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The effect of active and passive confining pressure on compressive behavior of STCC and CFST

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Abstract. In this paper, an experimental study was conducted on the compressive behavior of steel tube confined concrete (STCC) and concrete-filled steel tube (CFST) columns with active and passive confinement. To create active confinement in the STCC and CFST specimens, an innovative method was used in this study, in which by applying pressure on the fresh concrete, the steel tube was laterally pretensioned and the concrete core was compressed simultaneously. Of the benefits of this technique are improving the composite column behavior, without the use of additives and without the need for vibration, and achieving high prestressing levels. To achieve lower and higher prestressing levels, short and long term pressures were applied to the specimens, respectively. Nineteen STCC and CFST specimens in three groups of passive, short-term active, and long-term active confinement were subjected to axial compression, and their mechanical properties including the compressive strength, modulus of elasticity and axial strain were evaluated. The results showed that the proposed method of prestressing the STCC columns led to a significant increase in the compressive strength (about 60%), initial modulus of elasticity (about 130%) as well as a significant reduction in the axial strain (about 45%). In the CFST columns, the prestressing led to a considerable increase in the compressive strength, a small effect on the initial and secant modulus of elasticity and an increase in the axial strain (about 55%). Moreover, increased prestressing levels negligibly affected the compressive strength of STCCs and CFSTs but slightly increased the elastic modulus of STCCs and significantly decreased that of CFSTs.

Keywords: active confinement; prestressing; mechanical properties; confining pressure; STCC; CFST

1. Introduction

The use of steel tube-confined concrete (STCC) and concrete-filled steel tube (CFST) columns in modern structures including houses, marine structures, arch bridges, and high-rise structures is increasing day by day. In STCC columns, widely used in concrete structures, the compressive load is applied only on the concrete core. In this type of composite columns, steel tubes are cut at a position near the end of the column so that no axial load is applied directly on the tube. In CFST columns which are only used in steel structures (Zhao *et al*. 2010), the compressive loading is applied on the concrete core and steel tube simultaneously. Among the advantages of STCC and CFST columns, their better performance in terms of strength and ductility compared to that of the concrete or steel columns can be mentioned (Lai and Ho 2014), which is the result of the composite action of their components. However, the compressive behavior of these two composite sections is different from each other. STCC columns exhibit higher load-carrying capacity and ductility and lower stiffness compared to CFST ones (Yu *et al*. 2010). This is due to different behaviors of steel tube in the two composite sections as the steel tube exhibits a more confining role in STCC columns and a more axial load-carrying role in CFST ones. In addition, in CFST columns, the steel tube is under axial compressive load, thus there is a possibility of local buckling, while it does not occur in STCC ones (Yu *et al*. 2010).

Extensive research has been conducted on the behavior of CFST columns (Han *et al*. 2008, Gupta *et al*. 2015, Alhatmey *et al*. 2018) and the behavior of the STCC columns (Tomii *et al*. 1985, 1987, Aboutaha and Machado 1998, Xiao *et al*. 2005, Han *et al*. 2005, Nematzadeh and Haghinejad 2017, Ghadami and Nematzadeh 2018) separately, but few studies have compared the two types of composite columns. Yu *et al*. (2010) investigated STCC columns and compared them with CFST columns in terms of compressive strength. Their results showed that the load-carrying capacity of the STCC columns is higher than that of the CFST ones. They also found that the portion of the axial load for the steel tube in the STCC is lower than that in the CFST columns.

Confinement in STCC and CFST columns is applied in passive and active manners. When there is no lateral pressure on the concrete core prior to the application of the axial loading, the confinement is passive. In this type of confinement, for effective lateral pressure, concrete needs large lateral deformations, and based on the deformation limitations specified in codes, the behavior improvement resulted from the confinement is not allowed in the designs (ACI318 2008, AS3600 1994). One of the ways to prevent large deformations of concrete and the resulting damage is to impose a primary lateral pressure on the concrete core, which leads to the active confinement. In this confinement,

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the appearance of primary cracks on the concrete is delayed and the growth of internal cracks is slowed down, which in turn results in an improvement in the composite section behavior and a significant increase in strength and ductility. The most commonly used methods for prestressing the composite columns to create active confinement include introducing materials with expansive property in the concrete (Chang *et al*. 2009, Mortazavi *et al*. 2003), prestressing the transverse hoops (Shinohara 2008, Feeser and Chinn 1962, Martin 1968, Janke *et al*. 2009, Moghaddam *et al*. 2010), prestressing the steel confining elements thermally (Mokari and Moghadam 2008) and employing composites with the self-stressing property (Krstulovic-Opara and Thiedeman 2000, Shin and Andrawes 2010). One of the latest prestressing methods in the concrete confined with steel tube is to compress the fresh concrete inside the steel tube, which in turn compresses the concrete core and prestresses the steel tube (Nematzadeh *et al*. 2017a-d).

Mortazavi *et al*. (2003) added an expansive agent to the concrete mixture to create a pre-tensioning of confining tubes. Their results showed that pre-tensioned tube-confined columns could increase the bearing capacity by up to 35% compared to non-pre-tensioned confined concrete and four times as much as the non-confined concrete. In an experimental investigation, Martin (1968) used prestressed spirals to confine concrete specimens. The results showed that the ultimate axial strength increased about 2.5 times which was practically independent from lateral prestressing. Shinohara (2008) carried out an experimental investigation and finite element analysis on high-strength concrete columns confined with prestressed transverse stirrups to evaluate the effectiveness of active confinement. Moghaddam *et al*. (2010) used experimental results to perform a parametric study on the compressive behavior of concrete with active confinement by metal strips under axial loading. Their findings showed that due to the active confinement caused by the prestressed metal strips, the strength and ductility of the specimens increased significantly. In addition, it was observed that the ductility of the confining material played the most important role in increasing the ductility of the concrete. In an experimental and analytical study, Shin and Andrawes (2010) investigated active confinement using shape memory alloys (SMAs) in reinforced concrete columns. The results showed that the proposed technique using SMA spirals increased the strength and stiffness as well as the concrete damage. Despite these investigations, there is still insufficient information on the performance of active confinement in confined concrete, and little has been provided in this area in design codes and literature. Moreover, most of the techniques proposed for achieving the active confinement of composite columns lead to low prestressing levels; therefore, providing and mechanically evaluating a suitable method for creating active confinement in STCC and CFST composite columns was one of the goals of this study.

In this paper, the innovative method was used to prestress the STCC and CFST specimens by actively confining the fresh concrete and prestressing the steel tube. In this method, fresh concrete inside the steel tube is compressed, which causes the steel tube to undergo pretension in the circumferential direction. Among the advantages of this method are a significant improvement in compressive behavior and lack of the need to use additives and vibration. Axial compressive loading was applied to the STCC and CFST specimens in three groups of passive, short-term prestressed, and long term prestressed. The results including the compressive strength, modulus of elasticity and axial strain were explored. Based on the findings, prestressing the STCC columns led to a significant improvement in the compressive strength, initial and secant modulus of elasticity and a considerable reduction in axial strain. In the CFST columns, prestressing significantly increased the compressive strength, slightly affected the secant and initial modulus of elasticity and increased the axial strain. Moreover, increasing the prestressing level had a negligible effect on the compressive strength of the STCC and CFST specimens, while it increased the initial modulus of elasticity of the STCC concrete slightly and reduced that of the CFST specimens significantly.

