Performance of Plain Concrete Column Confined with Cold-Formed Steel Subjected to Axial Compression

Venkat Raj Konam, Pranoy Roy, and Amiya K. Samanta

Abstract Thin gauge sheets of cold-formed steel are commonly utilized in non-structural elements such as pre-engineering buildings, roofing sheets, and frames. An investigation to explore the potential use in structural aspect of these steel sections in civil engineering as the confinement material for the column is conferred through this report. The main intention of this investigation is to study the effect of confinement of cold-formed steel lipped channel built-up tubular column in filled with concrete. For this an experiment study was carried out for 12 columns of height 500 mm having the square cross-section of side 140 mm filled with two different grades of infilling material M30 and M40 were cast. Out of 12 columns 6 number of columns were confined with connected channel-lipped sections of thickness 2 mm each, and another 6 number of columns were unconfined specimens. The aspect ratio of depth to width is 1.0, and the depth-to-plate thickness ratio for the confinement steel is 70. These columns were tested on a 2000 kN capacity universal testing machine under axial compression. The parameters including ultimate bearing capacity, axial shortening, load vs deflection curve, ductility index, failure pattern of the concrete columns was studied. The study showcased that the ultimate bearing capacity is improved with the addition of the confinement material. The effect of M40 grade concrete is prominent in unconfined specimens when it is compared to confined specimens. The confinement restricts the axial shortening of the column specimens due to its triaxial effect on the infilled concrete. Crushing failure of the concrete is more prominent in case of the unconfined specimens as compared to confined one. The prediction of EC4 is in good agreement to the experimental results, whereas AISC overestimates the strength.

Keywords Cold formed steel · Channel-lipped section · Confinement · Plain concrete · Axial compression

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1 Introduction

Cold-formed steel (CFS), which is typically available in the form of sheets and formed into desired shapes under room temperature using various cold-forming techniques, has dominated the use of steel in recent years as opposed to traditional, heavier hot-rolled steel due to its greater strength, lighter weight, and thinner size. Many studies on the use of hot-rolled steel in structural applications have been conducted, while there have been relatively few studies on the use of CFS in structural applications. CFS material was employed as a confining material to strengthen the concrete columns. Steel—concrete composite columns are popular in various civil engineering structures as compression members, arch ribs, pylons, abutments, and bridge piers due to their stiffened nature, ductility, and absorption capacity, as well as their high strength-to-weight ratio [1, 2] The steel tube not only serves as formwork for the concrete but also avoids the need for additional reinforcement. Furthermore, it is clear that CFST columns are more tougher than the concrete core and the steel tube when viewed independently. As a result, CFST columns gain advantage. Columns (RCC), such as reduced construction time and cost reductions, make them an attractive choice for various construction practices. In an effort to enhance performance, the proposal of using CFST columns with a round corner (either roll formed or built-up) has been put forth [3]. Experimental research on the compressive behaviour of square sections filled with concrete was given by Lam et al. [4]. Ellobody et al. [5] explored the behaviour of tubular columns that were filled with concrete that possessed normal as well as high strength. Later it has been noted that corner-welded concrete-filled steel box columns have a greater cross-sectional width than typical tube sections, making them appropriate for usage in high-rise buildings in high seismic zones [6]. It is crucial to note that local buckling or cracking may be noticed at the welded corner of thin-walled concrete-filled steel box columns [7–9]. Tao et al. [10] researched how stiffener affected the columns made of thin-walled steel tubes filled with concrete. A nonlinear study has performed by Liang et al. [11] to investigate the impact of local buckling on concrete-filled box columns. In addition to it, Liew et al. [12] looked at the impact of preload on composite columns that were filled with concrete. Apart from that, recent research has demonstrated that stiffened plates are stronger than unstiffened plates when subjected to simultaneous axial and lateral loads. [13–15] therefore, it has been proposed to use stiffened outer tubes to minimize the cross-section of CFST columns [16–18]. In more recent times, Rahnavard et al. [19, 20] presented a novel design for a built-up composite column made of concrete-filled cold-formed steel (CFCFS), with lightweight concrete as infill material built-up CFS sections were filled. Very few studies on CFCFS welded built-up steel columns are vailable, even though there has been substantial research on the behaviour of CFST columns.

