unconfined concrete. Concrete cylinders confined by a variety of FRP types of the same stiffness as the FRP tube were studied by Fahmy and Wu (2010), who found that the mechanical performance are irrelevant to the FRP type and proposed an axial stress computational model based on the lateral stiffness. Furthermore, 253 experimental researches on FRP-confined concrete cylinders were reviewed and analysed by Ozbakkaloglu and Lim (2013); the accuracy of the test data was assessed based on trends obtained from a large database. The authors suggested that the actual rupture strain is smaller than the material test data and is the key parameter required to compute the ultimate stress. In addition, the reduction coefficient of FRP was proposed to establish models of the axial ultimate stress and strain. Vincent and Ozbakkaloglu (2013) followed this work with a study of the relationship between the reduction coefficient and the unconfined concrete strength. These prior research results can be summarized as follows: 1) the reduction coefficient is independent of the thickness of the FRP tube; 2) the reduction coefficient decreases with increasing unconfined concrete strength; and 3) the existing stress model cannot accurately forecast the characteristics of high-strength concrete. Moreover, Dong *et al*. (2015) concluded that the intersection point between the two curve stages is related to the stiffness of the FRP and that the ultimate stress is related to the actual rupture strain, that is, the reduction coefficient should be introduced into the stress-strain models. In addition, the FRP types were studied by Bouchelaghem *et al*. (2011); the results indicated that carbon FRP (CFRP) has a high stiffness, a small rupture strain and a large reduction coefficient, i.e., the material utilization rate is high. In summary, the confined concrete in circular sections is confined by uniformity stresses, it can be as the research foundation for all kinds of confined concrete. The confining effect is depended on the confining materials, unconfined concrete strength and sectional size.

2.1.2 Non-circular sections

In addition to FRP-confined concrete cylinders, square and rectangular columns are widely used in practical engineering. The core concrete in these two sections is non-uniformly confined, as shown in Fig. 2(b). Therefore, the mechanical performance are relatively complex. Multiple experimental and theoretical researches (Lo *et al*. 2015, Lim and Ozbakkaloglu 2015b, Saleem *et al*. 2017, Zhang *et al*. 2010) have been conducted over the past two decades to characterize square and rectangular FRP-confined concrete columns. The mechanical performance can be summarized as follows: 1) the ultimate axial strain of the two sectional columns is larger than that of circular columns; 2) the core concrete in the two sectional columns is subjected to non-uniform confining pressure (the confining effects are shown in Fig. 4; the section can be divided into two parts: the effective confined area, which is the shaded area in Fig. 4, and the invalid confined area, which is the blank area in Fig. 4); 3) the lateral strain of the sectional corner is the region that governs the ultimate failure; 4) the sectional corner is chamfered, and the effective confinement area increases with increasing chamfer radius, leading to an improved confining effect; and 5) the effective confinement area increases with decreasing length-to-width ratio, and, according to the length-to-width ratio study of Wu and Wei (2010), the length-to-width ratio does not change the axial ultimate strain of the columns, with the peak stress enhancement effect in the concrete being negligible for a length-to-width ratio greater than 2.

Sectional corners were studied by Ozbakkaloglu (2013), who found that the radius of the section chamfer plays an important role in the mechanical performance of the confined concrete. They observed that with increasing chamfer radius, the effective confinement area increases, whereas the axial ultimate strain decreases. Moreover, based on further study of the corner strengthening phenomenon, the confining pressure was found to become more uniform, and the confining effect was found to improve as the ultimate stress increases. The most important finding is that the FRP rupture area changes from the corner to the central area. The mechanical performance of FRP-confined square and rectangular concrete are complex due to the non-uniform confinement; the axial stress-strain curves of rectangular concrete for various FRP-confinement effects (Wu and Wei 2010) are shown in Fig. 5. The characteristics of the stress-strain curves of FRP-confined rectangular concrete are summarized as follows: 1) if the confining pressure is adequate, then the curves show bilinear trends, in agreement with concrete of circular section; 2) if the confining pressure is low, then the curves

Table 1 The mechanical performance of FRP-confined concrete

Section form	Confining type	Mechanical performance	Stress-strain curve
Circular section	Uniform confining	Great strength improvement; ductility improvement, depend on the property of FRP tube.	The curve shows a bilinear ascending trend.
Rectangular section	Non-uniform confining, effective confining section is distribution at corners.	Great ductility improvement; Larger strength improvement, it is negligible for length to width ratio greater than 2.	a) With enough confining effect, the curve shows a bilinear ascending trend; b) With dividing confining effect, the curves show two ascending stages and a horizontal stage; c) With insufficient confining effect, the curves show two ascending stages and a decreasing stage.
Capsule section	Non-uniform confining, effective confining section is distribution at short sides.	Great ductility improvement; Larger strength improvement, it is greater than the property of rectangular sections.	Great ductility improvement; Larger strength improvement, it is greater than the property of rectangular sections.

