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Compression and stability response of short CFS battened columns with light-weight composite chords

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Abstract
Columns being primary structural members are critical in controlling the overall behaviour in framed structures. They need to perform satisfactorily both from strength as well as stiffness considerations. In cold-formed steel (CFS) framing systems, two channels are fastened in a back-to-back arrangement to form a built-up column. This is approach is very convenient, but limits the load carrying potential the channels (chords of the built-up column) can develop, when gapped adequately in the transverse direction. The previous research on gapped built-up columns have indicated the development of better axial strength and stability (particularly the torsional one), when compared to the conventionally built built-up columns. However, the occurrence of local buckling between the lateral connectors still limits the performance of gapped built-up columns. The adoption of CFS composite members have significantly defeated the early local buckling failures, especially when a hard material like concrete is used. Nevertheless, it also weakens one of the key advantages of using CFS section i.e., light-weight construction. The past research on light-weight CFS composite members which although has been slim, has been limited to flexural members. In this study, an experimental investigation has been carried out on short fixed ended CFS battened columns composed of composite channel sections. The effect of various strengthening schemes for the web of the channel sections using conventional stiffening and different light-weight packing materials was investigated. The effect of these variations on the axial compression capacity and stability response of CFS battened columns was assessed. The structural performance of the built- columns was evaluated in terms of their peak loads resisted, load-displacement response and the failure modes. Lastly, the North American Specification and Eurocode for CFS structures were used to determine the design strengths for comparison. The predictions of both these standards showed inconsistency in their accuracies.

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1. Introduction

The use of cold-formed steel (CFS) members in buildings has emerged significantly and is so, mainly due to the preferrable structural qualities the most important of which are light self-weight and fast construction due to easy fabrication and erection. These characteristics make it more appropriate for building structures, particularly when the construction location is remote and the ease of transportation and handling of the structural elements is necessary. Since, it only takes the integration of different structural members to finish the job, it also promotes timely completion of the building assignments that gives it an edge over building materials. Although there are several key benefits in CFS sections that promote their use in construction, because of the local buckling instability of the different cross-sectional thin plate components, the thin-walled nature of the CFS section still limits their adoption (Yu 2010; Zeimian 2010). This has motivated researchers (particularly the ones working on structural steel) to research in this field, and to find a reasonable solution to these problems of uncertainty. Many studies have identified reliable, efficient and affordable initiatives to improve the buckling characteristics of different types of improved sections (Rasmussen et al. 2020; Landesmann et al. 2016; Camotim et al. 2018; Kumar & Sahoo 2016; Bian et al. 2016; Kesawan et al. 2017; Paratesh et al. 2019; Maderia et al. 2015; Gatheeshgar et al. 2020).

2. CFS built-up columns

Generally, by joining two channel sections (in the back-to-back configuration) with the use of self-drilling screws fastened through the webs, at standard longitudinal spacing, a CFS built-up column is produced. These types of sections are widely used in building CFS structures. Several steel researchers have worked towards improving the performance of such built-up columns by recommending specific flat width-to-thickness values for the various cross-sectional elements and by suggesting the pattern of the screw and its arrangement at various locations (Fratamico et al. 2018a-b, Selvaraj & Madhavan 2021). The incorporation of an adequate transverse gap between the channels can further enhance the performance of these types of columns (Subramanian 2016). To ensure the proper structural integrity between the chords, various connecting systems have been considered. The transverse gap is another parameter that governs stability response and torsional strength in such columns (Dabaon et al. 2015; Anbarasu & Dar 2020; Zhang & Young 2015; Vijayanand & Anbarasu 2020; Anbarasu et al. 2015). However, the face-to-face arrangement between the chords has displayed better performance output when compared to the back-to-back one (Meza et al. 2020a-b; Kherbouche & Megnounif 2019), and owes that enhancement to the closed sectional feature of these built-up cross-sections, which has been confirmed by more studies (Zhang & Young 2018; Liao et al. 2017; Dar et al. 2018a; 2019a-b; 2021a-b; Roy et al. 2019). From the limited studies on CFS battened columns (EI Aghoury et al. 2010; 2013; Dar et al. 2021c-d; 2020a-b; Anbarasu & Dar 2020; Anbarasu 2020), the chords between the lateral connectors still fail by local buckling, in short and intermediate columns, which restricts their ultimate strength, and calls for better solutions.