Based on this literature review, the effectiveness of cold-formed square built-up sections made of two channel sections connected face to face by welding at lips as confining material to concrete columns is elaborated in the present study.

Table 1 Mechanical properties of the steel

Thickness of steel t (mm)	f_y (MPa)	f_u (MPa)	E_s (GPa)
2	280.3	315.5	201

2 Research Implication

The main goal of employing cold-formed steel as confinement in composite columns for the concrete core is strengthening, as well as protecting the concrete core from environmental threats and studying its efficacy as low-cost housing. Since the strength and allied qualities of the parts of such a system vary greatly, it is required to analyse the mechanical properties, particularly the compressive behaviour and their most effective combination, mostly the thickness of the steel and the grade of concrete. Additionally, in order to maintain the geometrical dimensions of such composite systems, it is necessary to investigate the impact of the confinement material as well as the concrete grade on the compressive behaviours of cold-formed concrete steel columns since this steel replaces some of the concrete when the conventional concrete columns do not require the use of formwork. As a result, a comparative experimental investigation has been reported in this paper with respect to the study of the effects of confinement material, considering of two different core-concrete strengths on compressive behaviour of the cold-formed concrete steel columns, including ultimate strength, load–compression curve. The work could be expanded with a reinforced concrete column if this investigation proves beneficial for a better conclusion.

3 Experimental Program

3.1 Material Characteristics of Cold-Formed Sections

The material characteristics of steel such as yield stress (f_y), ultimate strength (f_u), and elastic modulus (E_s) calculated as per coupon test [28] given in Table 1.

3.2 Material Properties of Concrete

The suggested investigation makes use of local sand, also known as fine aggregate (FA), and crushed stone aggregate was used as coarse aggregate (CA). Based on the gradation test, well graded coarse aggregate of 20 mm and 12.5 mm size in equal amount was used in the investigation based on IS 383: 2016 [21]. Portland slag cement of Grade 53, which complies with IS 455: 1989 [22] with specific gravity is 3.14, standard consistence, initial and final setting time of 33%, 124 min and 380 min, respectively, as calculated according with IS 4031: 1989. To guarantee that they are

Table 2 Physical properties of fine and coarse aggregate used in the design of concrete mix

Property	FA	CA	
		20 mm	12.5 mm
Zone as per IS383: 1970	Zone—III	NA*	NA*
Fineness modulus	2.46	7.86	7.36
Specific gravity	2.64	2.799	2.8411
Water absorption capacity (%)	0.76	1.21	1.09

NA* not applicable

Table 3 Mix proportion for M30 and M40

Grade of mix	Cement (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)		Water* (kg/m^3)	Water–binder ratio	Chemical admixture (kg/m^3)	Slump (mm)	f_{ck} (MPa)
			20 mm	12.5 mm					
M30	355	658	671	671	169	0.48	3.54	80	38.16
M40	438	604	661	661	168	0.38	4.38	80	47.6

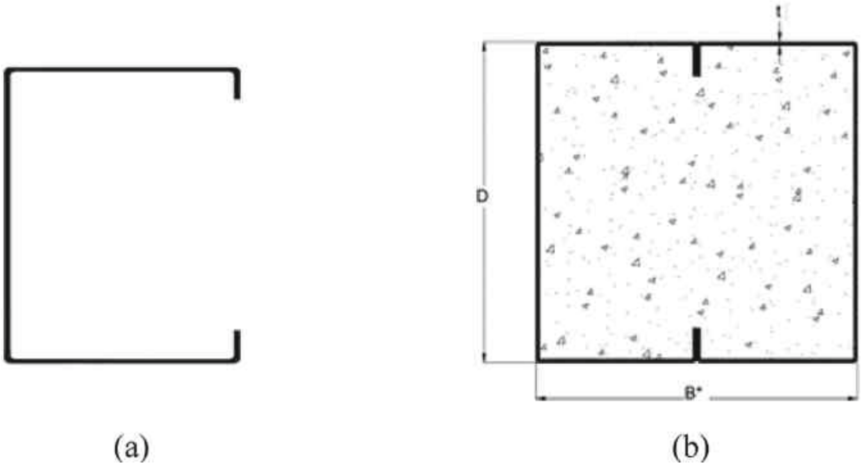
* Includes unrestricted water as well as additional water needed to create aggregates in saturated surface dry. (SSD) condition