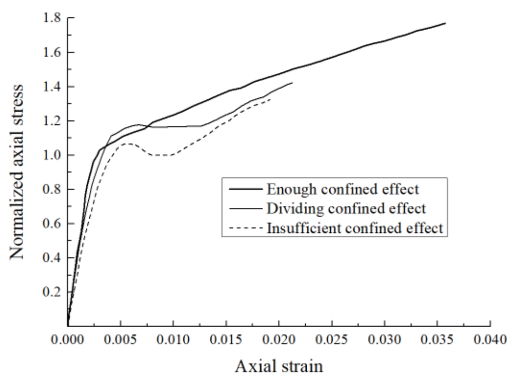


Fig. 5 Axial stress-strains of rectangular FRP-confined concrete (Wu and Wei 2010)

exhibit trilinear trends with a horizontal stage; and 3) if the confining pressure is insufficient, then the curves show trilinear trends with a decreasing stage. Generally, with the confining pressure provided by non-circular sectional FRP, most FRP-confined square and rectangular concrete configurations show the third type of curve. According to the study by Tan *et al*. (2013), the corner area is the governing part of the special-shape section, as mediated by the expansion of this area (called capsule shape), as shown in Fig. 1(d). With confinement of the semi-circular side, the stress-strain curve shows a bilinear trend; that is, the concrete is strongly confined by the FRP tube. However, the engineering application value is low.

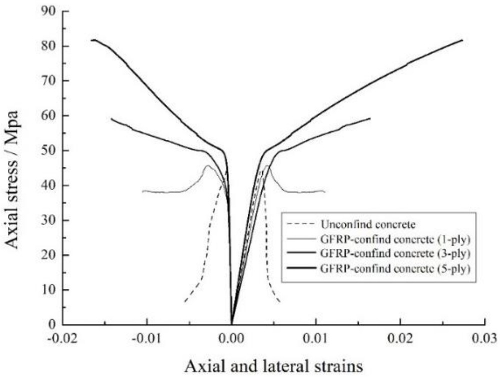
2.1.3 Summary

Based on above researches about composite columns, the core concrete could be divided into actively confined concrete (i.e., concrete filled steel tube and stirrup confined concrete) and passively confined concrete (i.e., FRP-confined concrete). The confining materials could improve the strength property and ductility of concrete. However, the mechanical performance of passively confined concrete is complex, and they were summarized in Table. 1. As is shown in Table 1, the section form could reflect the distribution of confining pressure, and the confining effect could reflect the relationship between confining pressure and unconfined concrete strength. Finally, the following conclusions could be drawn: 1) strength improvement effect ranking is circular section, capsule section, rectangular section; 2) ductility improvement effect ranking is rectangular section, capsule section, circular section; 3) with the large or low confining pressure, the stress-strain curves show different trends for rectangular confined concrete.

2.2 Further study of FRP-confined concrete

Most factors for the mechanical performance of FRP-confined concrete involve the interaction between the confining pressure and the concrete. In generally, most of the studies about FRP-confined concrete cylinder were focused on well confining effect, and the stress-strain curves show bilinear trend. However, the FRP-confined concrete is more complex under insufficient confining effect. It is necessary to study the properties of an FRP-confined concrete cylinder under various confining pressures. Therefore, in this section, an experiment is described that addresses the effect of the confining pressure. In the experiment, the cylinder had a bottom diameter of 150 mm and a height of 300 mm. The peak stress of unconfined concrete was 44.6 MPa. The FRP tubes, which were prefabricated using a wet-layup process by wrapping resin-impregnated glass fibre sheets around a foam core with an overlapping length of 150 mm, were composed of one, three, or five plies of fibres; each layer had a nominal thickness of 0.165 mm based on the fibre weight. Moreover, the FRP used in the study had an average elastic modulus of 82.11 GPa and a tensile strength of 1223.4 MPa. For each FRP tube, four lateral strain gauges with a gauge length of 20 mm were attached to the tube at mid-height, and all four strain gauges were evenly located outside the overlapping zone. For each specimen, two linear variable displacement transducers (LVDTs) were placed diagonally and used to measure the overall axial contraction. For some specimens, two additional diagonally placed LVDTs were used to measure the axial deformation of the 100-mm mid-height region; the two LVDTs were installed on two rings that were fixed to the outer FRP tube of the specimens using screws. The loading rate was 0.2 mm per minute for all FRP-confined specimens.

(a) Photograph of the specimen during the test

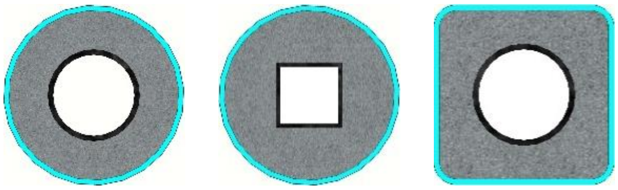


(b) The experimental results

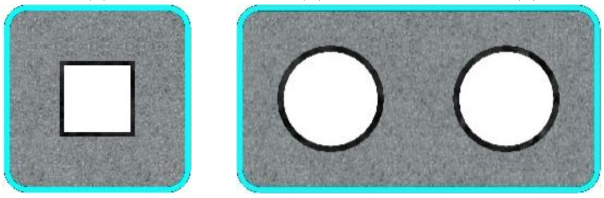
Fig. 6 The experiment of FCCs

The axial stress versus the axial and lateral strains of GFRP-confined concrete is shown in Fig. 6. Based on the results and the analysis, the following conclusions can be drawn: 1) the FRP tube has less of an effect on the first stage of the stress-strain curves than on the second stage because the lateral strain is small and the lateral confining pressure is linearly increasing; 2) the stress-strain curve shows a bilinear trend under large confining pressure, as shown in the specimen with 5-ply FRP; 3) if the confining pressure is insufficient, then the stress-strain curves show a trilinear trend that is similar to that of the curves of the rectangular section; however, the third stage is a horizontal line, as shown in the specimen with one-ply FRP, and because the lateral confining pressure is linearly related to the lateral strain, the low consistent stiffness precludes a decrease in stress; and 4) the stress-strain curve shows a bilinear trend under low confining pressure, as shown in the specimen with 3-ply FRP, but a horizontal transition occurs between two stages, similar to the stress-strain curves of FRP-confined high-strength concrete (Ozbakkaloglu and Lim 2013).

