Primljen / Received: 2.12.2015
Ispravljen / Corrected: 15.3.2017.
Prihvaćen / Accepted: 4.7.2017.
Dostupno online / Available online: 10.7.2019.

Assessing influence of active and passive confinement on flexural behaviour of CFST beams

Authors:

Prof. **Morteza Naghipour**, PhD. CE
Babol Noshirvani University of Technology, Iran
Faculty of Civil Engineering
m-naghi@nit.ac.ir

Assist.Prof. **Marzieh Nemati**, PhD. CE
Babol Islamic Azad University, Iran
Faculty of Civil Engineering
marziehnemati1362@gmail.com

Assist.Prof. **Javad Jalali**, PhD. CE
Babol Noshirvani University of Technology, Iran
Faculty of Civil Engineering
javad.jalali@nit.ac.ir

Assoc.Prof. **Mahdi Nematzadeh**, PhD. CE
University of Mazandaran, Iran
Department of Civil Engineering
m.nematzadeh@umz.ac.ir

Original scientific paper

Morteza Naghipour, Marzieh Nemati, Javad Jalali, Mahdi Nematzadeh

Assessing influence of active and passive confinement on flexural behaviour of CFST beams

The aim of this study is to investigate the effect of active and passive confinement on the flexural behaviour of concrete-filled steel tubes. Three-point flexural test is carried out on twelve confined specimens. The main variable parameters are: tube diameter to thickness ratio (20, 30, and 60), compressive strength of concrete core (15 MPa and 45 MPa), and type of confinement (active or passive). The flexural capacity, energy absorption, flexibility and failure mode of confined specimens, as well as the cracking pattern of concrete core at failure point, are evaluated in this study. The results show that active confinement leads to lower ductile behaviour in specimens with higher strength of concrete core.

Key words:
concrete-filled steel tubes, active and passive confinement, flexural behaviour, absorbed energy

Izvorni znanstveni rad

Morteza Naghipour, Marzieh Nemati, Javad Jalali, Mahdi Nematzadeh

Ocjena utjecaja aktivnog i pasivnog ovijanja na karakteristike savijanja betonom ispunjenih čeličnih cijevi

U radu se analizira utjecaj aktivnog i pasivnog ovijanja na ponašanje pri savijanju betonom ispunjenih čeličnih cijevi. Dvanaest ovijenih uzoraka podvrgnuto je ispitivanju čvrstoće na savijanje u tri točke. Osnovni varijabilni parametri bili su: odnos promjera i debljine cijevi (20, 30 i 60), tlačna čvrstoća betonske jezgre (15 MPa i 45 MPa) i vrsta ovijanja (aktivno ili pasivno). Ispitana je savojna čvrstoća, apsorpcija energije, fleksibilnost i način popuštanja ovijenih uzoraka, isto kao i način pucanja betonske jezgre u točki sloma. Rezultati pokazuju da aktivno ovijanje dovodi do manje duktilnosti uzoraka koji se odlikuju većom čvrstoćom betonske jezgre.

Ključne riječi:
čelične cijevi ispunjene betonom, aktivno i pasivno ovijanje, savojna svojstva, apsorbirana energija

Wissenschaftlicher Originalbeitrag

Morteza Naghipour, Marzieh Nemati, Javad Jalali, Mahdi Nematzadeh

Bewertung des Einflusses der aktiven und passiven Ummantelung auf die Biegeeigenschaften von Stahlrohren mit Betonkern

Die Arbeit analysiert den Einfluss der aktiven und passiven Ummantelung auf die Biegeeigenschaften von Stahlrohren mit Betonkern. Zwölf ummantelte Proben wurden einer Biegefestigkeitsprüfung an drei Punkten unterzogen. Die grundlegenden variablen Parameter waren: das Verhältnis von Durchmesser und Dicke der Rohre (20, 30 und 60), die Druckfestigkeit des Betonkerns (15 MPa und 45 MPa) und die Art der Ummantelung (aktiv oder passiv). Die Biegefestigkeit, die Energieabsorption, die Flexibilität und die Art und Weise des Nachgebens der ummantelten Proben sowie die Art und Weise des Brechens des Betonkerns an der Bruchstelle wurden geprüft. Die Ergebnisse zeigen, dass die aktive Ummantelung zu einer geringeren Biegsamkeit der Proben führt, die durch die höhere Festigkeit des Betonkerns gekennzeichnet sind.

Schlüsselwörter:
Stahlrohre mit Betonkern, aktive und pasive Ummantelung, Biegeeigenschaften, absorbierte Energie

1. Introduction

Concrete filled steel tubes (CFST) have been used widely in the building and bridge industry [1-10]. Many studies have shown superior structural behaviour of CFSTs compared to reinforced concrete or steel sections [11-16]. Integrated performance of concrete and steel is such that the compressive strength of the concrete core increases because of confining effect of the tube on concrete. In addition, buckling of confining tube is delayed due to presence of the concrete core [17, 18]. Besides the above mentioned structural advantages, composite sections have other benefits such as ductile deformation, high seismic resistance, and good damping characteristics [4, 18].

The behaviour of composite columns and beam-columns has been widely studied in the past [12, 13,18-42]. The results of research on the behaviour of columns demonstrate a considerable increase in the bearing capacity of these sections as compared to ordinary steel or concrete sections [12, 13, 18-42]. Flexural behaviour of composite sections has also been studied by many researchers [14, 16-18, 22, 31, 40, 41, 43-53]. Kang et al. proposed a new composite section of concrete and steel as bridge girders. It is relatively easy to build, and has lower cost of concrete casting and welding [50]. The results of Kang et al. showed that CFST girders behave in a ductile manner and retain their strength till the end of loading [50]. Studies conducted by Tomii and Sakino [54], Lu and Kennedy [43], and Kilpatrick and Rangan [28], on the flexural behaviour of CFST sections, have shown remarkable flexibility of these sections. Also, the infill concrete leads to change in failure mode of tube at compression zone, from inward buckling to outward buckling, at relatively higher loads [17]. It should be noted that results reported by Probst et al. [14] and Prion and Boehme [31] showed that enough confinement for developing the plastic capacity of concrete is not provided, due to local buckling of the tube wall in very thin tubes. Based on the results of previous studies [19, 31, 33], the axial load of the steel tube that provides confinement for the concrete is unknown. But it has been found that circular sections are the most effective sections for these members, especially for columns with a low L/D of the steel tube. Also, Kilpatrick [28] proposed shear span ratio of 2.7 to observe the complete load transfer, without any slip between the steel tube and concrete core. Since there was a significant difference between the values of D/t of the steel tubes recommended by various codes, such as AIJ [55], BS 5400 [56], EC4 [57], and LRFD-AISC [58], Elchalakani et al. [44], investigated flexural behaviour of CFST members with different D/t of steel tubes. Results presented in [44] show that the concrete core prevented local buckling of the tube for the D/t of less than 40, while several plastic ripples were formed in inelastic range for specimens with D/t between 74 and 110. It was also found that the plastic limit of D/t was equal to 112.

The concept of post-tensioning of concrete core was for the first time used in the arch bridge of Aurora [59]. Tuan [21] and Deng [16] investigated the post-tensioning effect on flexural behaviour of CFSTs. In their research, a high-strength cable was embedded inside the steel tube to post-tension the concrete core. Then the expanded concrete was pumped into the tube. When the concrete hardened, the cable was pulled, and a compressive force was created in the concrete core [16, 59]. Results of Tuan and Deng's research [16, 21] reveal a significant increase in flexural capacity of the section, due to application of post tensioning force on the concrete core.

Shawkat et al [18] investigated the flexural behaviour of composite sections of steel and FRP rectangular tubes with various ratios of shear spans. In their study, they examined cracking pattern, failure mode and flexural capacity of these sections. Their results, considering the critical shear span for both materials of tube, indicate that the crack pattern and its size are very much dependent on the slip between concrete and tube[18].

In their research, Nematzadeh and Naghipour changed the type of confinement from passive to active by applying initial pressure on the fresh concrete core of composite sections [60-62]. The results indicate an increase in parameters such as the modulus of elasticity and compressive strength of concrete due to active confinement [60-62].

The effect of active confinement on flexural behaviour of CFST sections under 3-point static loading is investigated experimentally in this study. Moreover, the effects of different parameters such as the compressive strength of concrete core, D/t of the steel tube, and type of confinement, are evaluated. Based on test results, the flexural capacity, absorbed energy, failure mode, and type of concrete cracking at the moment of failure, are investigated with regard to the mentioned parameters. Finally, experimental results regarding flexural capacity of specimens are compared with those predicted by ACI 318, AISC, and EC4 codes.

2. Experimental investigation

2.1. Pre-stressing apparatus

A device named pre-stressing apparatus was designed and built in order to achieve an active confinement (see Figure 1). Steel tubes filled with fresh concrete were placed inside the apparatus. Then the apparatus applies pressure on the fresh concrete. The water released from the specimen due to applied pressure was discharged through intended locations. The initial pressure applied on the specimen changed the confinement condition of the specimen from active to passive.