free of dust and other undesirable contaminants, these materials have been carefully selected. Table 2 lists the physical properties of natural sand and coarse aggregate as calculated in accordance with IS 383: 1970 and IS 2386-part III: 1963 [23]. The specimens in this study were filled with two different classes of concrete with nominal compressive strengths M30 and M40, and the mix was designed as shown in Table 3 in accordance with the guidelines of the IS 10262: 2019 [24]. The mixings were prepared using a tilting drum mixer. Along with the stub column experiment, cubes with sides of 150 mm were put through a conventional compression test in accordance with IS 516–1959[25] to ascertain their compressive strength at 28 days of curing (f_{ck}), which is used to describe each concrete filling of the column and is displayed in Table 3. Concrete cube samples were prepared for this task and allowed to cure under standard conditions for 28 days prior to the test day.

3.3 *Specimen Preparation*

Galvanized iron (GI) sheets were used during the manufacturing process for the structural channel-lipped sections. The sheets were initially cut to the required geometry and then cold-rolled at room temperature to make channel-lipped sections Fig. 1a. In order to create a square steel tubular cross-section, two of these channel sections were joined face to face utilizing welds at the lips over the whole length in Fig. 1b. These hollow built-up channel-lipped sections were next filled with concrete, and conventional plain concrete columns was cast using the square moulds infilled with concrete.

Twelve columns specimens were cast. Six out of 12 specimens were columns with confinement, and remaining 6 specimens are conventional concrete columns as shown in Fig. 2. A poker rod was used to compact each layer of concrete after it had been added to the corresponding steel tubes and square moulds. The all specimens were later covered in wet clothing for 28 days curing. The end layers of the concrete samples were treated and prepared before testing to guarantee simultaneous loading of both elements. Before applying the primer, the specimens were cleaned with a brush. For appropriate absorption of the primer into the concrete surface, specimens were allowed to set for 24 h after application. In order to correctly investigate the failure pattern on the column during the application of the load, the entire column surface was divided into several square grids after this operation.



(a) (b)

Fig. 1 Built-up channel-lipped cold-formed steel section

P5-T2-30	P5-T0-30	P5-T2-40	P5-T0-40
Confined specimens with M30 grade	Unconfined specimens with M30 grade	Confined specimens with M40 grade	Unconfined specimens with M40 grade

Fig. 2 Samples used during investigation

3.4 Specimen Details

Concrete-filled steel tubes using two channel-lipped section bonded face to face at lips called as cold-formed concrete-filled steel confined column (CCSC) and conventional plain concrete column were investigated. The section was cold rolled from flat strips of GI steel sheet. The test program involved of two test series that includes one test series is of CCSC, and another test series is of conventional concrete column. The series of specimens with designation P5-T2-30, P5-T0-30, P5-T2-40, and P5-T0-40 with geometry as follows, and its overall depth D for both confined and unconfined specimen is 140 mm with its overall width B* after joining the channel section at its lips is 140 mm (+ / − 1.5 mm). This is because the wrapping stresses generated during the weld of section and having the thickness t of 2 mm as shown in Fig. 1b. The measured average overall depth-to-thickness of plate (D/t) ratio is 70 mm for the cold-formed concrete-filled steel stub column series P5-T2-30, P5-T0-30, P5-T2-40, and P5-T0-40, respectively. The overall length (L) of the specimens used in this study is 500 mm. To prevent overall column buckling, the lengths were selected such that the length/depth ratio (L/D) normally stayed in limits of 3–5. M30 and M40 grade of concrete is used in this study. The dimensional parameters of the cold-formed concrete-filled steel stub columns (CCSC) are shown in Table 4 along with the area of steel (A_s) and area of the infilled concrete (A_c).