The main factors of FCC are lateral stiffness, sectional shape and the properties of the unconfined concrete. Comparing the curves with insufficient confining pressure in Fig. 5 and Fig. 6, the last stage of circular section shows horizontal trend, the last stage of rectangular section shows ascending trend. Meanwhile, comparing the curves with dividing confining pressure in Fig. 5 and Fig. 6, the horizontal stage of rectangular section is longer. The description reflects the following conclusions: 1) if the concrete is confined by insufficient pressure, which is with



(a) (b) (c)



(a) (e)

Fig. 7 Cross sections of hybrid DSTCs

stable growth, the stress-strain curves would trend to horizontal gradually; 2) the confining pressure is with faster growth in late loading stage of the confined rectangular concrete, due to the increasing effective confining area. Based on the above conclusions, we could assume that the constant growth lateral pressure could make up for the loss strength of concrete, while the faster growth lateral pressure would make the soften concrete have strengthening stage. More importantly, the assumption proved a discriminant method for the soften stage of confined concrete.

3. FRP-steel-confined concrete composite columns

In recent years, multiple new types of composite columns have been developed from FCCs; these new configurations consist of an FRP section, a steel section and a concrete section. The new composite columns can reduce the structural weight while providing sufficient seismic performance. First, Teng *et al*. (2004) proposed a hybrid DSTC with a steel tube inside, an FRP tube outside and concrete in between. Subsequently, FRP confined concrete-filled steel tube columns (CCFTs) and FRP-confined concrete-encased steel columns (FCCSCs) were proposed; the steel columns have bearing and confining effects in these composite columns. In this section, previous researches of FRP-steel-confined concrete composite columns are reviewed and analysed. Furthermore, an experiment is described that characterizes the contact function effect between FRP and steel.

3.1 Hybrid double-skin tubular columns (DSTCs)

DSTCs, which were proposed by Teng *et al*. (2004) at Hong Kong Polytechnic University, are new composite columns consisting of an FRP outer tube, a steel empty inner tube and internal confined concrete. Multiple experimental and theoretical researches have been conducted on DSTCs (Abdelkarim *et al*. 2016, Yu *et al*. 2016a). In the DSTCs, the cross-sectional area can be increased at a constant bearing capacity; therefore, increasing the slenderness ratio and decreasing the axial compression ratio can improve the seismic performance.

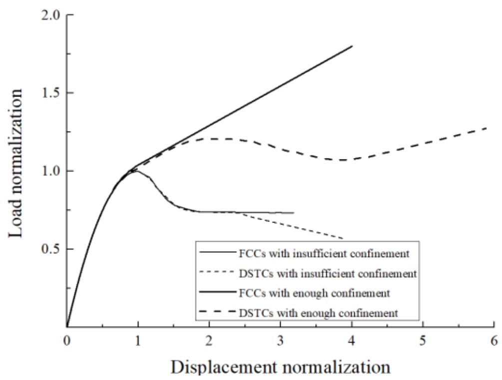


Fig. 8 Load-displacement curves of FCCs and DSTCs

Therefore, the steel tubes in DSTCs are assumed to be empty circular tubes in this study unless otherwise specified.

3.1.1 Section form

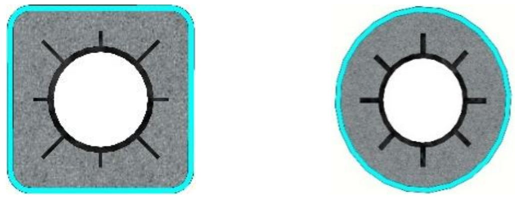
The FRP tube and steel tube have been circular in most researches. However, there are other shapes in practical engineering. All sectional shapes are a combination of a circular or square FRP tube and a circular or square steel tube, as shown in Fig. 7 (a)-(d), and a rectangular DSTC, as shown in Fig. 7(e).

From the study by Yu and Teng (2013), the comparison between circular DSTCs and square DSTCs can be summarized as follows: 1) the mechanical performance of square DSTCs are similar to those of square FCCs; 2) circular DSTCs have favourable mechanical performance due to the strong confining effect provided by the circular FRP tube; and 3) the hollowness ratio has an important effect on circular DSTCs but the opposite effect on square DSTCs. In the study by Fanggi and Ozbakkaloglu (2015), square DSTCs with different steel tubes were studied, and the following conclusions can be drawn: 1) the hollowness ratio has a significant effect on the mechanical performance of any column; 2) ultimate strain increases with the increasing diameter-to-thickness ratio of the steel tube; 3) the elastic modulus of the concrete in DSTCs is larger than that of unconfined concrete or the concrete in FCC; and 4) the ultimate stress and strain of DSTCs with circular steel tubes are larger than those of DSTCs with square steel tubes. Moreover, circular DSTCs with various steel tubes were studied by Fanggi and Ozbakkaloglu (2015), showing that 1) the confining effect is related to the lateral stiffness; 2) the use of a low-strength steel tube may lead to DSTCs with low mechanical strength; and 3) square inner steel tubes are disadvantageous to DSTCs.