Fig. 1 STCC and CFST specimens

2. Experimental programs

2.1 Details of specimens

In this study, experimental specimens were grouped into the STCC and CFST ones, each of which was divided into passive, short-term prestressed (S-active) and long term prestressed (L-active) groups. To achieve the desired prestressing level, the prestressing device can exert a certain pressure to the specimen for a desired length of time. By placing steel tubes filled with fresh concrete successively inside this apparatus and applying axial pressure to the concrete using a hydraulic jack, the fresh concrete was compacted and simultaneously the steel tube was pretensioned laterally. Steel tubes filled with fresh concrete in the apparatus are separated by rigid steel cylindrical coatings. The pressure was slowly exerted on the first confined specimen and transferred to the other specimens by the steel coatings. After the concrete became hardened and the pressure was removed, some of the circumferential tensile stress remained in the steel tube, which was considered as the prestressing level. The pressure applied to the specimens was both short- and long-term, the former to create low prestressing levels and the latter to create high prestressing levels. After reaching the stable pressure, which lasted about 15-30 minutes, the S-active specimens

Table 1 Outline of details of the test specimens

Specimens		Number	Confinement type	Pressure duration	Concrete core type	Concrete compressive strength (MPa)	*D/t*	*L/D*
STCC	Passive	3	passive	-	uncompressed	33.5	24.2	2.5
	S-active	3	active	short term	compressed	66.2	24.2	2.5
	L-active	3	active	long term	compressed	69.4	24.2	2.5
CFST	Passive	3	passive	-	uncompressed	33.5	24.2	2.3
	S-active	3	active	short term	compressed	66.2	24.2	2.3
	L-active	3	active	long term	compressed	69.4	24.2	2.3

Fig. 2 Prestressing apparatus

were removed from the prestressing apparatus, and the L-active ones were removed after 6 days of constant pressure. The durations of pressure application in the apparatus were selected through trial and error to achieve different prestressing levels. The details of the prestressing apparatus can be illustrated in Fig. 2.

For each test group, three similar specimens were built and tested under the axial compression. In CFST specimens, steel and concrete surfaces should be at the same level to be able to apply the load on steel and concrete sections simultaneously. For this reason, the lengths of the steel tube in the CFST and STCC were different from each other and equal to 140 mm and 150 mm, respectively. The height of concrete in the tubes in all of the passive specimens including STCC and CFST was about 140 mm. The passive STCC and CFST specimens are illustrated in Fig. 1, and some details of the specimens are given in Table 1. Seamless steel tubes were utilized in this work, with characteristics presented in Table 2. The compressive strength of the uncompressed concrete (reference concrete),

Table 2 Characteristics of steel tube

t (mm)	D (mm)	E_s (GPa)	E'_s (GPa)	ν_s	f_y (MPa)	f_u (Mpa)	ε_p (ε)	ε_u (ε)
2.5	60.5	210	1.4	0.28	339	480	0.0139	0.1144

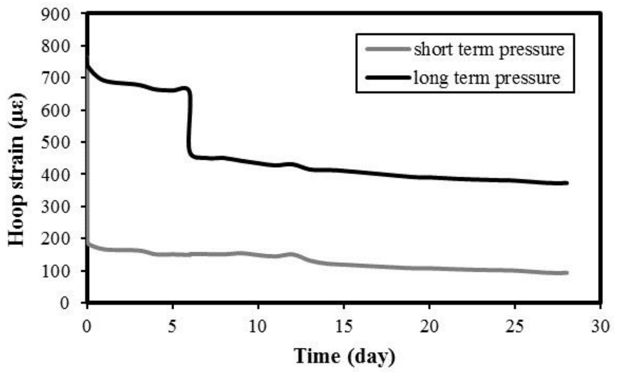

Fig. 3 The hoop strain versus time curve of steel tube for S-active and L-active specimens

short-term pressure compressed concrete and long term pressure compressed concrete were 33.5, 66.2 and 69.4 MPa, respectively.

2.2 Instrumentation and test setup

All active specimens were made in the prestressing device (see Fig. 2) which was able to compress the specimens at any level for a specified duration. The details of this device are found in the authors' previous papers (Nematzadeh and Naghipour 2012a, b). By applying the pressure on the fresh concrete, the concrete is compressed and steel tube experiences the hoop tensile stress. Therefore, after the hardening of the concrete, a prestressing is developed in the steel tube, through which the compressed concrete core is laterally pressured.

Horizontal strain gauges mounted on the outer surface of the steel tubes at mid-height were used to measure the initial pressure and its reduction during the curing period as well as the final pressure (during the compressive test). The initial hoop strain of the S-active and L-active specimens was equal to 762.8 microstrain. Also, the final hoop strain level of the specimens after 28 days of applying the pressure was equal to 94 microstrain for S-active and 374.3 microstrain for L-active specimens, which are equivalent to the prestressing value (the lateral load acting on the concrete core) of 1.78 and 7.08 MPa, respectively. Hence, the pressure reduction for S-active specimens during the

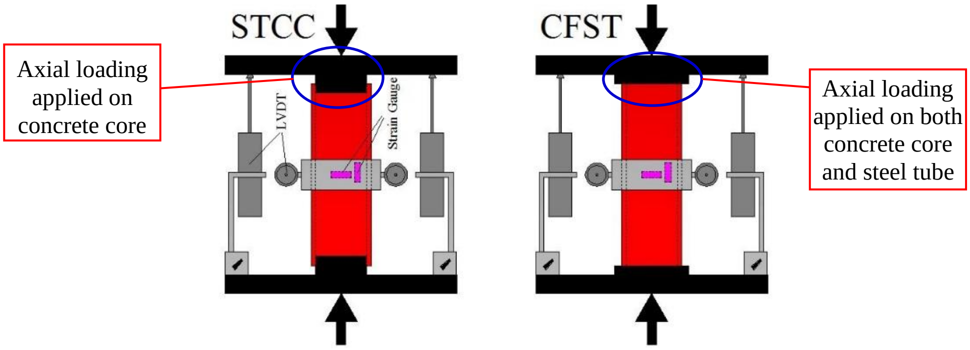

Fig. 4 Schematic view of loading conditions on CFST and STCC specimens with deformation measuring devices

curing was equal to 88% and for the L-active ones to 51%. In the S-active specimens, the internal pressure was greatly reduced after removal from the prestressing apparatus but was not completely eliminated. The main reason for this is the internal friction between the aggregates (Nematzadeh and Naghipour 2012a, b). In the L-active specimens, the internal pressure was significantly reduced after removal within 6 days. The reason is the conversion of the triaxial compressive stress of concrete core before removal from the apparatus to the biaxial stress after that. Furthermore, shrinkage and creep are among the important factors contributing to daily pressure reduction (Nematzadeh and Naghipour 2012b). Fig. 3 presents the hoop strain versus time curve for the S-active and L-active specimens.