The test specimens for cold-formed concrete-filled steel stub columns (CCSC) are labelled so that the confinement steel thickness and concrete strength can be determined from the label. Labels or nomenclature that began with the letter “P” indicate that the specimens are columns made of plain concrete, and the number after the letter indicates how long the specimen is. A number was added after the hyphen to indicate the grade of the concrete that is used, and the letter “T” and

Table 4 Geometric and area parameters of specimens

Sample designation	D (mm)	B^* (mm)	t_s (mm)	D/t_s	D/B^*	A_s (mm^2)	A_c (mm^2)
P5-T2-30–1	140	139	2	70	1.01	1204	18,256
P5-T2-30–2	140	140	2	70	1	1208	18,392
P5-T2-30–3	140	139.5	2	70	1	1206	18,324
P5-T2-40–1	140	139	2	70	1.01	1204	18,256
P5-T2-40–2	140	140	2	70	1	1208	18,392
P5-T2-40–3	140	138	2	70	1.01	1200	18,120
P5-T0-30–1	140	140	–	–	1	–	19,600
P5-T0-30–2	140	140	–	–	1	–	19,600
P5-T0-30–3	140	140	–	–	1	–	19,600
P5-T0-40–1	140	140	–	–	1	–	19,600
P5-T0-40–2	140	140	–	–	1	–	19,600
P5-T0-40–3	140	140	–	–	1	–	19,600

Fig. 3 Compression test machine set-up

number that indicate the confinement steel material's thickness were added before the hyphen. For instance, P5-T2-30 refers to a specimen made of plain concrete that is 500mm high and enclosed in steel that is 2mm thick with M30 grade concrete used as the infilling material.

3.5 Test Set-Up

2000 kN hydraulic compression machine with a loading rate of 0.36 MPa/s and load interval 2 kN/s was used during the process shown in Fig. 3. The compressive load and longitudinal displacement were measured automatically by the software set-up connected with the machine.

4 Test Results

4.1 Mode of Failure

The steel tubes in all of the CCSC specimens generally exhibited localized buckling, which was evidently caused by axial shortening of the entire specimen. After the tests were completed and the specimens had been released, Fig. 4 depicts the ultimate failure scenarios for each specimen.

Figure 4a–e shows the failure of the CCSC, whereas Fig. 4f–g depicts the failure pattern of the conventional concrete column. It is observed that all the CCSC columns undergone with outward buckling with several outward projections on the surface of the steel.