3. CFS composite sections

The fundamental local buckling weakness of thin-walled CFS sections under compressive forces has successfully been countered by concrete when used as a composite member, that carries enormous strength under the same nature of loading. Various schemes have been laid down for their improved performance (Dar et al. 2021e). While one of the core issues with CFS members stays addressed with this approach, it dilutes the performance of CFS concrete composite construction, due to heavy self-weight of concrete that limits its domain of adoption when compared to CFS construction alone. This triggered many researchers to look for other materials that are hard but light-weight at the same time. The limited past studies on light-weight CFS composite members has been confined to flexural members only (Dar et al.2020f; 2018b). This justifies the need for exploring the behaviour of CFS battened built-up columns with light-weight composite chords.

In this study, an experimental investigation has been carried out on fixed ended CFS battened columns composed of composite channel sections. The effect of various strengthening schemes for the web of the channel sections using conventional stiffening and different light-weight packing materials was investigated. The effect of these variations on the axial compression capacity and stability response of CFS battened columns was assessed. The structural performance of the built- columns was evaluated in terms of their peak loads resisted, load-displacement response and the failure modes. Lastly, the North American Specification and Eurocode for CFS structures were used to determine the design strengths for comparison.

4. Experimental Study

Details of the test specimens, findings of the material properties and the axial tests carried out are described in this section.

4.1 Test Specimens

Four short columns were fabricated to accomplish the aim of this research. The thickness of the steel sheet used for forming the channels and the batten plates for producing the built-up sections was 1.5mm. Two channels with slender webs were used to form the built-up cross-section for the column specimens. The longitudinal spacing between the centers of the battens was 150mm. Electric arc welding was used carefully, to connect the batten plates to the channels. The height of all the four columns was 1070mm (details shown in Fig.1) and the built-up columns were classified as short columns. The first specimen was the control specimen and comprised of plain channels connected together with batten plates, as shown in Fig.2a. This specimen will be labelled as CS (Control Specimen), and will be used to denote it for future references. The second specimen had similar details, except that the sigma shaped channels were used in place of the plain one, as shown in Fig.2b. This specimen will be labelled as SSS (Sigma-section Strengthed Specimen), and will be used to denote it for future references. The details of the third specimen matched with that of the first one except the plain web was strengthened by a glass fiber reinforced polymer (GFRP) sheet, as shown in Fig.2c. This specimen will be labelled as GSS (GFRP Strengthened Specimen), and will be used to denote it for future references. In the last specimen, the web was strengthened by a timber plank in addition to the GFRP sheet used in the previous case, as shown in Fig.2d. This specimen will be labelled as TSS (Timber-GFRP Strengthened Specimen), and will be used to denote it for future references. It must be noted that the length of the GFRP and the timber plank was slightly shorter than the channel section.

4.2 Material Properties

It is vital to establish the exact material properties of the steel used in the chords. This was done by testing coupons for their tensile strengths that complied with Indian Standards (IS 1608, 2005) and were derived from the channels. To perform these tensile checks, an MTS universal testing machine (UTM) was used. There were a total of three coupon tests conducted. Average yield strength (f_y in MPa), ultimate strength (f_u in MPa), elasticity modulus (E in GPa), and elongation (e in percent) values were recorded as 252, 351, 205 and 29 respectively. In Fig.3 the specifics of a typical material test are given.

4.3 Test Set-up

A sturdy loading frame (300 kN), as shown in Fig. 4, was used to test the built-up battened columns for axial compression, applied concentrically. A hydraulic jack (500kN) was used to apply the compression loading axially. A proving ring of same capacity was used to monitor the loading component during the testing of various specimens. Two dial gauges were used to note the axial shortening and lateral deflections (at the mid-height). The records were noted at specific intervals.