As above, for the section forms of DSTCs, the most existing researches mainly focused on the experiment about the random combination of internal and external sections. And the research conclusions were just based on the simple analysis of experimental results. It is short of researches about theoretical analysis for the interaction mechanism between each material and section design.

3.1.2 Mechanical performance

In order to study the mechanical performance in detail, we reviewed the research about DSTCs that consist of a circular FRP tube and a circular steel tube. And we studied the comparison between circular DSTCs and circular FCCs, each load-displacement curve was normalized by the first stage, as is shown in Fig. 8. Then the following conclusions can be drown: 1) the first stage of all curves showed similar trend; 2) all latter stage of DSTCs curves would show descending trend, due to local buckling of steel tubes; 3) for DSTCs with enough confining effect, the late stage would show ascending trend, due to the serious local buckling would lead to section increasing; and 4) later mechanical performance of the DSTCs depended on the local buckling of inner steel tube.



(a) Square (b) Circle

Fig. 9 Cross sections of hybrid DSTCs with ribbed slabs (Peng 2017)

The material parameters of DSTCs also should be studied. In the study by Ozbakkaloglu and Fanggi (2014), the parameters included the thickness of the FRP tube, the unconfined concrete strength, the sectional hollowness ratio, the yield strength and the diameter-to-thickness ratio of the steel tube. The conclusions drawn in the research can be summarized as follows: 1) increasing the thickness of the FRP tube and decreasing the unconfined concrete strength result in a better confining effect; 2) decreasing the yield strength can reduce the mechanical performance of confined concrete in DSTCs, but the effect is not significant; 3) increasing the thickness of the steel tube can improve the mechanical performance of the columns, but the mechanical mechanism differs between solid DSTCs and empty DSTCs; and 4) concrete fill can improve the ultimate stress of confined concrete with a slight decrease in the ultimate strain. However, the studied parameters are based on simple experiment, there is should deeply theorical research. According to the study by Abdelkarim and Elgawady (2016), mechanical performance are related to lateral stiffness, and oblique FRP wrapping might decrease the strength and increase the ultimate strain of DSTCs. Zhou *et al*. (2017) determined that the confining effect is significant for DSTCs with lightweight aggregate concrete and that the hollowness ratio does not strongly influence this effect.

It is well known that local buckling is an important parameter for DSTCs. The ribbed steel bar could be used to limit the local buckling of steel tube. Thus, ribbed steel tubes, as shown in Fig. 9, were introduced in the study by Peng (2017), who drew the following conclusions: 1) steel ribs can delay the local buckling of the steel tube, thereby improving the mechanical performance; 2) the mechanical performance improve with an increasing number of steel ribs under the same steel ratio; and 3) steel ribs distributed at the corner have a good effect in square DSTCs due to the non-uniform confining effect.

Researches have also addressed cyclic loading compression on DSTCs. Yu *et al*. (2012) determined that the stress-strain curves of most DSTCs under cyclic loading are the same as those under axial monotonic loading; however, the decreases in the stress between them are due to bonding slippage between the concrete and steel tube. The diameter-to-thickness ratio of the steel tube and the FRP wrapping method were studied by Abdelkarim and Elgawady (2014, 2016), resulting in the following conclusions: 1) a large diameter-to-thickness ratio of the steel tube leads to bonding slippage, which results in low mechanical performance; 2) FRP wrapping under a 45° oblique angle can increase the ultimate strain and decrease the ultimate stress; 3) FRP tubes with both hoop wrapping and oblique wrapping can have high ultimate strain and ultimate stress; and 4) the failure modes can be divided into two parts: the rupture of the hoop FRP and the rupture of the oblique FRP due to the axial-oriented strain of the FRP in the height direction.

3.1.3 Interaction mechanism

Furthermore, from the study by Wong *et al*. (2008), the internal mechanical mechanism of DSTC was revealed via comparisons of filled FCCs, hollow FCCs and DSTCs. The conclusions of that research can be summarized as follows: 1) the stiffness and peak stress of the concrete in the hollow FCCs in the first stage are higher than those of concrete in the DSTCs because the stress concentration of hollow FCCs improves the confining effect on the confined concrete; 2) the second stage of the stress-strain curve is the descending curve, the failure of the hollow FCCs is due to the destruction of the core concrete, and no hoop rupture of FRP occurs during loading; 3) the stress-strain curves of confined concrete in FCCs and DSTCs are similar because the inner steel tube can cause internal force redistribution in the concrete of DSTCs, and the redistribution can cause the lateral confining pressure to become uniform (that is, similar to the stress distribution in the FCCs); and 4) because the latter stage of the stress-strain curves of DSTCs might produce a descending curve due to the local buckling of the steel tube, the failure of DSTCs could be due to the hoop rupture of the FRP or the local buckling of the steel tube. In the study by Yu *et al*. [71], the mechanical performance of the confined concrete in DSTCs were further analysed by establishing a finite element analysis model. That study showed that the stiffness ratio of FRP, the increasing rate of lateral strain and the hollowness ratio are important parameters for DSTCs; based on the parameters, stress-strain models were proposed.