The compressive strength testing was conducted on the STCC and CFST specimens by an ELE testing machine with a capacity of 2000 kN after at least 28 days from the time of casting concrete. The monotonic loading applied considering the load-control strategy was increased until the specimens failed. The unconfined specimens experienced monotonic axial loading with the speed of 0.7 kN/s, equivalent to 0.29 MPa/s, which is within the 0.15–0.35 MPa/s range proposed in the ASTM C39 (2002). Furthermore, the loading rate on the composite specimens was small and equal to 0.7 kN/s. In order to restrain the top and bottom surfaces of the CFST specimens in the test, a 6 mm-deep indentation was created in the platens and the specimen was placed between them without clearance. Also, in the STCC specimens, the concrete surface was 5 mm away from the end of the steel tube so that the load from the platen was only transferred to the concrete core. To measure the axial and lateral deformations of the specimens, two vertical and two horizontal LVDTs, mounted on both sides of the specimen symmetrically, were employed. In addition, horizontal and vertical strain gauges mounted on the outer surface of the steel tube at the mid-height were used to measure the hoop and longitudinal strains of the steel tube. Fig. 4 illustrates a schematic view of load application on the STCC and CFST specimens and the location of the deformation measuring devices.

3. Results and discussion

Table 3 provides the test results of the actively- and passively-confined STCC and CFST specimens. The values given in the table are the mean results of the three similar specimens for each group.

Table 3 Experimental results of STCC and CFST specimens

specimens		σ_{cc} (MPa)	σ_y/σ_{cc}	E_i (MPa)	$E_{\sec,y}$ (MPa)	$E_{\sec,cc}$ (MPa)	E_r (MPa)	ε_{cc}
STCC	Passive	108.5	0.86	10873	6456	4541	18816	0.0239
	S-active	170.6	0.80	24276	20597	13149	21950	0.0130
	L-active	176.1	0.82	25804	22383	13680	21350	0.0129
CFST	Passive	97.6	0.88	26570	21318	7757	-	0.0126
	S-active	164.9	0.81	32976	25167	8823	-	0.0194
	L-active	163.7	0.61	25725	23707	11120	-	0.0158

3.1 Compressive strength of composite section

Knowing the compressive strength of different composite members, as important structural property, is essential for design purposes. The compressive strength of the STCC and CFST specimens with the passive, S-active and L-active confinement was evaluated in this study. In the CFST sections, although the total cross-sections of the concrete and steel tube participated in load-carrying, in order to compare their capacity with that of the STCC sections in which only the concrete core had a load-carrying role, the ratio of load applied to the concrete cross-sectional area was considered as the compressive stress for all the specimens.

According to the results of this study, the compressive strength of composite specimens occurred at the failure point. Since this point is associated with very large deformations, the compressive strength at the initial peak point was introduced to perform the comparison of strength of composite sections, and this strength was called the peak compressive strength (σ_{cc}). The relative maximum compressive stress in the axial stress-strain curve of active specimens (corresponding to the slope of zero) was taken as the peak compressive strength. Moreover, there was no relative maximum stress in passive specimens, thus the steel strain hardening point was regarded as the peak point. This point corresponds to the location in the stress-strain curve at which the concavity changes from downward to upward. It should be noted that in the active specimens, the high strength of compressed concrete led to the formation of a relative maximum point in the curve. In fact, with decreasing confinement ratio (lateral confining pressure to

Table 4 Experimental and theoretical load-carrying capacity for CFST specimens

Specimens		F_{Exp} (kN)	F_{Theo} (kN)
CFST	Passive	236.5	235.4
	S-active	399.5	314.6
	L-active	396.6	322.6

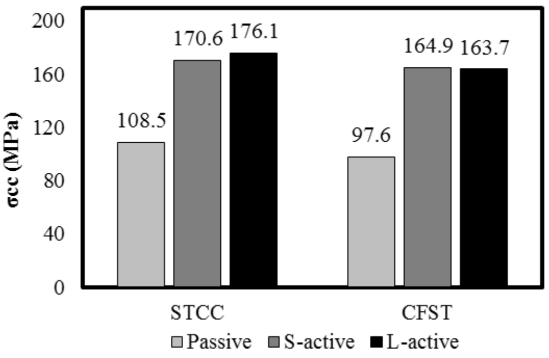

Fig. 5 Peak compressive strength of STCC and CFST specimens

concrete compressive strength ratio), the compressive behavior of the composite section approached that of the concrete, and the extremum point of the stress-strain curve became more visible. Also, when this ratio increased, the composite section's behavior tended toward the behavior of the steel, and the extremum point detection became difficult. This trend can be observed in other investigations on the compressive behavior of STCC and CFST composite columns, such as (Yu *et al.* 2010).

The peak compressive strength results of all the STCC and CFST specimens are presented in Table 3 and Fig. 5, based on which, the STCC specimens with active and passive confinement have higher compressive strengths than the CFST specimens. The steel tube in the CFST specimens was under axial load and its confining role was limited while in the STCC specimens, the steel strength was used for the concrete core confinement, and therefore, these specimens had higher compressive strength compared with that of the CFST ones (similar to the results obtained in the research of Liu *et al.* 2018). The compressive strength of the STCC specimens with passive, S-active and L-active confinement was 11%, 3%, and 8%, respectively, higher than that of the CFST specimens.

As can be seen in Table 3 and Fig. 5, the specimens with active confinement have a compressive strength significantly greater than those with passive confinement, being about 60% and 68% for the STCC and CFST specimens, respectively. This shows that prestressing the STCC and CFST specimens using the present method improves significantly the compressive strength. In the passive specimens, the effective confinement was achieved at high levels of axial load (Wan and Zha 2016), which reduced the load-carrying capacity of the composite column. On the other hand, this effective confinement occurred faster in the active specimens due to the existence of prestressing which increased the load-carrying capacity of the column.

According to Fig. 5, it can be observed that in both STCC and CFST, the compressive strength of L-active specimens differs negligibly from that of S-active specimens. Such observation suggests that increasing the prestressing level has a negligible effect on the compressive strength of the STCC and CFST specimens.