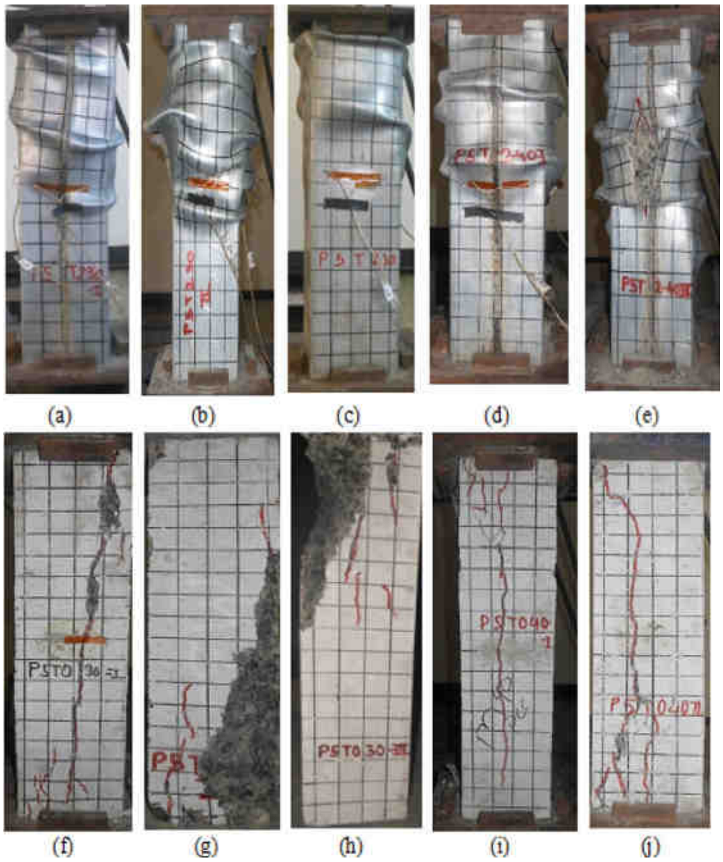


Fig. 4 Failure patterns of different specimens

In addition to the local buckling in the confining tube, steel fracture was seen in two CCSC specimens (Fig. 4b, e) in the weld area of the columns. Three factors primarily account for the fracture: (1) a significant axial distortion following local buckling; (2) welding property; and (3) residual stress brought on by the welding process. In the welded area, tensile stresses are generated, and compression stresses form in the area furthest from weld. The driving force behind the development of fracture was often the developed tensile stresses. Additionally, the quality of the welding must be ensured before using this built-up tubes in future applications. It should be noticed that neither specimen's weld fracture caused the column to suddenly collapse, showing that there had been some stress redistribution inside the composite column. However, the residual stresses brought on by welding should be taken into account in the analysis to further guarantee the dependability of CCSC columns.

It is further noted that all of the standard concrete columns in this investigation failed by crushing when the maximal load was attained. The failure of the specimens discussed above is shown in Fig. 4f–j. In contrast to CCSC columns, shear cracks formed on the end of the column specimen and expanded to the centre before it reaches the ultimate or peak load which indicating that CCSC columns postpone the collapse of the column compared with the conventional concrete columns.

4.2 Design Standards and Comparisons

The ultimate capacity of CCSC columns was calculated in this work using the design criteria from AISC360-10 [26] using Eq. 1 and EC-4 [27] using Eq. 2. The results were then compared to the calculated capacity. Different ways to calculating the load on columns are provided by design codes. Despite this, the design equations only considered contributions of the steel and concrete of the specimens into account. Because of factors such as variations in testing conditions, inconsistent material properties, and differences in data collection systems, current codes may yield less precise strength predictions when compared to experimental results.

$$P_{AISC} = f_y A_S + 0.85 A_c f_c' \tag{1}$$

$$P_{EC4} = f_y A_S + A_c f_c' \tag{2}$$

Note: $consider f\prime_c = 0.79 f_{ck}$

Table 5 summarizes the ultimate strengths ($P_{U.test}$) acquired from experimental tests and the predicted ultimate strength of columns as per AISC and EC-4 codal provisions as per Eqs. (1) and (2).

Table 5 Load-carrying capacity of specimens

Specimen ID	$P_{U.test}$ (kN)	Compression at $P_{U.test}$ (mm)	P_{AISC} (kN)	P_{EC4} (kN)	Failure pattern
P5-T0-30–1	504.00	3.600	747.94	502.24	Shear failure
P5-T0-30–2	411.00	4.665	747.94	502.24	Crushing of Column
P5-T0-30–3	418.00	4.441	747.94	502.24	Crushing of Column
P5-T0-40–1	425.00	4.823	932.96	626.48	Shear failure
P5-T0-40–2	418.00	2.891	932.96	626.48	Shear failure
P5-T0-40–3	709.00	4.257	932.96	626.48	Shear failure
P5-T2-30–1	829.00	6.058	887.47	804.92	Bulging failure
P5-T2-30–2	688.00	5.348	892.69	809.52	Weld failure
P5-T2-30–3	688.50	4.730	890.08	807.22	Bulging failure
P5-T2-40–1	902.00	4.980	1023.61	920.64	Bulging failure
P5-T2-40–2	933.00	5.598	1029.85	926.11	Weld failure
P5-T2-40–3	899.50	4.928	1017.38	915.18	Bulging failure