In summary, the DSTCs is a new type of composite structure for practical engineering. The mechanical performance of DSTCs could be concluded as follows: 1) in the early stage, the strength improving trend is similar to FCCs, depend on the confining material properties; 2) in the later stage, the axial mechanical performance are reduced, due to the local buckling of steel tube. Therefore, the local buckling should be dividing factor for the performance changes of DSTCs. Most of existing researches focused on the experimental analysis. There were few proposed models for predicting load-displacement curves. The future researches should focus on the following contents: 1) the mechanical performance of DSTCs with the local buckling on inner steel tubes; 2) the developing trend of mechanical performance of DSTCs should be studied in detail, such as the dividing points when mechanical performance is reduced, the accurate predicted mode considered the mechanical reduction; 3) the combination of the three materials should be studied to delay or even prevent the local buckling of steel tube. Therefore, the future researches should combine theorical analysis with experimental analysis, and focus on the failure model and curve prediction for the mechanical performance of DSTCs.

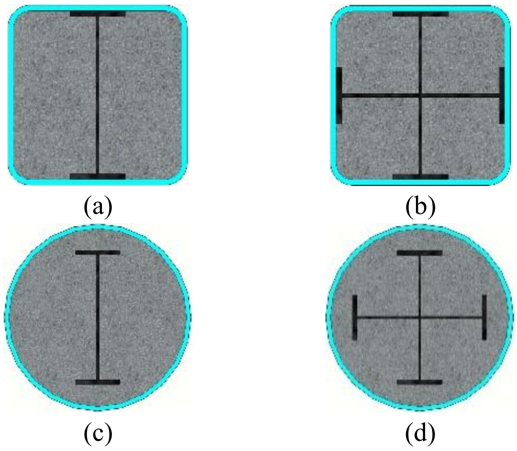


Fig. 10 Cross sections of FCCSCs

3.2 FRP-confined concrete-encased steel columns (FCCSCs)

Steel-reinforced concrete columns have been widely used in practical engineering, and FRP-confined columns have been studied in multiple researches (Karimi *et al*. 2011a, b, Yu *et al*. 2016b, Zakaib and Fam 2012). FCCSC consists of steel-reinforced concrete column and outer FRP jackets, the sectional shapes are shown in Fig. 10. As determined by Yu *et al*. (2016b), FCCSCs with an I-steel column can be confined by FRP, and the average strain of the composite columns follows the plain section assumption under eccentric loading. In the study by Karimi *et al*. (2011c), the slenderness ratios of FCCSCs with an I-steel column were studied for columns with an elasticity modulus of 16.5 GPa and a diameter of 200 mm. It was concluded that the effect of the slenderness ratios can be neglected when this ratio is less than 19.8 and that the limit values increase with the increasing elasticity modulus of the FRP tube. Huang *et al*. (2016) determined that the lateral deformation of the composite columns is related to the lateral stiffness and the axial stiffness of the I-steel columns. Although circular columns have favourable mechanical performance, I-steel columns do not provide a sufficient confining effect within square FCCSCs. Based on the above observations, Huang *et al*. (2017) studied FCCSCs with cross-sectional steel and determined that 1) cross-sectional steel can mitigate the weakness in the middle of the square section, 2) FRP can effectively constrain the local buckling of cross-sectional steel, 3) the

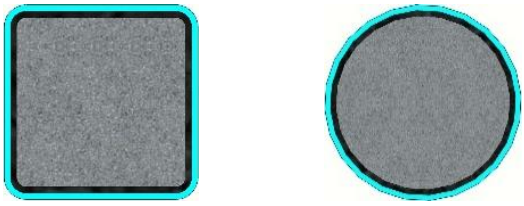


Fig. 11 Cross sections of CCFTs

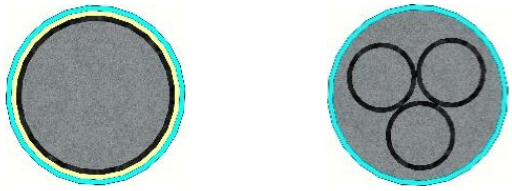


Fig. 12 Cross sections of a new type of FRP CCFT (Xiao *et al*. 2005, Yu *et al*. 2017)

mechanical performance of square FCCSCs can be improved by the confining effect of the FRP and cross-sectional steel, and 4) the failure mode of the composite column is the hoop rupture of the FRP at the midpoint of both the boundary and the height direction. Moreover, the above researches showed that the analysis-oriented model of FCCs can be applied to establish the finite element model of FCCSCs.

In summary, the mechanical performance of FCCSCs are equal to the superposition of FRP-confined concrete and section steel. And the cross-section steels could improve the confining effect in rectangular FCCSCs. It shows that the cross-section steels could prove limiting confining effect. It could be set in ineffective confining section to prove the obvious confining effect and improve the utilization ratio of FRP in non-circular FCCSCs.

3.3 FRP confined concrete-filled steel tube columns (CCFTs)

In recent years, concrete filled in steel tube (CFT) columns have been widely used in practical engineering structures. In CFT columns, the core-concrete can constrain only the inward buckling of the steel tube; strength and ductility degradation are related mainly to the outward buckling of the steel tube at both ends of the column. Based on the disadvantages of CFTs, CFTs confined by FRP were proposed in related researches. According to the study by Xiao (2004), the use of steel or FRP to confine both ends of the CFT can significantly constrain the local buckling of the steel stub and increase the bearing capacity and ductility; an important factor is that the confining effect of FRP is relatively strong. CCFTs have been studied by multiple scholars (Mao and Xiao 2006, Shan *et al*. 2007, Xiao *et al*. 2005), who determined that FRP can be applied in the consolidation of CFTs to design new composite columns (Fig. 11). In the present study, the CCFTs correspond to the FRP being wrapped around the surface of steel tube.