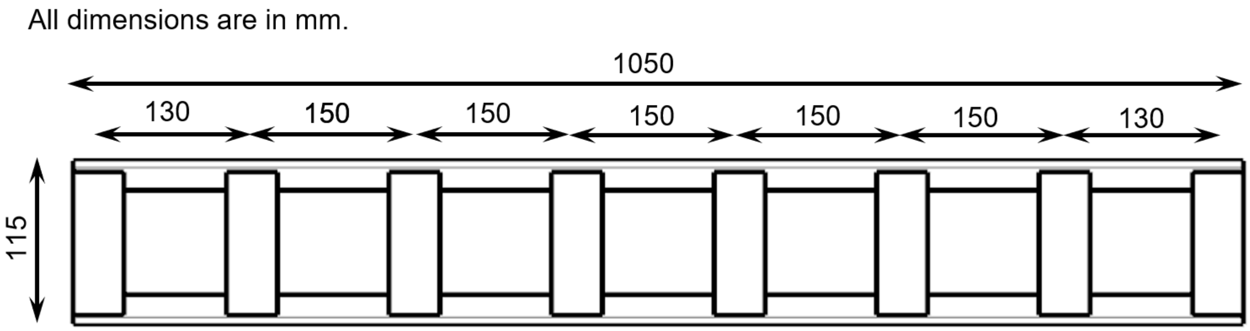
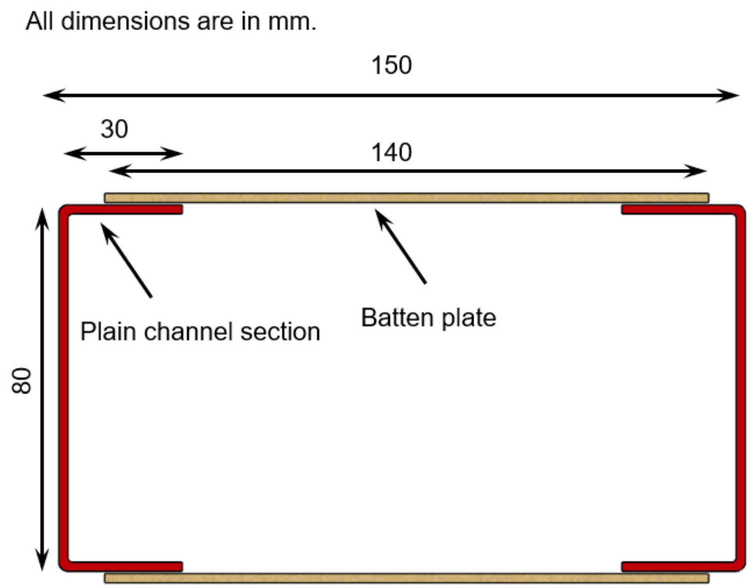
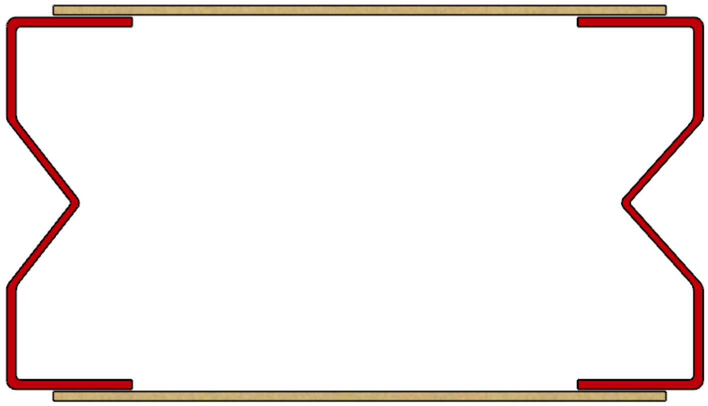