The pre-stressing apparatus is designed in such a way that it is able to apply pressure on only one specimen at a time. The pressure is applied on the top of the cylindrical specimen by means of the hydraulic jack embedded on top of the apparatus. This pressure is then transferred through the specimen length, causing discharge of excess water (water that is not used for hydration) from fresh concrete. According to experiments performed on extra specimens, around 20 % of water contained in concrete mixture was expelled during the compression process. In order to drain the excess water, four valves are placed along the specimen length. Also, water would be able to exit through the existing gap between the upper and lower elements of the apparatus and the specimen. All valves are equipped with special filters allowing nothing else but water

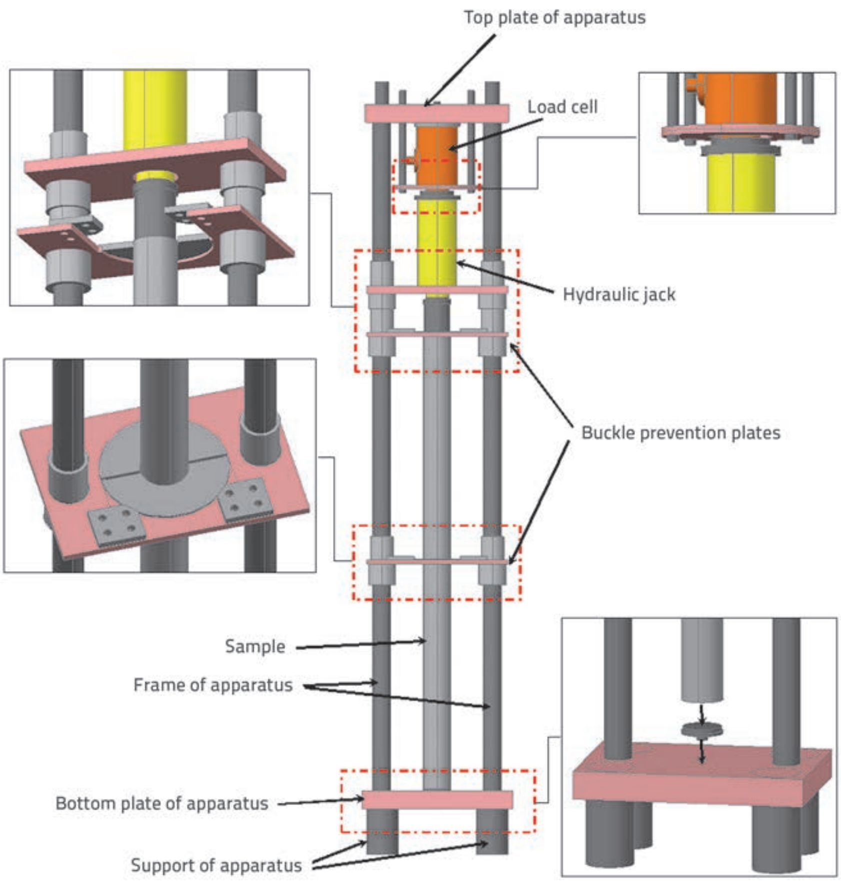


Figure 1. Details of pre-stressing apparatus

to get out. Furthermore, the distance between the upper and lower elements of the apparatus and specimens is defined in such a way that no other concrete particles can exit.

The water expelled from valves and accumulated on the baseplate of the pre-stressing apparatus is shown in Figure 2. As can be seen in Figure 2, the expelled water is pure. The purity of expelled water confirms proper performance of the specially designed filters.

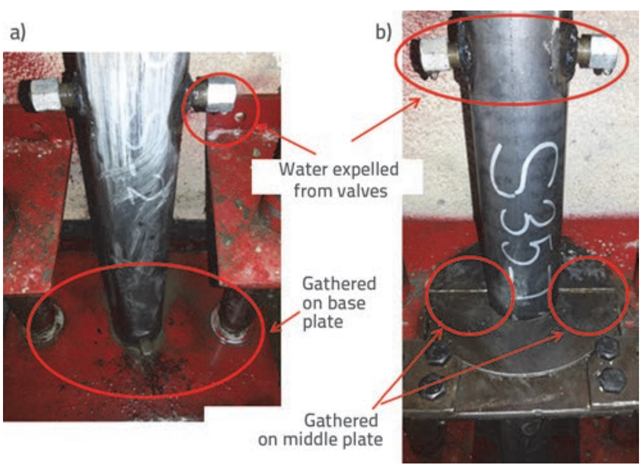


Figure 2. a) Water expelled from valves; b) Water accumulated on the baseplate

The hydraulic jack applies pressure on the specimen until no more water comes out of the specimen. Then the specimen is removed from the pre-stressing apparatus. The drainage of excess water may take 15 to 25 minutes. However, the excess water draining time may vary for different specimens, depending on both the level of pressure applied by the apparatus and the compressive strength of concrete.

2.2. Specimens

A total of 12 simply supported CFST beam specimens were examined experimentally. All the specimens' net length and span were 900 and 660 mm, respectively. The specimens were divided into two groups. Active specimens were categorized in the first group, while specimens with passive confinement were placed in the second group, as shown in Table 1. The initial pressure of 30MPa was applied on active specimens. Details of all specimens are provided in Table 1. According to this table, the name of each specimen is composed of three parts, representing the type of confinement, wall thickness of the steel tube, and the concrete compressive strength. The first and second parts of each specimen's name consist of a letter and a number. In the first part, the letter "S" stands for the word "static", indicating that the specimen is subjected to static loading.

Table 1. Specimens' details

Type of confinement	Specimen identifier	f_c [MPa]	t [mm]	D/t	D/t proposed by AISC [63]
active	S45-T1-A	45	1	60	111.1
	S45-T2-A	45	2	30	69.0
	S45-T3-A	45	3	20	79.0
	S15-T1-A	15	1	60	111.1
	S15-T2-A	15	2	30	69.0
	S15-T3-A	15	3	20	79.0
passive	S45-T1-P	45	1	60	111.1
	S45-T2-P	45	2	30	69.0
	S45-T3-P	45	3	20	79.0
	S15-T1-P	15	1	60	111.1
	S15-T2-P	15	2	30	69.0
	S15-T3-P	15	3	20	79.0

The number shows the compressive strength of concrete core in MPa. In the second part, the letter "T" stands for thickness and the number shows the wall thickness of the steel tube in mm. Finally, in the third part of the specimen's name, letters "A" and "P" represent active and passive confinement, respectively. As shown in Table 1, each sub-group contains three different specimens, each with a different confining steel tube thickness (1, 2 and 3 mm). The variation in wall thickness of steel tubes is made in order to investigate the effect of D/t of the steel tube on flexural behaviour of specimens. In addition, each group has two different values of compressive strength of concrete (15 MPa and 45 MPa) in order to evaluate the effect of compressive strength of the concrete core on flexural behaviour of active and passive specimens.

By calculating the area of steel and concrete of each specimen, the percentage of steel of 1, 2 and 3 mm specimens was determined as 3.3, 6.6, and 9.8, respectively. It can be seen that the minimum requirement for steel percentage, recommended by AISC and equalling to 1 %, has been fulfilled [63]. Also, D/t of the steel tube for each specimen satisfies the maximum ratio proposed by AISC [63].

In all specimens, concrete casting was done in upright position. In the first group, concrete casting was carried out without any compaction and vibration: specimens were placed in the pre-stressing apparatus. But, in the second group, concrete casting was performed in three layers, and each layer was compacted. Finally, to prevent evaporation of moisture, both ends of the tube were wrapped in nylon. Then, to prepare the specimens for bending test, they were kept in the standing position and at ambient temperature for 28 days. It should be noted that five cubic specimens were also prepared, simultaneously with concrete casting of the main specimens, to determine compressive strength of the concrete core. The cube specimens were demoulded after two days, and then cured in saturated condition. The composite specimen's flexural test, and the compression test on cubic specimens, were conducted on the same day.

2.3. Materials

Concrete mixture design was adopted based on the American Concrete Institute standard [15]. According to the Iranian Concrete Code [64] the maximum aggregate size cannot exceed 1/5 of the inner side of the concrete mould. Thus, the diameter of the maximum aggregate used in the mixture was 9.5 mm. Sand with the fineness modulus of 2.88 was used as fine aggregate. The maximum slump of 100 mm is proposed for beams in the ACI standard [15], and so 8-10 cm slump was used for all the specimens. No additives were used in concrete mixture in order to avoid their potential influence on the performance of confinement. The proportion of each material in the concrete mixture is shown in Table 2.

Commercially available steel tubes were used in this study. Due to the universal testing machine (bending test) limitations, the length and diameter of all specimens amounted to 900 mm and 60 mm, respectively. According to ASTM A370 [65], three dumbbell-shaped specimens were taken from each tube to determine the yield and ultimate strength of the steel tubes. Average results were recorded and presented in Table 3.