3.3.1 Mechanical performance

From the study by Hu *et al*. (2011), the following conclusions regarding a CCFT with a thin-walled steel tube can be drawn: 1) the wrapping FRP can constrain or prevent the local buckling of the steel tube; 2) the wrapping FRP can increase the ultimate stress and the ultimate strain of the concrete, resulting in the hoop rupture of the FRP; and 3) the stress-strain curves of CCFTs can be divided into three stages: the first stage is controlled by concrete, the second stage is controlled by the steel tube and FRP, and the third stage is controlled by the FRP. Moreover, Hu (2011) studied an FRP-confined thin-walled steel tube in detail; the study showed that FRP has a strong confining effect on a hollow steel tube and a CCFT. Tao *et al*. (2007) studied a circular CCFT and a square CCFT; based on that study, the following conclusions can be drawn: 1) the sectional shape has a significant effect on the mechanical performance; 2) the wrapping FRP has a strong confining effect on the circular CCFT; and 3) with increasing FRP thickness, the ductility of the circular CCFT decreases, whereas that of the square CCFT increases. Park *et al*. (2010) determined that increasing the thickness of the FRP can increase the strength and ductility of the CCFT; however, the wrapping of FRP has little effect on the bearing capacity of rectangular CCFTs. As studied by Yu *et al*. (2014), the mechanical performance of CCFTs under axial cyclic loading can be summarized as follows: 1) the failure mode of CCFTs under axial cyclic loading is the same as that under axial monotonic loading; 2) the enveloping curve under cyclic loading is the same as the stress-strain curve under monotonic loading; and 3) because repeated unloading and loading damage CCFTs, the stress-strain response under cyclic loading is dependent on the stress-strain curves under monotonic loading.

In summary, the core concrete is joint confined by FRP tube and steel tube. With the continuous expansion of concrete, the confining pressure provided by FRP tube is greater than that of steel tube. Therefore, the late mechanical performance of CCFTs are depended on the mechanical performance of FRP. Therefore, the future researches should focus on the contact relationship between FRP and steel tube, and the design for reasonable section.

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3.3.2 New section form

It is well known that the failure of the CCFT is generally due to hoop rupture of the FRP. To improve the mechanical performance of composite columns, Xiao *et al*. used foam plastic materials to set the gap between the FRP tube and the steel tube (Xiao *et al*. 2005); the new type of column, designated CCFY-G, is shown in Fig. 12(a). The study showed that the foam gap can delay the fracture of FRP and greatly improve the ductility of the composite column. The

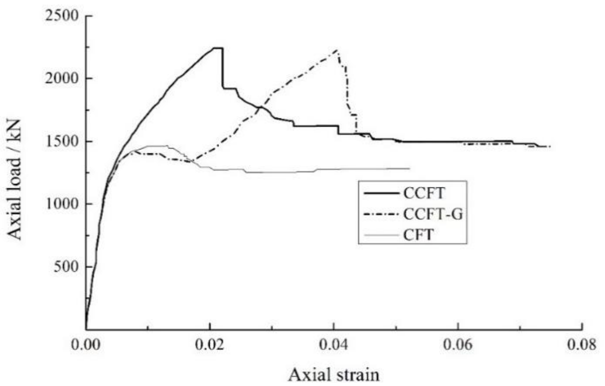


Fig. 13 Load-strain curves of the CFT, CCFT and CCFT-G (Xiao *et al.* 2005)

comparisons of the load-strain curves of CFT, CCFT and CCFT-G are shown in Fig. 13. The following conclusions can be drawn from the comparisons: 1) the first stage is similar for the three column types; 2) the gap generates a buffer that causes the lateral strain of the FRP tube to be smaller than that of the steel tube, and the FRP strongly constrains the local buckling of the steel tube, thereby increasing the ultimate strain; and 3) the ultimate stresses associated with the CCFT and CCFT-G configurations are similar. The 1 mm foam gap can't provide any pressure; thus, the lateral confining pressure of FRP in CCFT-G is similar to that in CCFT. Therefore, we conclude that the stress is path-independent, whereas the strain is path-dependent.

In general, it is challenging to produce oversized steel tubes for mega columns in practical engineering. Therefore, Yu *et al.* (2017) proposed a new type of composite column with multiple small steel tubes called the FRP multi-tube concrete composite column (MTCC), as shown in Fig. 12 (b). The mechanical performance of MTCCs can be summarized as follows: 1) the load-strain curves of MTCCs show a bilinear trend that is similar to that of FCCs; 2) no local buckling occurs in the steel tube, and the concrete can completely constrain the steel tube; and 3) the ductility of MTCCs is better than that of CCFTs with the same steel fraction.