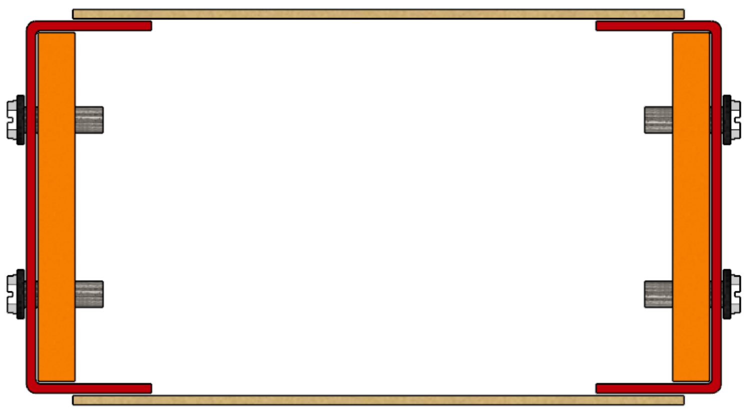
Figure 1: Longitudinal details



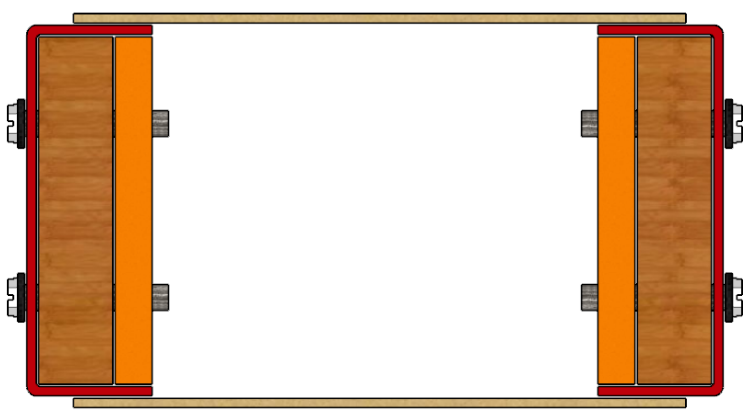
(a) CS



(b) SSS



(c) GSS



(d) TSS

Figure 2: Cross-sectional details of the built-up column specimens

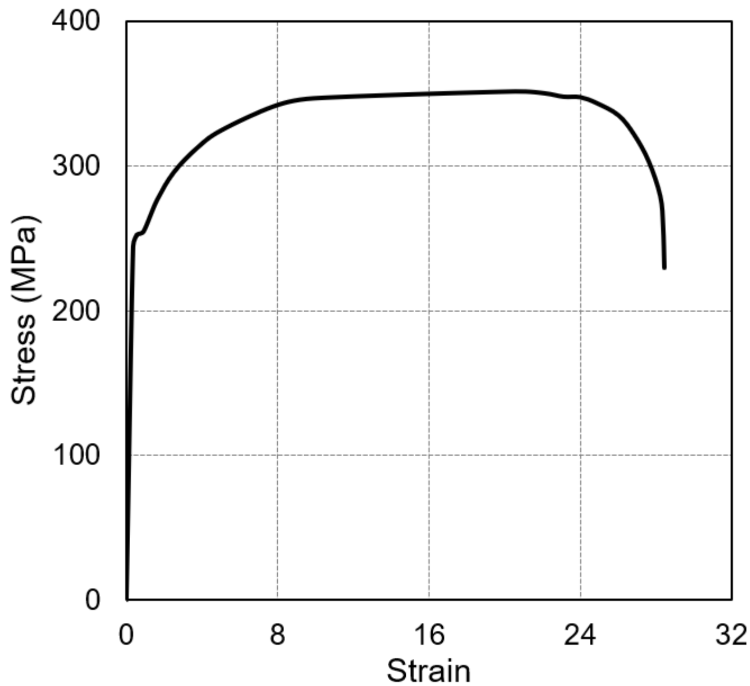


Figure 3: Typical stress-strain plot of the coupons

4.4 Test Results

Fig.5 represents the Compressive strength-axial shortening behavior of all the specimens. The specimen CS bore a maximum load of 72.25 kN with an axial displacement of 1.79 mm. Post this load, it ceased to carry further load, as was called as the failure load of the specimen. The maximum load resisted by SSS was 101.32kN with the corresponding axial shortening of 0.91mm. The adoption of sigma section in place of the plain channel section helped in the axial resistance improvement of 40.23%. GSS carried a maximum load of 118.71 kN with an axial shortening of 2.02mm. The use of GFRP sheet to strengthen the web of the plain channel enhanced the axial strength by 64.30%. TSS carried an ultimate load of 155.31 kN with an axial displacement of 3.09mm. like sigma profiling and the GFRP strengthening, the timber plank was also able to strengthen the web element, which enabled the built-up member to deliver better that the CS. The enhancement observed in this case was 114.97%. From the comparison between the three strengthening cases, it is evident that the timber strengthening (in TSS) was better than the GFRP strengthening (in GSS), which was in turn better than the sigma profiling of the web (in SSS). However, from the strength-to-weight performance comparison, the various specimens displayed a different trend, where, the SSS outperformed the other two. The lateral deflection at the mid-height in all the specimens was very small, clearly depicting the short column behaviour.