Table 3. Yield and ultimate strength of steel tubes

Tube thickness [mm]	Ultimate stress [MPa]	Yield stress [MPa]
1	305	270
2	500	435
3	420	380

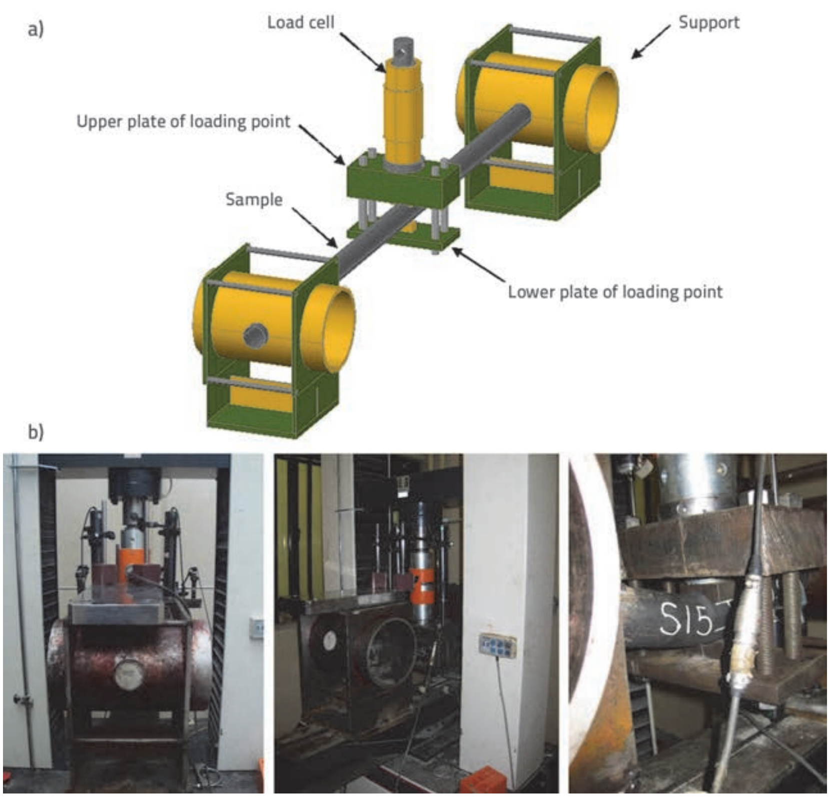


Figure 3. General view of the specimen and its equipment: a) schematic view; b) different views of experimental set up

Table 2. Mix proportions per 1 m³ concrete

f_c [MPa]	w/c	Slump [cm]	Water [kg]	Cement [kg]	Fine aggregate [kg]	Coarse aggregate [kg]
17.4	0.8	8-10	225.0	281.3	1117.6	661.2
44.2	0.38	8-10	225.0	592.1	806.7	661.2

2.4. Test set-up

All specimens were tested in 3-point bending. The test was done by universal STM 150 machine in a displacement control method at a rate of 2 mm/min. The load and midspan displacement was recorded at specified intervals. The general view of the specimen is shown in Figure 3. As shown in Figure 3, the supports were designed so as to ensure that specimens behave as a simply supported beam. In addition, two steel semi-circular pieces were built and installed at loading point to prevent stress concentration at that point. Active specimens were inserted into the testing machine taking care that all embedded valves are horizontal. Test was continued until a sudden drop in load was observed.

3. Results and discussion

3.1. Load-deflection relationship and failure mode

Figure 4 illustrates load-midspan deflection diagram for all specimens. As shown, all composite beams failed in a very ductile manner.

In addition, specimen failure occurred gradually, and no clear sign or sound was observed at the moment of failure. The failure mode of all specimens is illustrated in Figure 5. As shown, the failure mode of active specimens corresponds to that of passive specimens.

In all specimens, local buckling of steel tube occurred in compression zone (see Figure 5). Due to local buckling of the tube, some ripples formed in the upper part of the steel tube. In addition, failure occurred because of the tube rupture in tensile zone. In (S15-T3-A) and (S15-T2-P) specimens, failure was due to local buckling of the tube in compression zone, while in other specimens failure was induced by the tube rupture in tensile zone.

In specimens with the same concrete compressive strength and the same type of confinement, the decrease of the D/t of the steel tube reduced the height or number of ripples induced at the upper side of the specimens. Reduction in local

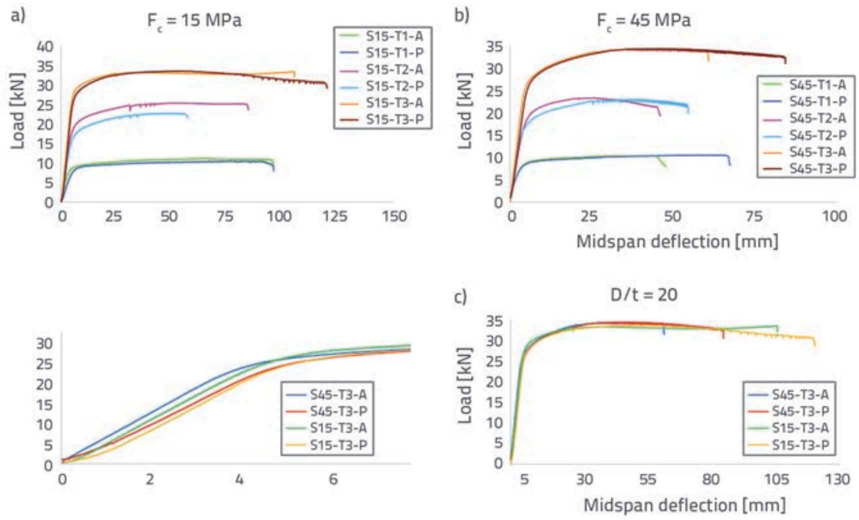


Figure 4. Load-midspan deflection diagram: a) specimens with f'_c = 15 MPa; b) specimens with f'_c = 45 MPa; c) specimens with D/t = 20

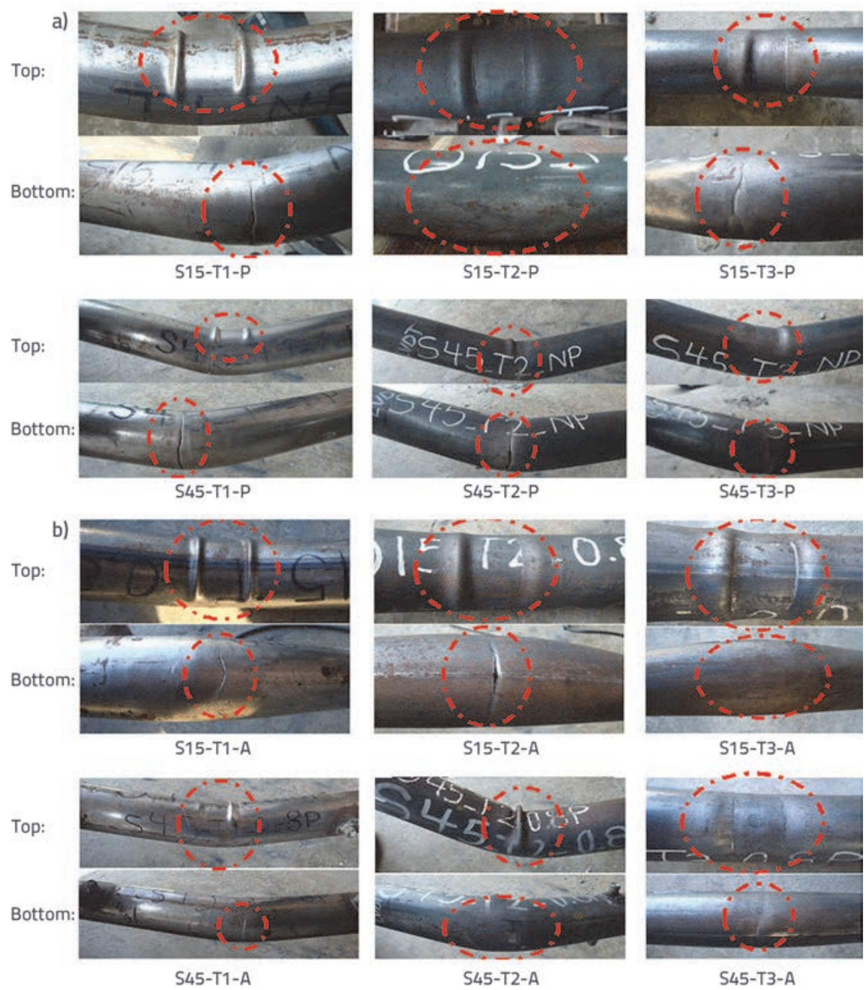


Figure 5. Failure mode of: a) passive specimens; b) active specimens

buckling of the steel tube at upper part is independent of the confinement type. In addition, local buckling of the steel tube decreased in all specimens with an increase in the compressive strength of concrete. Finally, it can be concluded that the type of confinement has no effect on the failure mode of specimens.