In summary, the local buckling of steel tube is the key and difficult problem in the researches about the mechanical performance of CFTs and CCFTs. Based on the reviews of existing researches, it is known that CCFTs with thin-wall steel tube or delaying the action stage of FRP have the well

Table 2 Wrapping methods of AFRP around the steel tube

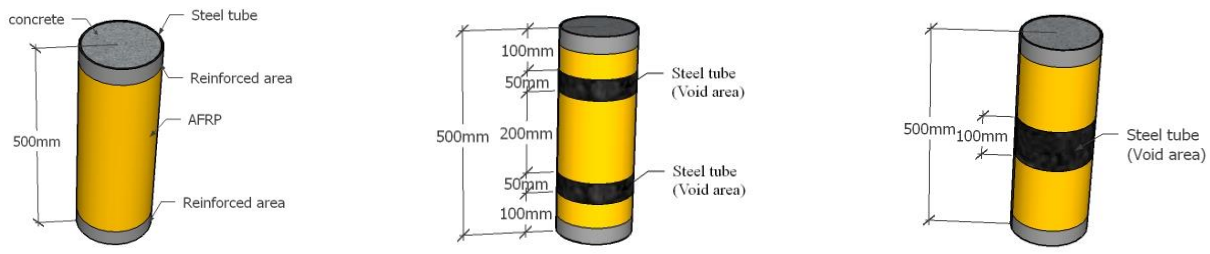
Item	Plies of FRP	Wrapping method
CFT	0	-
CCFT2	2	Overall wrapping
CCFT3	3	Overall wrapping
CCFT2B	2	Two-sectional wrapping
CCFT3B	3	Two-sectional wrapping
CCFT2T	2	Three-sectional wrapping
CCFT3T	3	Three-sectional wrapping

mechanical performance. However, it is necessary to study the CCFTs with thickness-wall steel tubes for the interaction relationship between FRP and steel tube.

3.4 Further study of CCFTs

As above, the local buckling of steel is the key parameters of the failure of FRP-steel-confined concrete composite. Most of existing studies were focused on CCFTs with thin thickness steel tube is studied. The thin wall steel tube could be consisted by FRP. However, mechanical transmission would be more complex in CCFTs with thick wall steel tube, which is common in practice engineering. Therefore, in this section, an experiment for CCFTs with thick wall steel tube is described to characterize the relationships among the materials of FRP, steel and concrete by changing the FRP-wrapping method.

In the experiment, the cylinder had a bottom diameter of 180 mm and a height of 500 mm. The peak stress of unconfined concrete was 53.6 MPa, and the peak strain was 0.0045. The steel tube had an outer diameter of 180 mm and a thickness of 45 mm. The FRP tubes were made using a wet-layup process by wrapping resin-impregnated aramid fibre with an overlapping length of 180 mm. The FRP wrapping methods are shown in Table 2. Each layer had a nominal thickness of 0.18 mm based on the weight of the fibres, as shown in Fig. 14. Moreover, the FRP used in the study had an average elastic modulus of 184 GPa and a tensile strength of 2741.6 MPa. For each FRP tube, four lateral strain gauges with gauge lengths of 20 mm were attached at the mid-height of the tube, and all four strain gauges were evenly located outside the overlapping zone. For each specimen, two diagonally placed LVDTs were used to measure the overall axial contraction. The loading rate was 0.5 mm per minute for all FRP-confined specimens.



(a) (b) (c)

Fig. 14 Sketches of new CCFT sections

Fig. 15 Failure models of the specimens

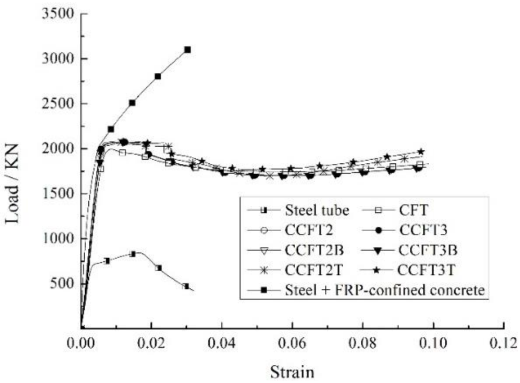


Fig. 16 Load-strain curves of the specimens

The failure modes of the specimens when loading is stopped are shown in Fig. 15. The failure modes of the CFT, CCFT and CCFTT were similar. In the failure process, local buckling first occurred at the ends of the steel tube, followed by the breaking of the hoop wrapping at the ends of the FRP tube and ending with the failure of the entire FRP wrapping. For CCFTT, in the failure process, local buckling of the steel tube at the void area first occurred, followed by the breaking of the hoop wrapping of the central FRP, and ending with the breaking of the two ends of the FRP wrapping.

Comparisons of the load-strain curves are shown in Fig. 16. The curve of "steel + confined concrete" in Fig. 16 is obtained by direct addition of the parameters for the confined concrete and the steel tube, and the load of the confined concrete is computed using the stress-strain model developed by Teng *et al*. (2007). The following conclusions can be drawn by comparing the curves in Fig. 16: 1) the confining effect of FRP is undetectable because the FRP is directly wrapped on the steel tube and the steel tube inhibits the transmission of the lateral pressure; 2) the local buckling of the steel tube is the key to the failure of the columns because, if the confining effect of FRP is inadequate, then the change in thickness can be neglected; 3) the load-strain curve of CCFTB is similar to that of CCFT, and the void area in the middle has no effect on the failure modes because local buckling occurs at the ends; 4) the ductility of CCFTT is satisfactory because the void area at the ends can serve as the reserve area for the local buckling of the steel tube, thereby slowing the expansion effect of the steel tube on the FRP; and 5) for CCFTT, more FRP layers lead to better ultimate strength, whereas fewer FRP layers lead to better ductility.