4.3 Discussions

The experimental results shows that cold-formed steel welded tube filled with concrete can be used in structure of building. Shear failure and crushing of column is observed in unconfined specimens, whereas for confined specimens bursting of confinement is observed due to shear failure of the core.

Figure 5 shows the load compression graph for both confined and unconfined specimens. Smooth S graphs are seen in case of confined columns, indicating good bonding between the steel and concrete interface. It is also evident that the load-carrying capacity is much higher in case of confined specimens as compared to unconfined specimens under similar displacement. Figure 6 shows the stress–strain graph for both confined and unconfined specimens. Similar nature of curve is observed in case of confined specimens. Variation in results is mainly due to the welded portion of the confined sections. Smoothness of confined specimens as compared to the unconfined specimens is the effect of confined nature of the steel, which provides strength to the inner concrete against crushing as well as carrying a part of the axial load. Figure 7 shows the average ultimate load-carrying capacity of the specimens as per the experimental results and the codal provisions. It can be observed that AISC overestimated the strength for both confined and unconfined specimens, whereas the results of EC-4 are similar to the experimental results showing good agreement. Further study with varying parameters will add more accuracy.

5 Conclusion

This study presents the results of investigation conducted on thin welded concrete-filled columns. The following conclusions may be drawn from the study:

- Improved compressive strength is observed with the addition of confinement in concrete. The bonding between the steel and concrete, grade of concrete, and the thickness of confining material are the main influencing factors for the strength.
- Localized failure with crushing of concrete and bulging of confinement is observed. Some of the specimens failed due to welding due to lower weld strength.
- AISC overestimates the strength of specimens, whereas EC-4 shows closer agreement with the experimental results.