3.2. Cracking pattern

To investigate the concrete cracking pattern at the moment of failure, parts of the steel tube in the compression and tensile zone were cut after the bending test (see Figure 6). Concrete crushing and crack distribution at the compression and tensile zones can be seen in Figure 6.

Confinement type is an effective factor with regard to the area of crushed concrete in compression zone. Thus, in specimens with the same D/t of steel tube and concrete compressive strength, passive confinement causes a wider crushing area of concrete compared to active confinement. Compressive strength of concrete core also influence the area of crushed concrete, and so the crushing area of the concrete reduces with an increase in compressive strength of concrete. Another effective parameter with regard to concrete crushing is D/t of the steel tube. There is a direct relationship between D/t of the steel tube and the area of concrete crushing, i.e. the lower D/t of the steel tube, the lower the crushing area of concrete.

The composite performance of two types of materials is the cause of layered failure of concrete core, as shown in Figure 6. For the same concrete compressive strength and D/t of steel tube, cracks in the specimens with active confinement occurred in a wider area compared to passive specimens. However, the depth of cracks in active specimens was lower compared to passive specimens. Moreover, in the same confinement type and D/t of steel tube, higher compressive strength of concrete core resulted in shallower cracks over wider area of concrete core. D/t of the steel tube is another parameter that affected distribution of cracks in specimens, so that reduction in D/t of the steel tube leads to an increase in depth of induced cracks where area of cracked concrete is almost the same.

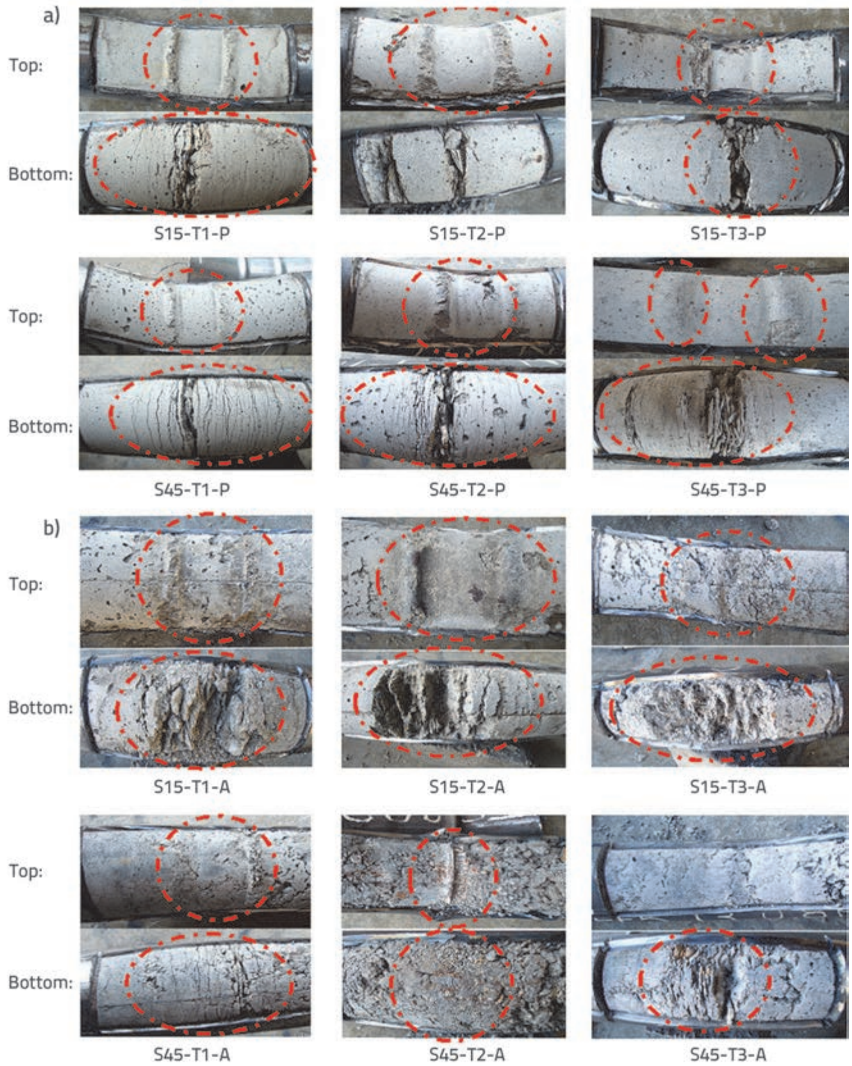


Figure 6. Failure mode of: a) passive specimens; b) active specimens

3.3. Flexural capacity and absorbed energy

The amount of absorbed energy (E_{abs}) for each specimen is determined by calculating the area under the load-displacement graph. Experimental results for ultimate load (P_{exp}), ultimate bending moment (M_u), and the amount of absorbed energy (E_{abs}), are presented for all specimens in Table 4.

Table 4. Experimental results for active and passive specimens

Specimen identifier	P_{exp} [kN]	E_{abs} [kNm]	M_u [kNm]
D/t = 60			
S45-T1-A	11.3	1015.1	1.9
S45-T1-P	10.5	952.1	1.7
S15-T1-A	10.4	480.5	1.7
S15-T1-P	10.6	668.7	1.7
D/t = 30			
S45-T2-A	25.4	2115.7	4.2
S45-T2-P	22.8	1251.8	3.8
S15-T2-A	23.7	2609.2	3.9
S15-T2-P	23.1	1178.7	3.8
D/t = 20			
S45-T3-A	34.3	2839.2	5.7
S45-T3-P	34.4	1933.0	5.7
S15-T3-A	33.5	3809.0	5.5
S15-T3-P	33.6	4079.1	5.5

As can be seen in Table 4, when f'_c = 15 MPa and D/t = 30, the change in the type of confinement from passive to active led to simultaneous increase in M_u and E_{abs}, while such a thing was not observed in other cases. So active confinement shows the best performance when D/t = 30 and f'_c = 15 MPa.

For D/t = 20 with different compressive strength of concrete core, the change in the type of confinement from passive to active has a reverse effect on flexural behaviour of specimens, resulting in reduction in M_u and E_{abs}

3.4. Parametric study

3.4.1. Confinement type

In order to evaluate the effect of confinement type on flexural behaviour, the composite specimens are divided into three groups, each group has a constant D/t of steel tube including passive and active confinement, with two values of concrete compressive strength (as subgroups). In Figure 7, the results of active specimens including M_u and E_{abs} are compared with M_u and E_{abs} of passive specimens (as reference specimens).

In group A, for specimens with f'_c = 45 MPa, M_u increases by 12 % as the confinement type is changed from passive to active, whereas the value of E_{abs} reduces by 28 %. Nevertheless, for specimens with f'_c = 15 MPa, E_{abs} increases by 7 % due to active confinement while M_u reduces by 2 %.

In Group B, for f'_c = 45 MPa, however M_u increase by 11 % as the confinement type is changed, while E_{abs} reduces by 15 %. The change of the type of confinement has a substantial effect on specimens with f'_c = 15 MPa. The change of the type of confinement not only leads to 3 % increase in M_u, but also causes an increase of 69 % in E_{abs}.

In Group C, both M_u and E_{abs} tend to decrease with the change of confinement type. It was clear that for specimens with f'_c = 45 MPa, the reduction of E_{abs} is greater compared to specimens with f'_c = 15 MPa.

It can also be concluded that active confinement exhibits the best performance in specimens with f'_c = 15 MPa in group B. Also, the worst performance is shown by specimens from group C, especially those with f'_c = 45 MPa. In case of specimens with f'_c = 45 MPa, active specimens have a lower midspan deflection (less ductile behavior) compared to passive specimens (see Figure 4). Such conclusion cannot be made for specimens with f'_c = 15 MPa.

3.4.2. Compressive strength of concrete

The effect of compressive strength of concrete core on the load-deflection relationship, M_u and E_{abs} of the specimens is investigated. All specimens are classified into three groups; in each group, D/t of the steel tube is constant and active and passive specimens are in separate subgroups.

By comparing the specimens with different compressive strengths (see Figure 4), it can be seen that the midspan deflection of specimens degrades as the compressive strength increases. The reduction of midspan deflection seems to be independent of the confinement type and wall thickness of steel tube.