The portion of active confinement in increasing the compressive strength of the CFST specimens can be determined from the difference between the experimental results and the results from Eq. (1) in which the interaction between the concrete core and steel tube is not considered.

$$F_{Theo} = A_s f_y + A_c f_c \tag{1}$$

In this equation, F_{Theo} is the load-carrying capacity of CFST. Also, f_y and A_s are the yield strength and cross-sectional area of the steel tube, and f_c and A_c are the compressive strength and the cross-sectional area of the concrete core, respectively. The compressive strength of the concrete core in S-active and L-active specimens can be obtained by the Eqs. (2) and (3), respectively (Nematzadeh and Naghipour 2012b)

$$f_{cS} = -0.0370 f_{cR}^{\,2} + 3.217 f_{cR} \tag{2}$$

$$f_{cL} = -0.0331 f_{cR}^{\,2} + 3.185 f_{cR} \tag{3}$$

where f_{cS} and f_{cL} are the compressive strength of compressed concrete in S-active and L-active specimens, respectively, and f_{cR} is the strength of the corresponding uncompressed specimen, all expressed in MPa. The results of experimental (F_{Exp}) and theoretical (F_{Theo}) load-carrying capacity for the CFST specimens are presented in Table 4. It can be observed that the experimental and theoretical results in the passive specimens are almost equal, which indicates that the load-carrying capacity of passive CFST specimens does not exceed the total capacity of its components, and as a result, the effect of concrete core confinement on the compressive strength improvement is negligible. Furthermore, according to Table 4, it can be seen that the experimental load-carrying capacity of S-active and L-active specimens is 27% and 23% higher than the theoretical results, respectively, which demonstrates the significant influence of prestressing the steel tube on the improvement of the load-carrying capacity of the CFST specimens. In addition, the comparison of the results of S-active and L-active specimens indicates that increasing the prestressing level has no significant effect on improving the compressive strength of CFST specimens.

Here, the yielding compressive strength of the composite member (σ_y) was defined as the compressive strength at the yielding of the steel tube. Normalized yield strength is obtained as the ratio of the yield strength to the peak compressive strength of the composite sections, and its values for all the STCC and CFST specimens are presented in Table 3 and Fig. 6. According to these results, the normalized yield strength for all the specimens is about 0.83 except for the L-active CFST specimen. This indicates that the yield compressive strength of the composite sections, regardless of the type of the section (STCC or CFST) and confinement (active or passive), was about 83% of the peak compressive strength. The reason for this is that the steel

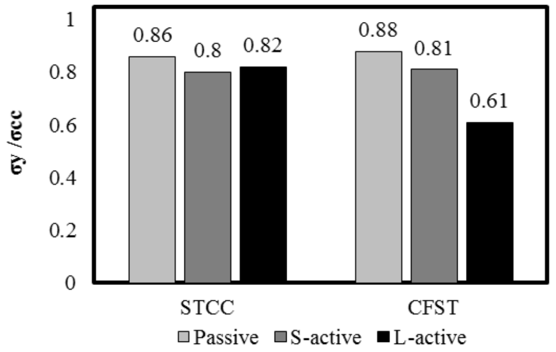

Fig. 6 The yielding to the peak compressive strength ratio of STCC and CFST specimens

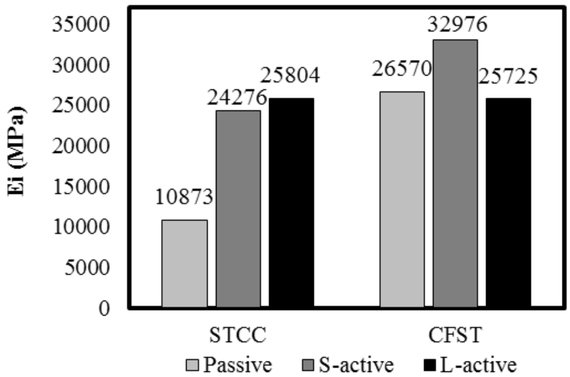

Fig. 7 The initial modulus of elasticity of STCC and CFST specimens

tube was under a significant hoop tensile stress at the beginning of loading caused by prestressing and longitudinal compressive stress caused by the direct loading. These two factors caused the steel tube in the active CFST specimen to experience quick yielding once the normalized yielding strength of 0.61 was achieved.

3.2 Modulus of elasticity

A major property of composite sections is their modulus of elasticity, which has a significant role in determining elastic deformations (Ho and Lai 2013). It is defined as the ratio of engineering stress to associated engineering strain or the increment ratio of them, which are called the secant modulus and tangent modulus, respectively. In this study, the initial modulus of elasticity, secant modulus at the initial peak point and modulus of elasticity under reloading for the STCC and CFST specimens with passive, S-active and L-active confinement were investigated.

3.2.1 Initial modulus of elasticity

Table 3 and Fig. 7 present the initial modulus of elasticity (E_i) values of the active and passive specimens are provided. Note that the modulus of elasticity values reported in this study are lower than the actual values. The reason is the existence of additional deformations in the specimen caused by the concentration of stress at the top and bottom ends of the specimen in contact with the loading plates, which in turn reduces the modulus of elasticity (Nematzadeh *et al*. 2017d). Although this effect is negligible in the middle region, and the deformation and modulus of elasticity have their real values, measuring the axial deformation at mid-height of the concrete core in the STCCs by LVDTs was not possible. Hence, the total height of the specimens was considered for measuring the modulus of the STCC and CFST, for the purpose of comparison.

Fig. 7 demonstrates that the initial modulus of the CFST specimens with S-active and passive confinement is significantly greater relative to that of the STCC ones. The reason is attributed to the significant load-carrying portion of the steel tube in the CFST specimens. Since the stiffness of the steel is higher than that of the concrete, a high load-carrying portion of the steel tube leads to an increase in the stiffness of the composite section. Although the steel tube in the STCC specimens carries the axial compressive load due to the friction at the concrete-steel interface, its amount at the early moments of loading is negligible. The findings show that the initial modulus of the CFST specimens with passive confinement is 144% higher than that of the STCC specimens. This value is 36% for the S-active specimens. Unlike the trend observed for the S-active specimens, the elastic modulus values of the STCC and CFST specimens with L-active confinement are almost equal to each other. The reason for this is a decline in the initial modulus of the CFST specimens from S-active confinement to the L-active one. It should be noted that after removing the L-active specimens from the prestressing apparatus, some microcracks appeared in the concrete core that reduced its modulus of elasticity (Nematzadeh and Naghipour 2012b). Moreover, when the L-active CFST specimens are subjected to an axial compressive load, due to a higher Poisson's ratio of steel than that of the concrete at the early moments of loading, the amount of prestressing and lateral pressure on the concrete core is reduced (Milan *et al.* 2019). This increases the concrete cracking and reduces the elastic modulus of the composite section. This did not happen in the S-active CFST specimens due to the low level of prestressing and in passive specimens due to a lack of prestressing. Also, this trend was not observed in the STCC specimens because of small compressive axial stresses in the steel tube.

According to Table 3 and Fig. 7, the initial modulus of elasticity of the S-active and L-active STCC specimens is about 123% and 137%, respectively, greater than that of the STCC specimens with passive confinement. Thus, applying the prestressing on the STCC specimens by the present technique significantly increases the initial modulus of elasticity. Also, it is observed that the initial elastic modulus of the S-active CFST specimen is 24% higher and that of the L-active one is 3% lower than that of the passive specimen. As a result, prestressing the CFST specimens is seen to negligibly affect the improvement of the initial modulus of elasticity (similar results were obtained in Nematzadeh *et al*. 2017d). In addition, high elastic modulus of the compressed concrete core insignificantly affected the initial elastic modulus of the CFST specimens since a major load-carrying portion at the early moments of loading belonged to the steel tube (Lai and Ho 2017), while in the STCCs, the concrete core played the main role in carrying

Table 5 Real experimental and theoretical initial modulus of elasticity for CFST specimens

Specimens		E_R (MPa)	E_{Theo} (MPa)
CFST	Passive	54806	58862
	S-active	88086	70671
	L-active	59357	63261

the load and in the initial modulus of elasticity.