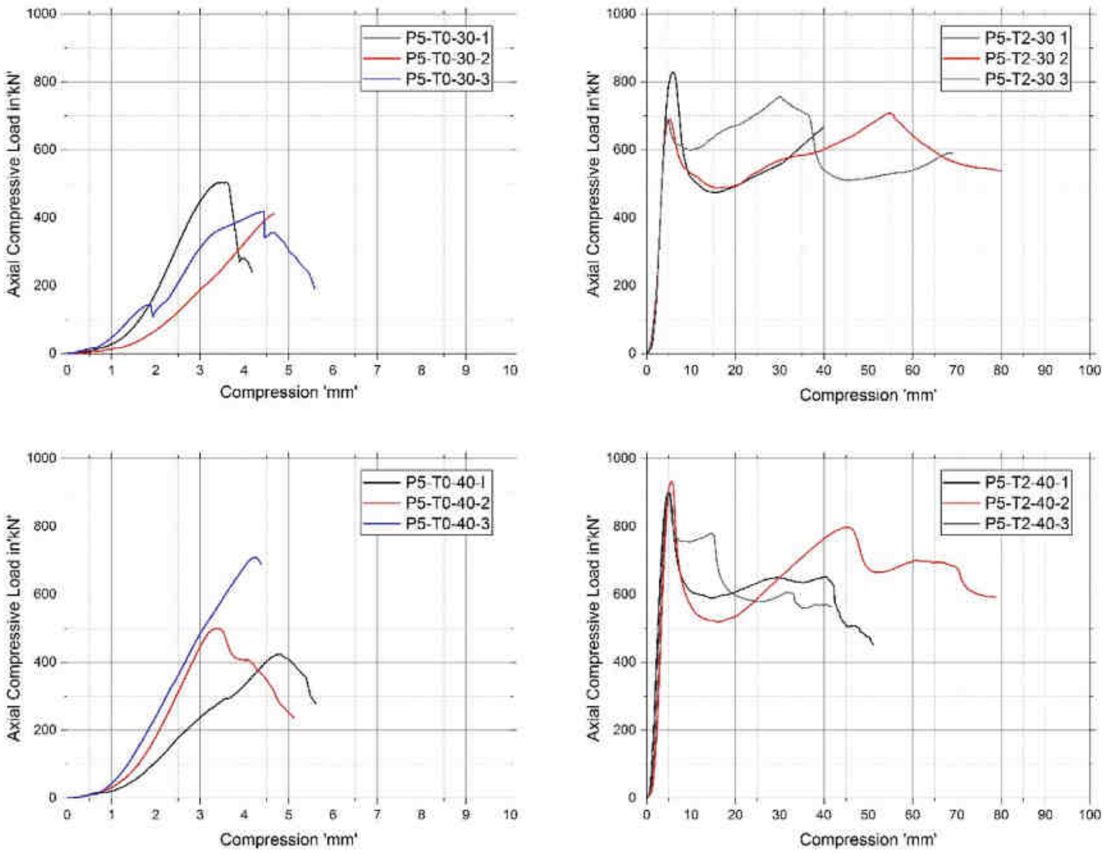
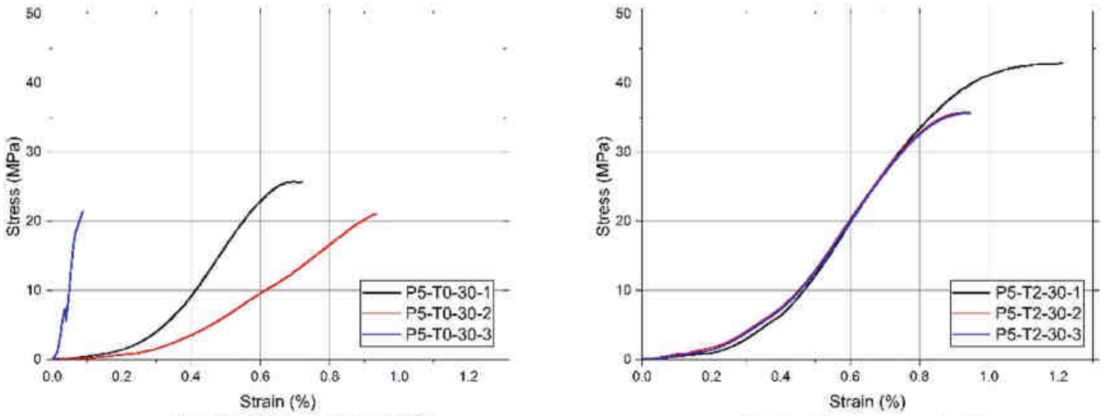
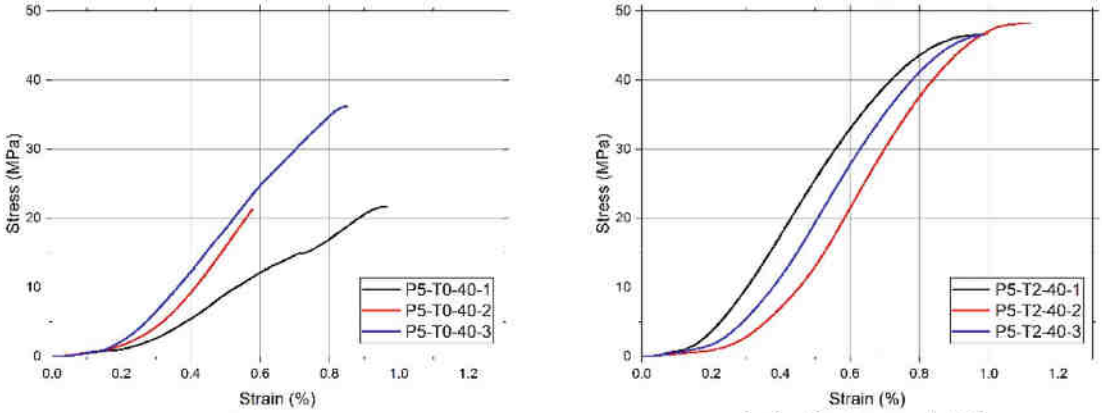