To determine the variation in M_u and E_{abs} by increasing the compressive strength of concrete core, the percentage of

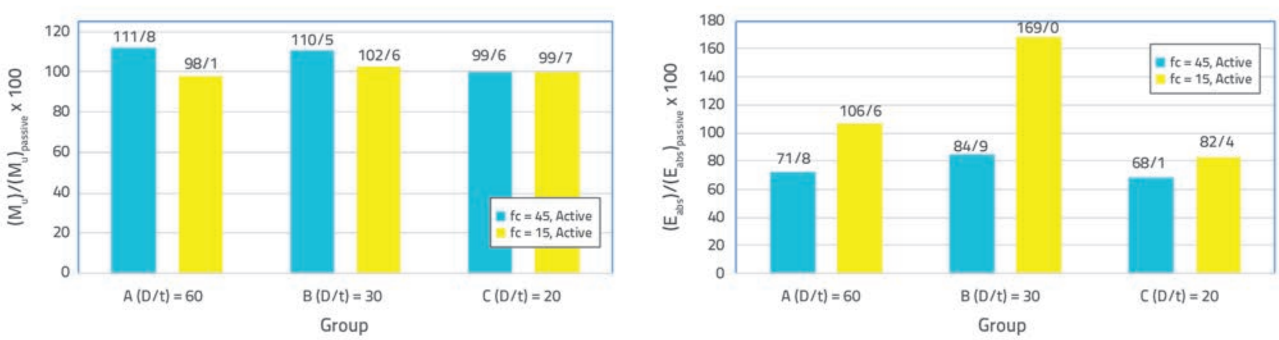


Figure 7. Percentage of variation – effect of confinement type: a) M_u; b) E_{abs}

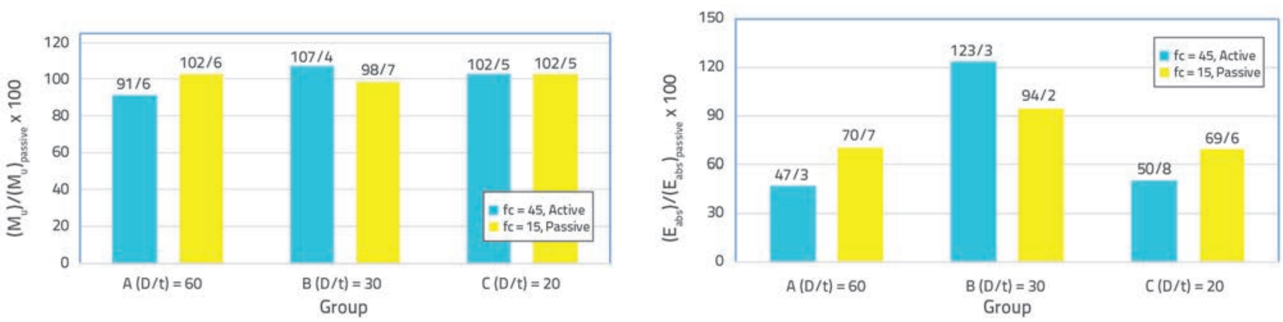


Figure 8. Percentage of variation – effect of compressive strength of concrete core: a) M_u; b) E_{abs}

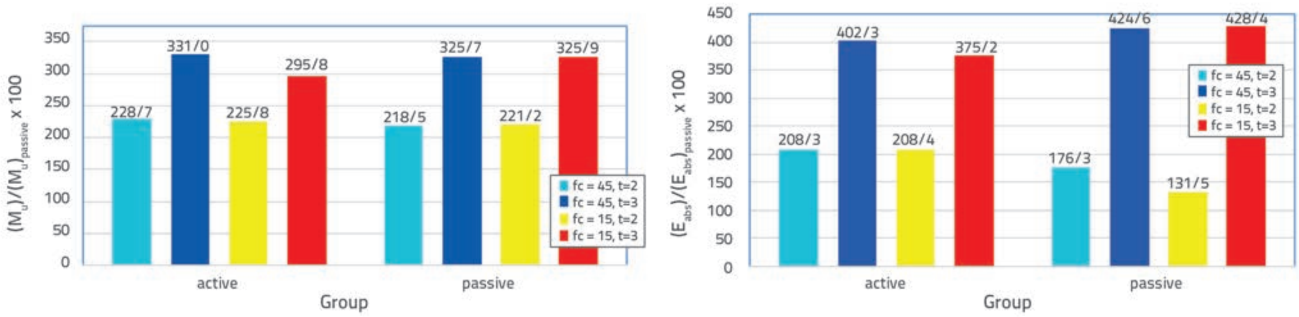


Figure 9. Percentage of variation – effect of D/t of steel tube: a) M_u; b) E_{abs}

change in M_u and E_{abs} for specimens with f'_c = 45 MPa is compared with (M_u) and (E_{abs}) for specimens with f'_c = 15 MPa (as reference specimens), as shown in Figure 8.

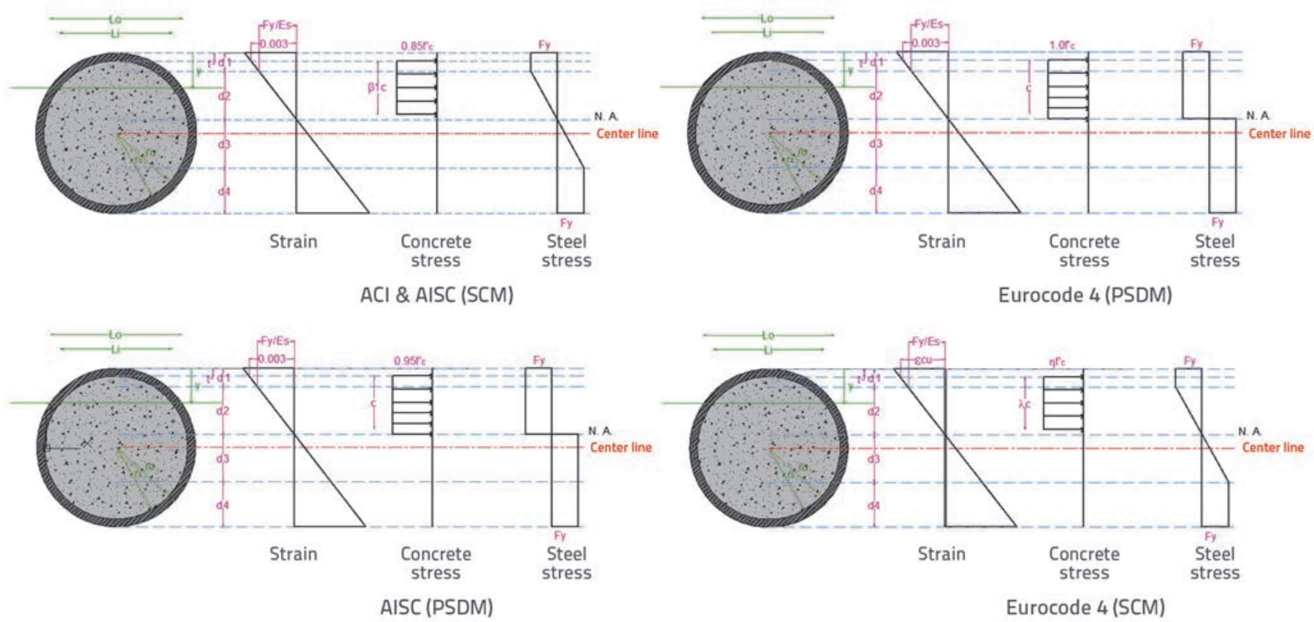
It is evident that in all cases, an increase in the compressive strength of concrete core leads to lower values of E_{abs}, except for active specimens of group B. In groups A and C, the reduction of E_{abs} due to an increase in the concrete compressive strength in active specimens is more significant compared to passive specimens.

In group B, It could be concluded that M_u of active specimens somewhat increases with an increase in the compressive strength of concrete core, while M_u of passive specimen reduces. In Group C, the loss of E_{abs} due to concrete strength increase is about 50 % for active confined specimens, whereas it is about 31 % for passive confined specimens. This means that active confinement leads to a more significant decrease in the influence on E_{abs} of specimens compared to passive specimens. Moreover, M_u increases with an increase in compressive strength of concrete core in both active and passive confined specimens.

3.4.3. Diameter to thickness ratio of steel tube

In order to investigate the effect of the steel tube D/t on flexural behaviour of composite specimens, all specimens are divided into two groups: active and passive confinement.

As shown in Figure 9, M_u increases significantly with a decrease in the steel tube D/t. In addition, it can be seen that specimens have a more ductile behaviour for a lower D/t of the steel tube. Moreover, the active specimen with D/t = 30 and f'_c = 45 MPa, has the lowest midspan deflection compared to other specimens. To study the effects of D/t of the steel tube on



Legend:

*d_1, d_2, d_3 and d_4: vertical distances relating to specific locations from the neutral axis and yield parts in the zones of compression and tension

β_1: ratio of depth of rectangular stress block to the depth of neutral axis [66]

λ: factor defining the effective height of the compression zone [67]

η: factor defining the effective strength [67]

Figure 10. Strain and stress distribution of concrete and steel according to assumptions of design codes

flexural behaviour of specimens, the percentage of change in M_u and E_{abs} of specimens with D/t = 20 and 30 is calculated and compared with specimens with D/t = 60 (as reference specimen), as shown in Figure 9.
It can be seen from Figure 9 that the values M_u and E_{abs} increase as the value D/t of the steel tube decreases. This indicates that the effect of tube thickness on flexural capacity is significant. The greatest change in M_u occurs in case of active specimens with D/t = 20 and f'_c = 45 MPa, while the greatest change in E_{abs} occurs for passive specimens with D/t = 20 and f'_c = 15 MPa.
In addition, the minimum increase of M_u and E_{abs} amounts to 120 % and 30 %, respectively, which points to a significant influence of D/t on M_u and E_{abs}.