The experimental findings indicated that the initial modulus of elasticity of the L-active STCC specimen was 6% higher than that of the S-active one, while in the L-active CFST specimen it was 28% lower than the S-active one. This indicates that increasing the prestressing level (from the S-active to L-active) results in a slight increase in the elastic modulus of STCC and a significant reduction in that of CFST.

3.2.2 Real elastic modulus of CFST specimens

Since the axial strains of the steel tube and concrete core were equal in the CFST specimens, it was possible to use the longitudinal strain gauges mounted on the outer surface of the steel tube at the mid-height to measure the axial strain of CFST specimens. Despite the fact that the axial strain measured by the LVDTs was the average strain along the entire height of the specimens including the end effects, the strain recorded by the strain gauges at mid-height of the specimens did not contain the end effects and the obtained values of the modulus of elasticity were the real values. Table 5 gives the real modulus of elasticity results of CFST specimens (E_R). Note that in this section, the stress of CFST specimens is obtained by dividing the load by the composite cross-sectional area (the loading surface). According to Table 5, the initial modulus of the S-active and L-active CFST members is considerably and slightly, respectively, greater than the members with passive confinement, which suggests the negative influence of high prestressing levels on the modulus of elasticity of the CFST specimens, as concluded previously.

Since concrete and steel are in the linear stage at the early moments of loading, the initial elastic modulus of CFST specimens can be obtained by the classical equations of material strength and assuming no concrete core-steel tube interaction, as follows.

$$E_{Theo} = \frac{A_c E_c + A_s E_s}{A_t} \tag{4}$$

where E_{Theo}, E_c and E_s are the modulus of elasticity of the composite, concrete and steel section, respectively. Also, A_t, A_c and A_s are the cross-sectional area of the composite section, concrete core and steel tube, respectively. By comparing the experimental results with the theoretical ones and conducting subtraction, it is possible to determine the portion of the interaction between concrete and steel in the modulus of elasticity of CFST specimens. In Eq. (4), the elastic modulus of uncompressed concrete in the passive specimens and the elastic modulus of compressed concrete in the active specimens can be determined by the following equations (Nematzadeh and Naghipour 2012b).

$$E_{cR} = 3000\sqrt{f_{cR}} + 13000 \quad \text{for uncompressed concrete} \tag{5}$$

$$E_{cS} = 3500\sqrt{f_{cS}} + 15900$$

$$\text{for concrete under short-term lateral pressure} \tag{6}$$

$$E_{cL} = (0.8336\, e^{-0.223 P_f} + 1) E_{cR}$$

$$\text{for concrete under long-term lateral pressure} \tag{7}$$

where E_{cR}, E_{cS} and E_{cL} are elastic modulus of uncompressed concrete, short-term pressure compressed concrete and long-term pressure compressed concrete, respectively. Furthermore, P_f is the ultimate lateral force (prestressing level) exerted on the concrete core, expressed in MPa. Note that in the compressed concrete with long term pressure, there were many cracks due to the release of the lateral strains after removal from the tube, which significantly reduced the modulus of elasticity (Nematzadeh and Naghipour 2012b). Although using the modulus of elasticity of the compressed concrete under long-term pressure for calculating the elastic modulus of L-active STCC is incorrect due to the prevention of the lateral strains of concrete core by the steel tube, it can still be used to obtain the modulus elasticity of L-active CFST due to the separation of concrete and steel at the early moments of the loading. Based on Eqs. (5)-(7), the elastic modulus of the concrete core in the uncompressed concrete, short- and long-term pressure compressed concrete was calculated as 30364, 44377 and 35584 MPa, respectively. Therefore, based on Eq. (4), the modulus of elasticity of the CFST specimens with passive, S-active and L-active confinement was obtained as 58862, 70671 and 63261 MPa, respectively, as seen in Table 5. In the table, it is observed that the theoretical modulus of the passive CFST is near the real one. This demonstrates that in passive CFST specimens, the composite action between the concrete core and steel tube does not occur at the initial moments of loading and each component of the composite section acts independently in carrying the axial load. The same trend was seen in the specimens with L-active confinement. It can be seen in Table 5 that the real modulus of elasticity of the S-active specimens is about 25% higher than the theoretical value. The difference indicates the importance of the composite action between concrete and steel in increasing the initial modulus of elasticity of the S-active specimens via prestressing.

3.2.3 Modulus of elasticity at steel yielding point

The secant modulus of elasticity of a composite section at the yielding point of the steel tube ($E_{\sec,y}$) is obtained as the ratio of the yielding compressive strength to the associated axial strain, which is called the yield secant modulus. Table 3 and Fig. 8 present the experimental yield secant modulus values for the actively- and passively-confined STCC and CFST specimens. In addition, the initial modulus of elasticity values are displayed in Fig. 8 for comparison. The yield secant modulus is seen to be smaller than the initial secant modulus in all specimens, which is caused by the microcracks formed in the concrete core during the loading (Yang *et al.* 2015). The yield secant modulus was lower than the initial secant modulus by 41%, 15%, and 13% for the STCC specimens with passive, S-

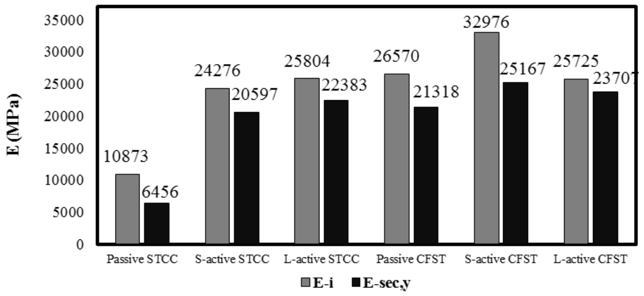

Fig. 8 Yield secant modulus of STCC and CFST specimens along with the initial modulus of elasticity

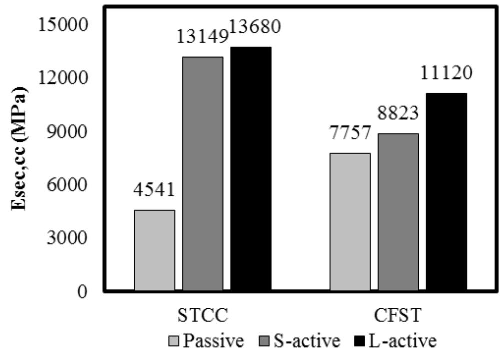

Fig. 9 Peak secant modulus of STCC and CFST specimens

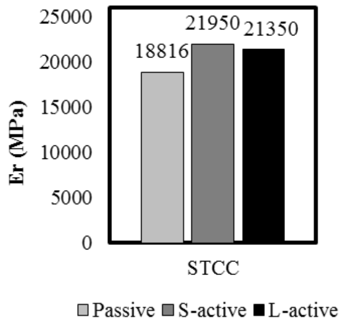

Fig. 10 Reloading modulus of elasticity of STCC specimens

active and L-active confinement, respectively. It can be found from the results that the proposed method of prestressing can notably lower modulus reduction while increasing the prestressing level has no significant effect on it. In fact, the high strength of the compressed concrete core and the existence of an effective initial confining pressure applied on it increased the linear behavior of active STCC specimens.