Fig. 5 Load–displacement graph for confined and unconfined specimens



Unconfined Specimens grade M30

Confined Specimens grade M30



Unconfined Specimens grade M40

Confined Specimens grade M40

Fig. 6 Stress–strain graph for confined and unconfined specimens

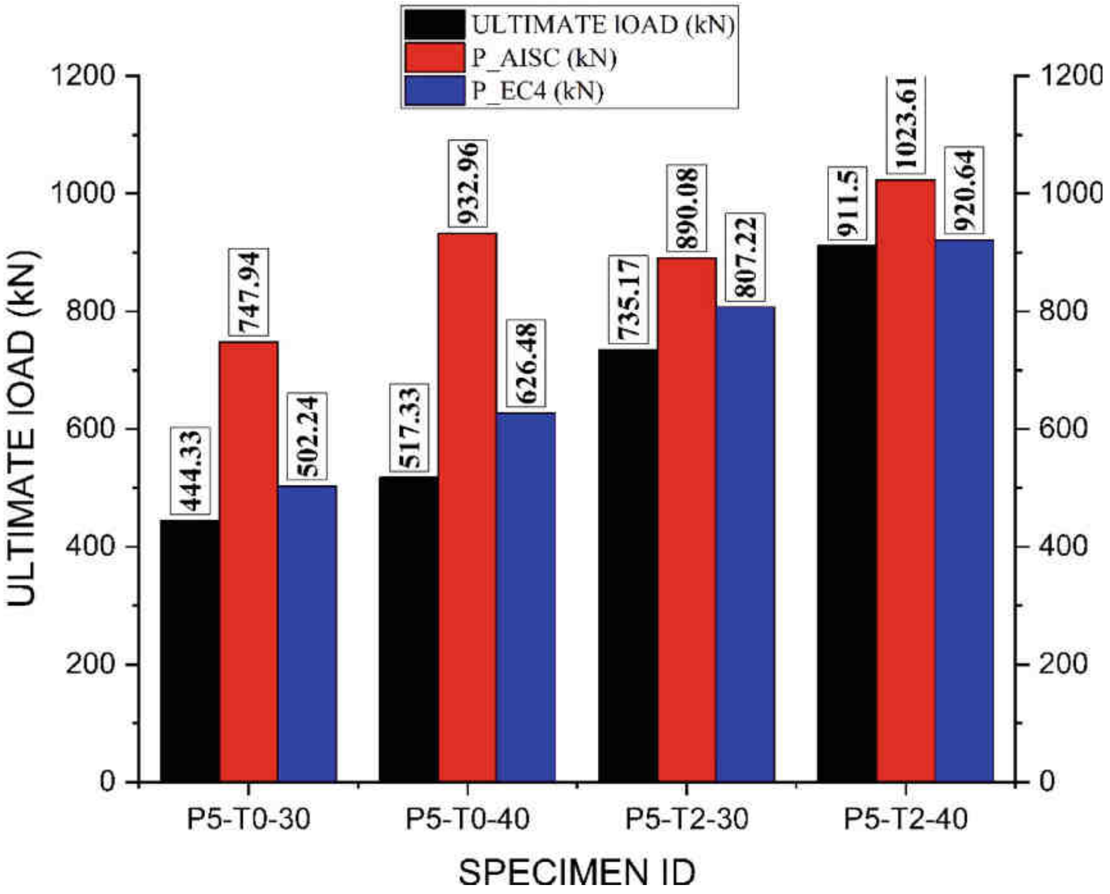


Fig. 7 Ultimate load-carrying capacity for specimens

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