4. Analytical study

4.1. Ultimate flexural capacity

The flexural strength of CFST specimens can be calculated according to a number of codes. The calculated flexural capacity of CFST beams varies depending on the design code applied. The flexural capacity of CFST specimens is predicted in various design codes according to two methods: strain compatibility method (SCM), and plastic stress distribution method (PSDM). The SCM is used by the ACI [66], and both SCM and PSDM are used by the AISC [63] and Eurocode4 [57].
Each code has different assumptions with different stress distributions of concrete and steel and, hence, dissimilar values of flexural capacity are predicted by design codes. The strain and stress distribution of concrete and steel according to each method is shown in Figure 10. A comparison between calculated and experimental results of flexural moments is made in order to evaluate the accuracy of the codes in predicting flexural capacity of CFST beams.
A logical flowchart for calculating the flexural moment capacity of CFST beams is shown in Figure 11. In the first step, material properties (f'_c, F_y, e_{cu} and E_s) and section geometry (D_o and t) are entered. Then the design code is selected. After that, the sectional analysis is started. The algorithm is set to find the neutral axis of the section. The neutral axis is found by equilibrium condition. The algorithm iterates the process until the equilibrium condition is met. After finding the neutral axis of section, the flexural strength is calculated by means of related equations.

4.2. Comparison

Since flexural strength values of active and passive specimens are quite close to each other, as concluded in Section 3.3, and as all equations in design codes are related to passive specimens, the accuracy of equations of individual design codes is evaluated by experimental results of passive specimens only.
Predicted flexural capacity $(M_n)_c$ is compared using different methods with experimental results $(M_u)_{exp}$ in Table 5. Also, mean values of the $(M_u)_{exp}$ / $(M_n)_c$ are presented in Table 5 for different methods. The results clearly show that all these design methods are conservative.
As can be seen, in most specimens, experimental results exceed the predicted ultimate moment capacity. However, it can be found that a good agreement is obtained for PDSM results in EC4 code with a mean ratio of 1.1. Predictions using other codes underestimate more the ultimate moment capacity, which is especially obvious for SCM method used in ACI and AISC codes. The main reason is that in this method the reduction factor of 0.85 is used for concrete strength. Better prediction is obtained for higher concrete compressive strength, especially for higher D/t (see PDSM results for EC4 and AISC in Table 5).
It can be seen that the SCM analysis according to the AISC and ACI methods give a moment capacity that is about 20 % lower than test results. Also, in case of both AISC and EC4 codes, PDSM method provides a mean value of 1.1. Therefore, these codes have the best predictions.

Table 5. Comparison between experimental and calculated strength of CFST beams

Specimen identifier	ACI & AISC-SCM analysis		AISC-PSDM analysis		EC4-PDSM analysis		EC4-SCM analysis		$(M_u)_{exp}$ [kNm]
	$(M_n)_c$ [kNm]	$(M_u)_{exp}$ / $(M_n)_c$	$(M_n)_c$ [kNm]	$(M_u)_{exp}$ / $(M_n)_c$	$(M_n)_c$ [kNm]	$(M_u)_{exp}$ / $(M_n)_c$	$(M_n)_c$ [kNm]	$(M_u)_{exp}$ / $(M_n)_c$	
S45-T1-P	1.7	1.0	1.7	1.0	1.7	1.0	1.7	1.0	1.7
S45-T2-P	3.5	1.1	3.8	1.0	3.8	1.0	3.6	1.1	3.8
S45-T3-P	4.6	1.2	4.9	1.2	4.9	1.2	4.7	1.2	5.7
S15-T1-P	1.4	1.2	1.5	1.1	1.5	1.1	1.5	1.2	1.7
S15-T2-P	3.1	1.2	3.4	1.1	3.4	1.1	3.2	1.2	3.8
S15-T3-P	4.2	1.3	4.4	1.2	4.5	1.2	4.2	1.3	5.5
Mean	1.18		1.11		1.10		1.16		

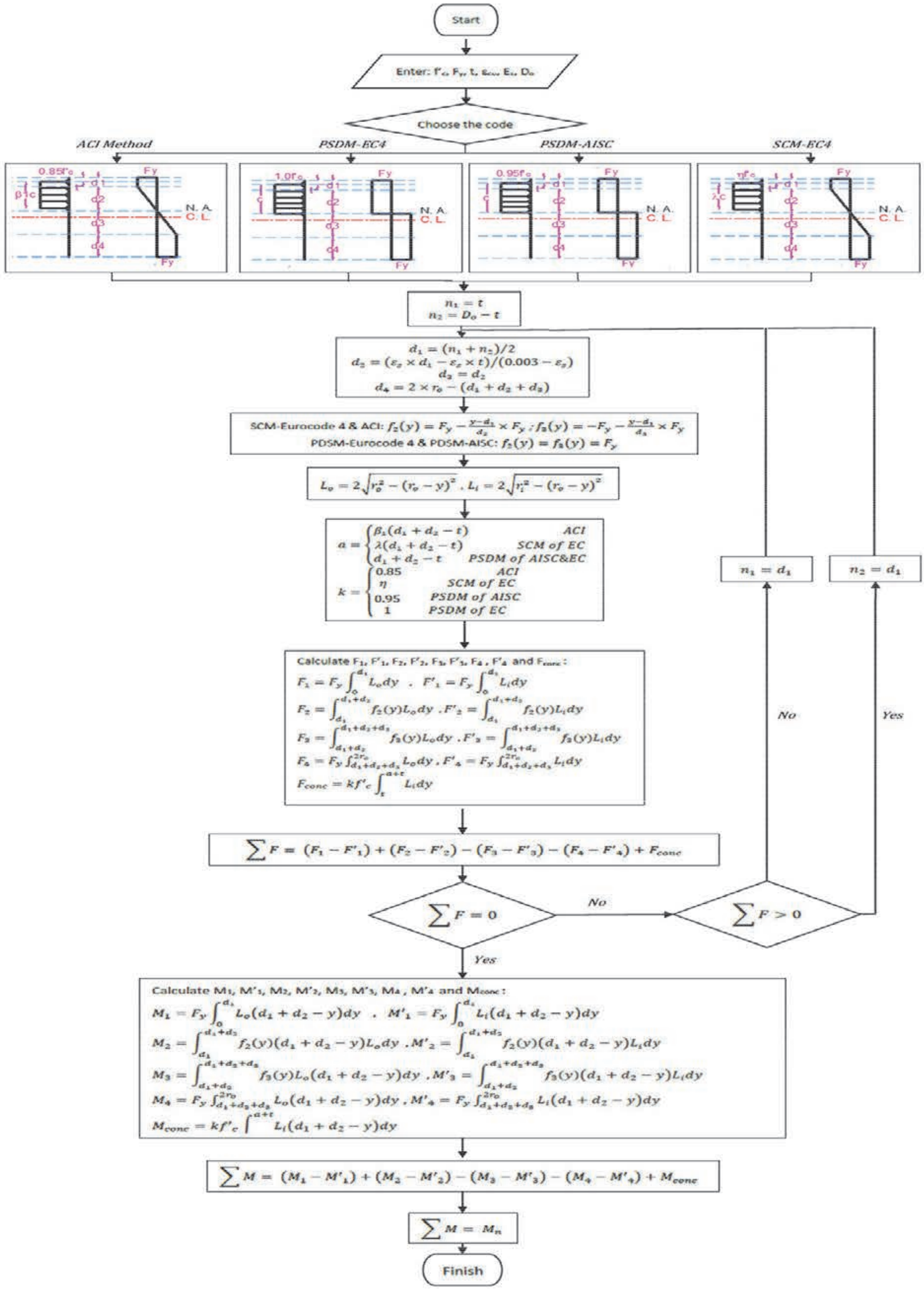


Figure 11. Flowchart for calculating the flexural strength of CFST beam

5. Conclusion

An experimental investigation of flexural behaviour of concrete filled steel tubes was conducted in this study for active and passive confinement conditions. Twelve CFST specimens were subjected to flexural loading and the effect of three variables, i.e. the tube's diameter to thickness ratio, concrete compressive strength, and confinement type, was studied. Based on the results of this study, the following observations and conclusions can be made:

1. All active and passive specimens behaved in a ductile manner and the ductility of CFST specimens reduced with an increase in compressive strength of concrete core. For the specimens with f'_c = 45 MPa, passive confinement revealed a more ductile behaviour compared to active confinement, and the diameter to thickness ratio of the steel tube did not affect the ductility of the specimens. However, no certain relation between the type of confinement could be established for f'_c = 15 MPa, and ductility of the specimens and active and passive confinement showed different behaviour versus D/t of the steel tube.
2. The Failure of all CFST specimens was accompanied by local buckling of steel tube in compression zone and its rupture in tensile zone. In addition, an increase in compressive strength of concrete core reduced the height or number of ripples generated in compression zone of the steel tube. Moreover, the type of confinement had a negligible effect on the failure mode of the specimens.
3. The concrete core was crushed in the area where the local buckling of steel tube occurred. The area of crushed concrete in the specimens with passive confinement was more pronounced than that in active specimens. Furthermore, the area of crushed concrete had an inverse relationship with the compressive strength of concrete core while there was a direct relationship between the crushed concrete area and D/t of the steel tube.
4. The concrete core was cracked in the tensile zone of all active and passive specimens. The type of confinement and compressive strength of concrete affected the crack extension area and depth of the cracks in the concrete core. The cracked area of concrete in the active specimens with f'_c = 15 MPa was wider in comparison with the corresponding passive specimens. Also, for f'_c = 45 MPa, concrete cracks in passive specimens were deeper than those in active specimens. In all specimens, D/t of the steel tube was inversely proportional to the crack depth.
5. The energy absorption of active and passive CFST specimens reduced with an increase in compressive strength of concrete, so that the reduction in active specimens was more significant than that in passive specimens. Furthermore, for sections with low D/t = 20, the use of concrete with f'_c = 15 MPa resulted in higher energy absorption compared to concrete with f'_c = 45 MPa. In addition, D/t of the steel tube dramatically altered the amount of absorbed energy.
6. Best performance as to changing the type of confinement from passive to active was observed in the specimen with D/t = 30 and f'_c = 15 MPa so that its absorbed energy and flexural capacity increased simultaneously. Moreover, for sections with low D/t (D/t = 20), the change in the type of confinement from passive to active led to a simultaneous reduction in flexural capacity and absorbed energy. Therefore, using active confinement condition in low D/t led to a weaker performance compared to passive confinement.
7. An increase in compressive strength of concrete core improved flexural capacity of passively confined specimens, while there was an inversely proportional relationship between the flexural capacity and compressive strength of concrete in actively confined specimens. In addition, an inverse relationship was observed between the flexural capacity and D/t of the specimens so that D/t of the steel tube affected the bending moment capacity significantly.
8. Predicted flexural capacity of specimens by PDSM analysis according to AISC and EC4 codes was in a good agreement with test results of CFST specimens.

REFERENCES

[1] Hosaka, T., Umehara, T., Nakamura, S., Nishiumi, K.: Design and experiments on a new rail way bridge system using concrete filled steel pipes, ASCCS Seminar, Concrete filled steel tubes- a comparison of international codes and practices, ASCCS seminar, Innsbruck, Austria (1997)

[2] Liu, Z., Goel, S.C.: Cyclic load behavior of concrete-filled tubular braces, J Struct Div, ASCE, 114 (1988) 7, pp. 1488-506, https://doi.org/10.1061/(ASCE)0733-9445(1988)114:7(1488)

[3] Zhao, X.L., Grzebieta, R., Lee, C.: Void-filled cold-formed RHS braces subjected to large deformation cyclic axial loading, J Strcut Eng. ASCE, 128 (2002) 6, pp. 746-753, https://doi.org/10.1061/(ASCE)0733-9445(2002)128:6(746)

[4] Hajjar, J.: Concrete-filled steel tube columns under earthquake loads, J. Progress Struct, Engng Mater, 2 (2000) 1, pp. 1-10, https://doi.org/10.1002/(SICI)1528-2716(200001/03)2:1<72::AID-PSE9>3.0.CO;2-E

[5] Roeder, C.W.: Overview of Hybrid and composite systems for seismic design in the United States, Engng Struct, 20 (1998) 4-6, pp. 355-363, https://doi.org/10.1016/S0141-0296(97)00035-7

[6] Fukumoto, Y.: Structural stability design. steel and composite structures. Oxford, Pergamon, 1997.

[7] Karbhari, V.M.: Structural characterization of fiber-reinforced composite short and medium span bridge systems, In: proceedings of European conference on Composite Materials (ECCM-8), pp. 35-42, 1998.

[8] Fam, A., Pando, M., Filz, G., Rizakalla, S.: Precast composite piles for the route 40 bridge in Virginia using concrete-filled FRP tubes, PCI J, 48 (2003) 3, pp. 32-45, https://doi.org/10.15554/pcij.05012003.32.45

[9] Fam, A., Greene, R., Rizkalla, S.: Field applications of concrete-filled FRP tubes for marine piles, Field application of FRP reinforcement: case studies, ACI special publication SP-215-9, pp. 161-180, 2003.

[10] Bondi, R.: Concrete filled tubular flange Girder Bridge. Modern Techniques in Bridge Engineering: Proceedings of 6th New York City Bridge Conference, pp. 137-147, 2011, https://doi.org/10.1201/b11340-14

[11] Webb, J., Beyton, J.J.: Composite concrete filled steel tube columns, In: Proceeding of Structural Engineering Conference, Adelaide: The Institution of Engineers Australia, pp. 181-185, 1990.

[12] Han, L.H., Zhao, X.L., Tao, Z.: Tests and mechanics model of concrete-filled SHS stub columns, columns and beam-columns, Steel & Composite Structures. An International Journal, 1 (2001) 1, pp. 51-74, https://doi.org/10.12989/scs.2001.1.1.051

[13] Neogi, P.K., Sen, H.K., Chapman, J.C.: Concrete filled tubular steel columns under eccentrical loading, Journal of Structural Engineering, 47 (1969) 5, pp. 187-195.

[14] Probst, A.D., Kang, T.H.K., Ramseyer, Ch, Kim, U.: Composite Flexural Behavior of Full-Scale Concrete-Filled Tubes without Axial Loads, Journal of Structural Engineering, pp. 1401-1412, 2010, https://doi.org/10.1061/(ASCE)ST.1943-541X.0000241

[15] ACI Committee 211.1-91.: Standard practice for selecting proportions for normal, heavyweight, and mass concrete, ACI manual of concrete practice, part 1. Michigan (USA): American concrete institute, pp.38, 2000

[16] Deng, Y., Tuan, C., Zhou, Q., Xiao, Y.: Flexural strength analysis of non-post-tensioned and post-tensioned concrete-filled circular steel tubes. Journal of Constructional Steel Research, 67 (2011), pp. 192–202, https://doi.org/10.1016/j.jcsr.2010.08.005

[17] Tomii, M., Sakino, K.: Elasto-plastic behavior of concrete filled square steel tubular beam-columns, Transactions of Architectural Institute of Japan, 280 (1979), pp. 111-120, https://doi.org/10.3130/aijsaxx.280.0_111

[18] Shawkat, W., Fahmy, W., Fam, A.: Cracking patterns and strength of CFT beams under different moment gradients, Composite Structures, 84 (2008), pp. 159-166, https://doi.org/10.1016/j.compstruct.2007.07.005

[19] Knowles, R.B., Park, R.: Strength of concrete filled steel tubular columns, Journal of Structural Division, ASCE, 95 (1969), pp. 1565-1587.

[20] Mei, H., Kiiousis, P.D., Ehsani, M.R., Saadatmanesh, H.: Confinement effects on high strength concrete, ACI structure journal, 98 (2001) 4, pp. 548-553, https://doi.org/10.14359/10297

[21] Christopher, Y., Tuan, M.: Flexural Behavior of Nonposttensioned and Posttendsioned Concrete-filled Circular Steel Tubes. Journal of Structural Engineering, pp. 1057-1060, 2008, https://doi.org/10.1061/(ASCE)0733-9445(2008)134:6(1057)

[22] Furlong, R.W.: Strength of steel-encased concrete beam-columns, Journal of Structural Division, ASCE, 93 (1967) ST5, pp. 113-124.

[23] Gardner, J., Jacobson, R.: Structural behavior of concrete filled steel tubes, ACI Journal of Structural Division, 64 (1667) 38, pp. 404-413.

[24] Ge, H.B., Usami, T.: Strength analysis of concrete-filled thin-walled steel box columns, Journal of Constructional Steel Research, 30 (1994), pp. 607-612, https://doi.org/10.1016/0143-974X(94)90003-5

[25] Han, L.H.: Concrete filled steel tubular structures, Peking, China, China Science Press, (2000) [in Chinese]

[26] Han, L.H.: Tests on stub columns of concrete-filled RHS sections, Journal of Constructional Steel Research- An International Journal, 58 (2002) 3, pp. 353-372, https://doi.org/10.1016/S0143-974X(01)00059-1

[27] Kato, B.: Column curves of steel-concrete composite concrete columns, Research Report No. 1/97, School of Civil Engineering, University of Technology Western Australia, 1997.