Modulus decline in the CFST specimens with passive, S-active and L-active confinement was obtained as 20%, 24%, and 8%, respectively. It was observed that the modulus reduction in the L-active specimen was notably smaller than that of the other specimens. This is attributed to the fact that the steel tube in the L-active CFST specimen yields rapidly, as mentioned in Section 3.1, and the microcracks in the concrete core cannot be developed in a short time. Therefore, the modulus of elasticity experiences a small reduction from the starting point of loading until the steel yielding point. Since the steel modulus of elasticity plays a major role in determining the elastic modulus of CFST specimens in the elastic stage, there is no significant difference between the modulus reduction of the passive and S-active specimens.

According to Table 3 and Fig. 8, it can be deduced that the present method of prestressing considerably increases the yield secant modulus of STCC specimens, while this increase in CFST specimens is much lower. Furthermore, increasing the prestressing level has little effect on the yield secant modulus of STCC and CFST specimens.

3.2.4 Modulus of elasticity at peak point

The secant modulus of elasticity at the initial peak point ($E_{\mathrm{sec},cc}$) is called the peak secant modulus and is defined as the slope of the line that links the origin of coordinates with the initial peak point on the axial stress-strain curve. It is obtained as the strength at the initial peak point divided by the corresponding axial strain. Test results of the peak secant modulus for the actively- and passively-confined STCC and CFST members are presented in Table 3 and Fig. 9.

According to the experimental results, the peak secant modulus of the passive CFST specimens was 71% higher than that of the STCC ones, while the peak secant modulus of the CFST specimens with S-active and L-active confinement was 33% and 19%, respectively, lower than that of the STCC ones. No similar trend is seen between the peak secant modulus results of the specimens with S-active and L-active confinement and the initial modulus of elasticity results. This is because the axial deformation of the CFST specimens with S-active and L-active confinement at peak point is significantly higher than that of the STCC specimens, as discussed later.

Fig. 9 demonstrates that the peak secant modulus of the composite members increases by applying the prestressing on the specimens. In this regard, the peak secant modulus of the STCC specimen with S-active and L-active confinement was 190% and 201%, respectively, greater than that of the members with passive confinement. The corresponding values are 14% and 43%, respectively, in the CFST specimens. The results indicate that the peak secant modulus improvement caused by prestressing the CFST specimens was significantly lower than that of the STCC ones.

3.2.5 Reloading modulus of elasticity

Reloading modulus of elasticity (E_r) is a mechanical property of composite columns with particular interest for simulating the behavior of these columns under dynamic loading. To determine this parameter in the STCC specimens, axial loading is stopped after an axial deformation of about 30 mm and then the initial modulus of elasticity is measured in the reloading phase. In the CFST specimens, the local buckling of steel tubes occurs in the first loading phase thus it is not possible to investigate their properties under reloading.

Table 3 and Fig. 10 give the reloading modulus of elasticity results for the STCC specimens, according to which, the reloading modulus of elasticity values in columns with S-active and L-active confinement are very close to each other and are only about 15% higher than that

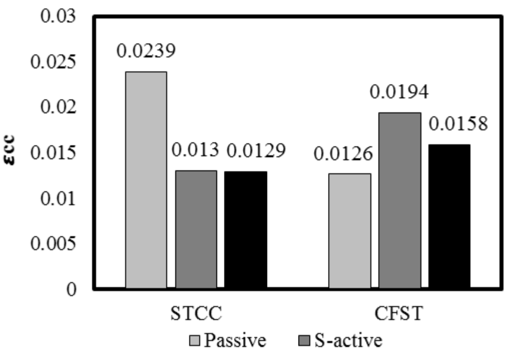

Fig. 11 Peak axial strain of STCC and CFST columns

of the passive one, while this increase is obtained about 230% in the first loading phase. The test results also showed that the reloading modulus of elasticity of the active specimens was reduced by 14% compared to the first loading modulus, contrary to the increase of 73% in the reloading modulus of elasticity of the passive specimens. The main reason is that the large deformation of the passive STCC specimen created in the first loading leads to significant compression of the concrete core and reduction of its porosities. Hence, in the reloading, the concrete core of the passive specimen is a compressed concrete similar to that of the active specimens and behaves similarly. Moreover, the steel tube yielded in the first loading, and hence in unloading, residual stresses remained in the steel tube, resulting in the prestressing of the confined concrete in the reloading. Based on the similar conditions of the concrete core in passive, S-active and L-active specimens and the existence of prestressing in all of them in the reloading, their mechanical properties including the modulus of elasticity were expected to be close to each other. In addition, in the passive specimens, the two factors of prestressed steel tube and compressed concrete core led to a notable increase in modulus of elasticity in the reloading, while in the active specimens, these two factors existed in the first loading and no improvement in the mechanical properties was achieved in the reloading.

3.3 Axial strain at peak point

The peak axial strain of composite columns is the axial strain at the initial peak point (ε_{cc}) and is calculated as the ratio of axial shortening to the initial length of the specimens. Table 3 and Fig. 11 present the peak axial strain of the STCC and CFST specimens with passive and active confinement. Fig. 11 demonstrates that the peak axial strain of the STCC column with passive confinement is significantly greater than that of the CFST column with active one by about 90%. The main reason of this fact is that in the passive CFST, the steel tube creates a significant stiffness against the axial deformation from the start of loading while in the passive STCC, a considerable axial deformation occurs before the effective confinement, and after that, the confinement reduces the rate of increase in the axial strain. Unlike the passive specimens, the peak axial strain of the STCC specimens with S-active and L-active confinement was less than that of the CFST ones, being 33% and 18%, respectively. This is because the effective confinement at the beginning of loading due to prestressing and the compressed concrete core play significant roles in reducing the axial deformation of the STCC specimens (Tran *et al*. 2015), while in the CFST specimens, the main load-bearing share is for the steel tube, and hence the two mentioned factors are less effective. Therefore, it can be concluded that the impact of prestressing on reducing the axial deformation of STCC specimens is much more than that of CFST ones.

Based on Fig. 11, the peak axial strain of the STCC specimens with active confinement is considerably less than that of those with passive one, while in the CFST specimens, prestressing leads to an increase in the peak axial strain. The reason is that the prestressing in the CFST specimens leads to a quick yielding of the steel tube and a rapid increase in deformation. Although this behavior is also present in the STCC specimens, the initial confinement, and the compressed concrete core significantly reduce the axial deformation.