Table 3 Wrapping methods of AFRP around the steel tube

Item	Characteristic	Disadvantage
FRP	Linear elasticity	Brittle failure
Steel	Linear elasticity before yielding, constant stress after yielding.	Decreased mechanical performance due to local buckling.
Concrete	The property depends on confining stress.	The mechanical performance is complex, the influence factors include confining types and confining effect.

The experimental results show that FRP prove weak confining effect for CFTs with thick-wall steel tube. There is non-uniform expansion between inside and outside wall of the thick steel tube, which is wildly used in practical engineering. The small expansion of outside steel wall would lead to weak confining stress from FRP tube at early loading stage. Meanwhile, the thickness FRP tube should be enough to limit the local buckling of steel tube at later loading stage. Therefore, it is waste to wrap FRP on steel tube directly. It is necessary to adopt effective design method to limit local buckling of steel tube.

4. Discussion about the composite column

In summary, material properties and section form are two main factors for the mechanical performance of FRP composite columns. The former is the foundation of research. The latter is a design method that can effectively combine several materials. Thus, the section form should follow the complementary effect of material properties, to optimize the structure performance.

There were many existing researches for mechanical performance of FRP composite columns with different sectional form. However, there are some deficiencies in existing researches. For FRP-confined concrete, the concrete with low confining effect should be studied. Meanwhile, FRP-confined concrete would suddenly decrease with the FRP disrupt. For FRP confined composite, many researches are the experimental studies of new section forms, few researches focus on the design method. It is necessary to study the complementary effect of materials, and find the reasonable design method for any practical engineering structure.

As mentioned, material properties are deeply analysed, as is shown in Table 3. The section forms would show different properties, a lot of researches can be concluded as follows: 1) the concrete should be confined to prevent brittle failure; 2) the circular section have well confining effect; 3) In non-circular section, FRP should be whole wrapped, only the corner play effective confining effect; 4) the steel could put in inefficient confining region to confine concrete; 5) the local buckling of steel is key defect in composite column. Therefore, this paper proposes the reasonable design of section form, the flowchart can be shown in Fig. 17.

Based on the reasonable design flowchart of section form and above review in this paper, the following research pointes should be studied in future: 1) studying detailed

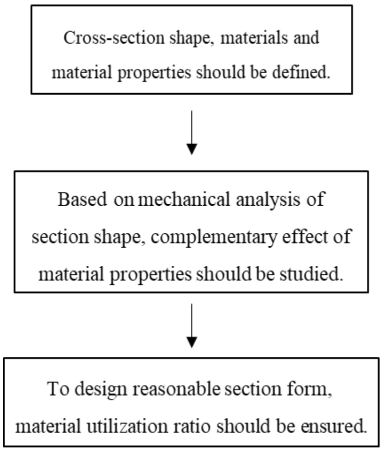


Fig. 17 The flowchart of reasonable section design

mechanical performance of confined concrete, including various types and intensity of confining stress; 2) designing reasonable section form to improve the disadvantage of materials; 3) studying the mechanical performance of core concrete confined by multiple confining materials; 4) studying the seismic performance of new composite structures.

5. Conclusions

To study the relationships among FRP, steel and concrete, we first reviewed and analysed previous research on FRP-confined concrete columns. Next, experiments involving various types of FRP-steel-confined concrete composite columns were conducted. Two experiments were configured to study the mechanical performance of confined concrete and the relationships among the three materials of composite columns. The results of this study provide a theoretical foundation for the design of composite columns with excellent performance. Based on the results, the following conclusions can be drawn:

• The mechanical performance of confined concrete are related only to the relative confining stiffness; concrete type has little effect. Therefore, the unified stress-strain model of confined concrete can be established based on confining characteristics.
• When the confinement effect is sufficient, the stress-strain curves show a bilinear trend. Otherwise, the stress-strain curves show a trilinear trend. The third stage of the circular section is a horizontal line, and the third stages of the square and rectangular sections are ascending lines. The non-uniform confining effect of the square and rectangular sections can increase the stiffness in the latter part.
• If the concrete does not undergo strength degradation, then the stress path is independent; otherwise, the path is dependent. Examples of stress path independence and strain path dependence are shown in Fig. 13.
• The enveloping curves of the composite columns under cyclic loading are the same as the stress-strain curves under monotonic loading. The combination of the three materials allows the composite columns to exhibit excellent mechanical performance, seismic performance and durability.
• The failure of composite columns is mainly controlled by the local buckling of the steel. Moreover, the local buckling of the steel tube cannot be constrained by the materials filled in a single-sided manner. For example, the failure of DSTCs is due to the interior local buckling of the steel tube, and the failure of CFTs is due to the outer local buckling at the ends of the steel tube.
• In previous researches of composite columns, it was concluded that the local buckling of a steel tube is constrained by the outer FRP tube and the inner confined concrete. However, the FRP tube benefits the thin-walled steel tube, whereas it has no effect on the thicker steel tube.
• As established in the studies by Huang *et al*. (2017), Xiao *et al*. (2005) and Yu *et al*. (2017), two methods exist to constrain local buckling. For a circle section, the concrete should fill the region between the steel tube and the FRP tube. For other sections, steel should fill the weak confined area to improve the confining effect of the FRP.

Acknowledgments

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