[28] Kilpatrick, A.E., Rangan, B.V.: Tests on high-strength composite concrete columns, Research Report No. 1/97, School of Civil Engineering, Curtin University of Technology, Perth, Western Australia (1997)

[29] Matsui, C., Tsuda, K., Ishibashi, Y.: Slender concrete filled steel tubular columns under combined compression and bending, Structural Steel. PSSC95, Fourth Pacific Structural Steel Conference, Steel-concrete composite structures. 3 (1995), pp. 29-36.

[30] O Shea, M.D., Bridge, R.Q.: Behaviour of thin-walled box sections with lateral restraint, Department of Civil Engineering Research, The University of Sydney. report No. R., pp. 739, 1997.

[31] Prion, H.G.L., Boehme, J.: Beam-column behaviour of steel tubes filled with high strength concrete, Canadian Journal of Civil Engineering, 21 (1994), pp. 207-218, https://doi.org/10.1139/l94-024

[32] Rangan, B.V., Joyce, M.: Strength of eccentrically loaded slender steel tubular columns filled with high-strength concrete, ACI Structural Journal, 89 (1991) 6, pp. 676-681, https://doi.org/10.14359/4137

[33] Schneider, S.P.: Axially loaded concrete-filled steel tubes. Journal of structural Engineering, ASCE, 124 (1998) 10, pp. 1125-1138, https://doi.org/10.1061/(ASCE)0733-9445(1998)124:10(1125)

[34] Shakir-Khalil, H., Mouli, M.: Further tests on concrete-filled rectangular hollow-section columns, Structural Engineer, 68 (1990) 20, pp. 405-413.

[35] Tomii, M., Yashimaro, K., Morishita, Y.: Experimental studies on concrete filled steel tubular stub column under concentric loading, Proceedings of the international colloquium on stability of structures under static and dynamic loads, Washington, SSRC/ASCE, pp. 718-741, 1977.

[36] Uy, B.: Strength of concrete filled steel box columns incorporating local buckling. Journal of Structural Engineering, ASCE, 126 (2000) 3, pp. 341-352, https://doi.org/10.1061/(ASCE)0733-9445(2000)126:3(341)

[37] Uy, B.: Strength of short concrete filled high strength steel box columns, Journal of Constructional Steel Research, 57 (2001) 2, pp. 113-134, https://doi.org/10.1016/S0143-974X(00)00014-6

[38] Varma, A.H., Ricles, J.M., Sause, R., Lu, L.W.: Seismic behavior and modeling of high-strength composite concrete-filled steel tube (CFT) beam-columns, Journal of Constructional Steel Research, 58 (2002) 5-8, pp. 725-758, https://doi.org/10.1016/S0143-974X(01)00099-2

[39] Wang, Y.C.: Tests on slender composite columns. Journal of Constructional Steel Research, 49 (1999), pp. 25-41, https://doi.org/10.1016/S0143-974X(98)00202-8

[40] Han, L.H., Huo, J.S.: Concrete-filled HSS columns after Exposure to ISO-834 standard fire, Journal of Structural Engineering, ASCE, 129 (2003) 1, pp. 68-78, https://doi.org/10.1061/(ASCE)0733-9445(2003)129:1(68)

[41] Uy, B.: Concrete-filled fabricated steel box columns for multistory buildings: behaviour and design, Progress in Structural Engineering and Materials, 1 (1998) 2,99. 150-158, https://doi.org/10.1002/pse.2260010207

[42] Han, L.H., Yao, Gh.: Effects of pre-stress in the steel tube on the behavior of concrete-filled steel tubular beam-columns, China Journal of Civil Engineering, 36 (2003) 4, pp. 8-18 [in Chinese].

[43] Lu, Y.Q., Kennedy, D.J.L.: The flexural behaviour of concrete-filled hollow structural sections, Canadian Journal of Civil Engineering, 21 (1994) 1, pp. 111-130, https://doi.org/10.1139/l94-011

[44] Elchalakani, M., Zhao, X.L., Grzebieta, R.H.: Concrete-filled circular steel tubes subjected to pure bending, Journal of Constructional Steel Research, 57 (2001) 11, pp. 1141-1168, https://doi.org/10.1016/S0143-974X(01)00035-9

[45] Han, L.H., Lu, H., Yao, G.H., Liao, F.Y.: Further study on the flexural behaviour of concrete-filled steel tubes, Journal of Constructional Steel Research, 62 (2006), pp. 554-565, https://doi.org/10.1016/j.jcsr.2005.09.002

[46] Han. L.H.: Flexural Behaviour of Concrete-Filled Steel Tubes, Journal of Constructional Steel Research, 60 (2004), pp. 313-337, https://doi.org/10.1016/j.jcsr.2003.08.009

[47] Elchalakani, M., Zaho, X.L., Grzebieta, R.: Concrete-filled steel circular tubes subjected to constant amplitude cyclic pure bending. Engineering Structures, 26 (2004), pp. 2125-2135, https://doi.org/10.1016/j.engstruct.2004.07.012

[48] Liao, F.Y., Han, L.H., He, Sh. H.: Behavior of CFST Short Column and Beam with Initial Concrete Imperfection: Experiments, Journal of Constructional Steel Research, 67 (2011), pp. 1922-1935, https://doi.org/10.1016/j.jcsr.2011.06.009

[49] Uenaka, K., Kitoh, H.: Mechanical behavior of concrete filled double skin tubular circular deep beams, Thin-Walled Structures, 49 (2011) 2, pp. 256–263, https://doi.org/10.1016/j.tws.2010.10.005

[50] Kang, J.Y., Choi, E.S., Chin, W.J., Lee, J.W.: Flexural Behavior of Concrete-Filled Steel Tube Members and Its Applications, Steel Structures, 7 (2007), pp. 319-324.

[51] Kim, Y.H., You, S.K., Jung, J.H., Yoon, S.J.: Strengthening Effects of the Shear Key on the Flexural Behavior of Concrete Filled Circular Tube, Steel Structures, 6 (2006), pp. 183-190.

[52] Hosaka, T., Umehara, T., Nakamura, S., Nishiumi, K.: Design and experiments on a new railway bridge system using concrete filled steel pipes, ASCCS seminar, Concrete filled steel tubes, A comparison of international codes and practice, Innsbruck, Austria, pp. 367-372, 1997.

[53] Nakamura, S., Momiyama, Y., Hosaka, T., Homma, K.: New technologies of steel/concrete composite bridges, Journal of civil engineering, 58 (2002), pp. 99-130, https://doi.org/10.1016/S0143-974X(01)00030-X

[54] Tomii, M., Sakino, K.: Experimental studies on the ultimate moment of concrete filled square steel tubular beam-columns, Translation AIJ, 275 (1979), pp. 55-65, https://doi.org/10.3130/aijsaxx.275.0_55

[55] Architectural Institute of Japan (AIJ). Recommendations for design and construction of concrete filled steel tubular structures, 1997

[56] British Standard Institute: BS 5400. Part 5, Concrete and composite bridges, 1979.

[57] Eurocode 4. Design of Composite steel and concrete structures, part 1.1: general rules and rules for buildings (together with United Kingdom National Application Document). DD ENV 1994-1-1, London W1A2BS, British Standards Institution, 1994.

[58] AISC. Load and resistance factor design specification for structural steel buildings, Chicago, American Institute of Steel Construction Inc, 1999.

[59] Tuan, C.Y.: Aurora arch bridge-confined concrete system speeds construction of walkway span, Concrete International, 26 (2004) 4, pp. 64–67.

[60] Nematzadeh, M., Naghipour, M.: Compressing fresh concrete technique and the effect of excess water content on physical-mechanical properties of compressed concrete, Materials and Design, 37 (2012), pp. 256-267, https://doi.org/10.1016/j.matdes.2011.12.051

[61] Nematzadeh, M., Naghipour, M.: Compressive strength and modulus of elasticity of freshly compressed concrete, Construction and Building Materials, 34 (2012), pp. 476-485, https://doi.org/10.1016/j.conbuildmat.2012.02.055

[62] Naghipour, M., Nematzadeh, M., Jalali, J., Salari, A., Nemati, S.T.: Hardened density of freshly compressed concrete and its effect on mechanical properties, European journal of environment and civil engineering, 19 (2015) 6, pp. 733-755, https://doi.org/10.1080/19648189.2014.968743

[63] AISC: American Institute of Steel Construction, Steel construction manual, 13th Ed. Chicago, 2005.

[64] Iranian concrete code. Management and Planning Organization of I.R. Iran, Technical Activities and Code Development Section, "Iranian Concrete Code (ABA)", Second Section, Second Edition, MPOrg Press, 1999.

[65] ASTM A370-10: Standard Test Methods and Definitions for Mechanical Testing of Steel Products, ASTM International, West Conshohocken, PA.) www.astm.org, 2010.

[66] ACI 318: Building code requirements for structural concrete and commentary, American concrete institute, Farmington Hills. Mi. USA, 2014.

[67] Eurocode 2: Design of concrete structures, part 1.1: general rules and rules for building, European committee for standardization, Brussels, Belgium, 2004.