4. Conclusions

According to the results of the experimental study, the following conclusions may be derived:

- The compressive strength of the STCC specimens with passive, S-active and L-active confinement was about 11%, 3%, and 8% greater than that of the CFST specimens, respectively.
- The present method of prestressing the STCC and CFST specimens with considerably increased the compressive strength by 60% and 68%, respectively. In addition, increasing the prestressing level (from S-active to L-active) had a negligible effect on the compressive strength of the STCC and CFST specimens.
- The load-carrying capacity of the CFST specimens with S-active and L-active confinement was 27% and 23% higher than the sum of the capacity of their components, respectively, while no improvement was observed in the load-carrying capacity of the passive CFST specimens.
- The yield compressive strength of the composite specimens regardless of the type of section (STCC or CFST) and confinement (S-active or passive) was about 83% of the peak compressive strength.
- The initial modulus of elasticity of the CFST columns with passive and S-active confinement was 144% and 36% higher than that of the STCC ones, respectively. Also, the modulus of elasticity values of the CFST and STCC specimens with L-active confinement was almost the same.
- Prestressing the STCC specimens led to a notable increase in the initial modulus of elasticity, which was about 130%, while it had little effect on that of the CFST specimens. Furthermore, increasing the prestressing level resulted in a negligible increase in the initial modulus of the STCC specimens and a considerable decrease in that of CFST specimens.
- The peak secant modulus of the passive CFST specimen was 71% higher than that of the STCC one,

while the peak secant modulus of the CFST specimens with S-active and L-active confinement was 33% and 19% lower than that of the STCC ones, respectively.
• The peak secant modulus of STCC specimens considerably increased with applying the prestressing, as much as 190% and 201% for S-active and L-active confinement, respectively. This improvement was smaller in the CFST specimens, being 14% and 43%, respectively.
• The reloading modulus of elasticity of the active STCC specimens compared to the first loading modulus of elasticity was somewhat reduced, while a significant increase was achieved in passive confinement. However, the values of reloading modulus of elasticity in the specimens with passive, S-active and L-active confinement were close to each other.
• The axial strain of the active STCC specimens was considerably less than that of the passive one, while in the CFST specimens, prestressing increased the axial strain. In addition, the axial strain in the STCC specimens with passive, S-active and L-active confinement was 90% higher, 33% and 18% lower than the corresponding value in the CFST specimens, respectively.

References

Aboutaha, R.S. and Machado, R. (1998), "Seismic resistance of steel confined reinforced concrete (SCRC) columns", *Struct. Des. Tall Build.*, **7**(3), 251-260. https://doi.org/10.1002/(SICI)1099-1794(199809)7:3<251::AID-TAL112>3.0.CO;2-J.

ACI Committee 318 (2008), Building Code Requirements for Structural Concrete and Commentary, ACI 318M-08, American Concrete Institute, USA.

Alhatmey, I.A., Ekmekyapar, T. and Alrebeh, S.K. (2018), "Residual strength capacity of fire-exposed circular concrete-filled steel tube stub columns", *Adv. Concrete Constr.*, **6**(5), 485-507. https://doi.org/10.12989/acc.2018.6.5.485.

ASTM C39/C39M (2002), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA.

Australia Standards AS3600 (1994), Reinforced Concrete Structures, Standards Australia, Sydney.

Chang, H., Huang, C.K. and Chen, Y.J. (2009), "Mechanical performance of eccentrically loaded prestressing concrete filled circular steel tube columns by means of expansive cement", *Eng. Struct.*, **31**, 2588-2597. https://doi.org/10.1016/j.engstruct.2009.06.007.

Feeser, L.J. and Chinn, J. (1962), "Strength and stiffness of spirally prestressed concrete cylinders", *PCI J/*, **7**(3), 55-62.

Ghadami, J. and Nematzadeh, M. (2018). "Effect of bond shear stress on compressive behaviour of steel tube-confined concrete with active and passive confinement", *Eur. J. Envir. Civil Eng.*, **22**(7), 783-810. https://doi.org/10.1080/19648189.2016.1219878.

Gupta, P.K., Verma, V.K., Khaudhair, Z.A. and Singh, H. (2015), "Effect of tube area on the behavior of concrete filled tubular columns", *Comput. Concrete*, **15**(2), 141-166. https://doi.org/10.12989/cac.2015.15.2.141.

Han, L.H., Wang, W.D. and Zhao X.L. (2008), "Behaviour of steel beam to concrete-filled SHS column frames: finite element model & verifications", *Eng. Struct.*, **30**, 1647-1658. https://doi.org/10.1016/j.engstruct.2007.10.018.

Han, L.H., Yao, G.H., Chen, Z.P. and Yu, Q. (2005), "Experimental behaviour of steel tube confined concrete (STCC) columns", *Steel Compos. Struct.*, **5**(6), 459-484. https://doi.org/10.12989/scs.2005.5.6.459.

Ho, J.C.M. and Lai, M.H. (2013), "Behaviour of uni-axially loaded CFST columns confined by tie bars", *J. Constr. Steel Res.*, **83**, 37-50. https://doi.org/10.1016/j.jcsr.2012.12.014.

Janke, L., Czaderski, C., Ruth, J. and Motavalli, M. (2009), "Experiments on the residual load-bearing capacity of prestressed confined concrete columns", *Eng. Struct.*, **31**, 2247-2256. https://doi.org/10.1016/j.engstruct.2009.04.006.

Krstulovic-Opara, N. and Thiedeman, P.D. (2000), "Active confinement of concrete members with self-stressing composites", *ACI Mater. J.*, **97**(3), 297-308.

Lai, M.H. and Ho, J.C.M. (2014), "Confinement effect of ring-confined concrete-filled-steel-tube columns under uni-axial load", *Eng. Struct.*, **67**, 123-141. https://doi.org/10.1016/j.engstruct.2014.02.013.

Lai, M.H. and Ho, J.C.M. (2017), "An analysis-based model for axially loaded circular CFST columns", *Thin Wall. Struct.*, **119**, 770-781. https://doi.org/10.1016/j.tws.2017.07.024.

Liu, J., Teng, Y., Zhang, Y., Wang, X. and Chen, Y.F. (2018), "Axial stress-strain behavior of high-strength concrete confined by circular thin-walled steel tubes", *Constr. Build. Mater.*, **177**, 366-377. https://doi.org/10.1016/j.conbuildmat.2018.05.021.

Martin, C.W. (1968), "Spirally prestressed concrete cylinders", *ACI J.*, **65**(10), 837-845.

Milan, C.C., Albareda-Valls, A. and Carreras, J. M. (2019), "Evaluation of structural performance between active and passive preloading systems in circular concrete-filled steel tubes (CFST)", *Eng. Struct.*, **194**, 207-219. https://doi.org/10.1016/j.engstruct.2019.05.037.

Moghaddam, H., Samadi, M., Pilakoutas, K. and Mohebbi, S. (2010), "Axial compressive behavior of concrete actively confined by metal strips; Part A: Experimental study", *Mater. Struct.*, **43**(10), 1369-1381. https://doi.org/10.1617/s11527-010-9588-6.

Mokari, J. and Moghadam A.S. (2008), "Experimental and theoretical study of reinforced concrete columns with poor confinement retrofitted by thermal post tension steel jacketing", *J. Appl. Sci.*, **8**(24), 4579-4586.

Mortazavi, A.A., Pilakoutas, K. and Son, K.S. (2003), "RC column strengthening by lateral pre-tensioning of FRP", *Constr. Build. Mater.*, **17**, 491-497. https://doi.org/10.1016/S0950-0618(03)00046-1.

Nematzadeh, M. and Haghinejad, A. (2017), "Analysis of actively-confined concrete columns using prestressed steel tubes", *Comput. Concrete*, **19**(5), 477-488. https://doi.org/10.12989/cac.2017.19.5.477.

Nematzadeh, M. and Naghipour, M. (2012a), "Compressing fresh concrete technique and the effect of excess water content on physical–mechanical properties of compressed concrete", *Mater. Des.*, **37**, 256-267. https://doi.org/10.1016/j.matdes.2011.12.051.

Nematzadeh, M. and Naghipour, M. (2012b), "Compressive strength and modulus of elasticity of freshly compressed concrete", *Constr. Build. Mater.*, **34**, 476-485. https://doi.org/10.1016/j.conbuildmat.2012.02.055.

Nematzadeh, M., Fazli, S. and Hajirasouliha, I. (2017c), "Experimental study and calculation of laterally-prestressed confined concrete columns", *Steel Compos. Struct.*, **23**(5), 517-527. https://doi.org/10.12989/scs.2017.23.5.517.

Nematzadeh, M., Fazli, S., Naghipour, M. and Jalali, J. (2017d), "Experimental study on modulus of elasticity of steel tube-confined concrete stub columns with active and passive confinement", *Eng. Struct.*, **130**, 142-153. https://doi.org/10.1016/j.engstruct.2016.10.008.

Nematzadeh, M., Hajirasouliha, I., Haghinejad, A. and Naghipour, M. (2017a), "Steel tube-confined concrete stub columns with active and passive confinement", *Steel Compos. Struct.*, **24**(3), 323-337. https://doi.org/10.12989/scs.2017.24.3.323.

Nematzadeh, M., Naghipour, M., Jalali, J. and Salari, A. (2017b), "Experimental study and calculation of confinement relationships for prestressed steel tube-confined compressed concrete stub columns", *J. Civil Eng. Manage.*, **23**(6), 699-711. https://doi.org/10.3846/13923730.2017.1281837.

Shin, M. and Andrawes, B. (2010), "Experimental investigation of actively confined concrete using shape memory alloys", *Eng. Struct.*, **32**, 656-664. https://doi.org/10.1016/j.engstruct.2009.11.012.

Shinohara, Y. (2008), "Effect of transverse prestressing on shear behaviors of high-strength concrete columns", *Proceedings of The 14th World Conference on Earthquake Engineering*, Beijing, China, October.

Tomii, M., Sakino, K. and Xiao, Y. (1987), "Ultimate moment of reinforced concrete short columns confined in steel tube", *Proceeding of Pacific Conference on Earthquake Engineering*, Wairakei, New Zealand, August.

Tomii, M., Sakino, K., Watanabe, K. and Xiao, Y. (1985), "Lateral load capacity of reinforced concrete short columns confined by steel tube", *Proceedings of The International Specialty Conference on Concrete Filled Steel Tubular Structures*, Harbin, China, August.

Tran, H., Balandraud, X. and Destrebecq, J.F. (2015), "Improvement of the mechanical performances of concrete cylinders confined actively or passively by means of SMA wires", *Arch. Civil Mech. Eng.*, **15**(1), 292-299. https://doi.org/10.1016/j.acme.2014.04.009.

Wan, C.Y. and Zha, X.X. (2016), "Nonlinear analysis and design of concrete-filled dual steel tubular columns under axial loading", *Steel Compos. Struct.*, **20**(3), 571-597. http://dx.doi.org/10.12989/scs.2016.20.3.571.

Xiao, Y., He, W.H. and Choi, K.K. (2005), "Confined concrete-filled tubular columns", *J. Struct. Eng.*, ASCE, **131**(3), 488-497. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:3(488).

Yang, Y., Wang, Y., Fu, F. and Liu, J. (2015), "Static behavior of T-shaped concrete-filled steel tubular columns subjected to concentric and eccentric compressive loads", *Thin Wall. Struct.*, **95**, 374-388. https://doi.org/10.1016/j.tws.2015.07.009.

Yu, Q., Tao, Z., Liu, W. and Chen, Z.B. (2010), "Analysis and calculation of steel tube confined concrete (STCC) stub columns", *J. Constr. Steel Res.*, **66**(1), 53-64. https://doi.org/10.1016/j.jcsr.2009.08.003.

Zhao, X.L., Han, L.H. and Lu, H. (2010), *Concrete-Filled Tubular Members and Connections*, CRC Press.

CC

Notations

CFST	Concrete Filled Steel Tube
STCC	Steel Tube-Confined Concrete
L-active	Long term Prestressed Steel Tube-Confined
S-active	Short term Prestressed Steel Tube-Confined
A_c	Cross-sectional area of concrete
A_s	Cross-sectional area of steel tube
A_t	Cross-sectional area of composite section
D	Outer diameter of steel tube
E_c	Modulus of elasticity of concrete
E_{cL}	Elastic modulus of long term-pressure
E_{cR}	Elastic modulus of uncompressed concrete
E_{cS}	Elastic modulus of short term-pressure
E_i	Initial elastic modulus of composite specimens
E_R	Real elastic modulus of CFST specimens
E_r	Reloading modulus of elasticity
E_s	Elastic modulus of steel tube
E_s'	Elastic modulus of steel tube at strain hardening
$E_{\sec,cc}$	Secant modulus of elasticity of composite
$E_{\sec,y}$	Secant modulus of elasticity of composite
E_{Theo}	Theoretical elastic modulus of CFST specimens
f_c	Compressive strength of concrete
f_{cL}	Compressive strength of long term pressure
f_{cR}	Compressive strength of uncompressed concrete
f_{cS}	Compressive strength of short term pressure
F_{Exp}	Experimental load-carrying capacity of CFST
F_{Theo}	Theoretical load-carrying capacity of CFST
f_u	Ultimate stress of steel tube
f_y	Yield stress of steel tube
P_f	Final lateral pressure on concrete core
t	Thickness of steel tube
ε_{cc}	Axial strain of composite section at the initial
ε_p	Steel strain at the starting point of strain
ε_u	Ultimate strain of steel tube
v_s	Poisson's ratio of steel tube
σ_{cc}	Peak compressive strength of composite section
σ_y	Yield compressive strength of composite section