Since all the four specimens were short columns, so local buckling was the predicted mode of their failure. CS failed by local buckling of the web and the flanges close to the top of the built-up column, as shown in Fig. 6a. In the SSS, the failure was mainly observed in the form of local buckling of the flanges, again close to the top of the column, as shown in Fig. 6b. No signs of buckling in the web were observed. Hence, the adoption of sigma profiling in the web prevented the local buckling in that region, through the height of the column, and served the intended purpose. The specimen GSS failed by local buckling of the flanges, again at the top of the

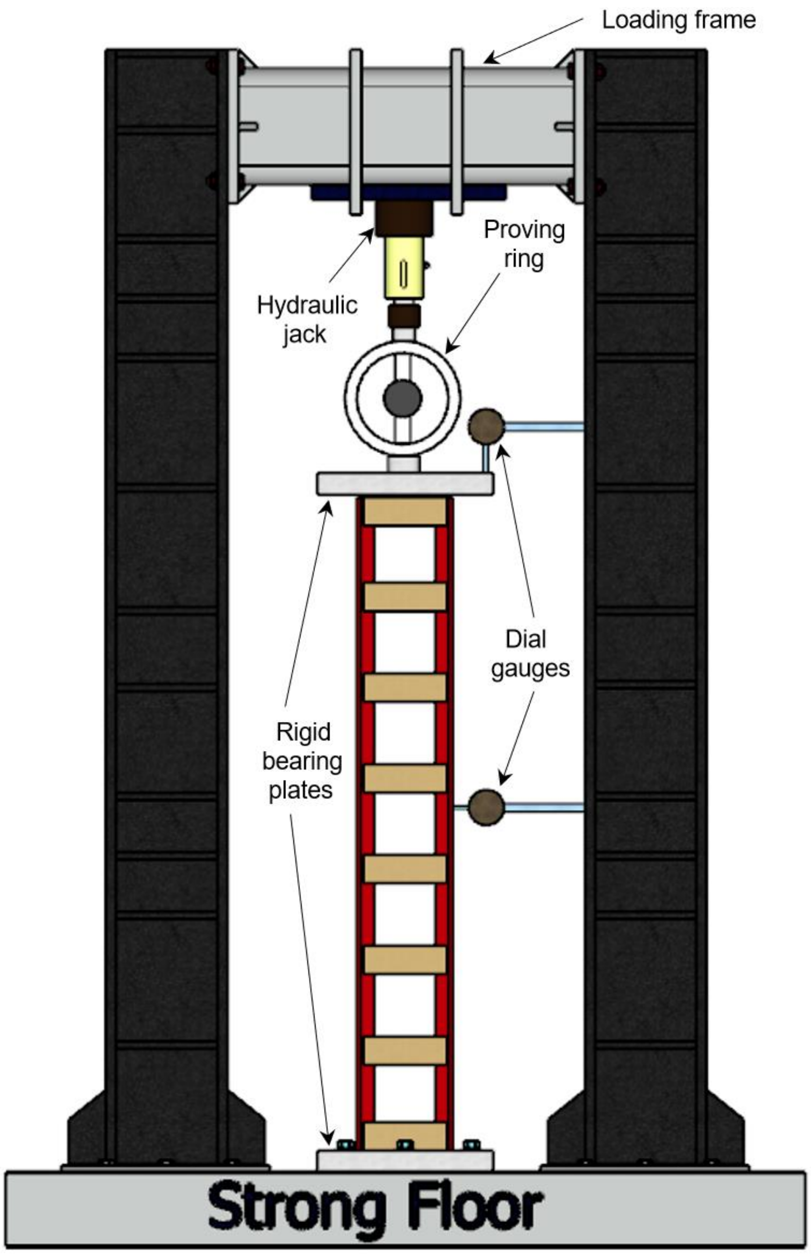


Figure 4: Details of the test set-up

column, accompanied by local buckling of the web (shown in Fig. 6c), which was smaller in magnitude, when compared to that of the CS. In TSS, local buckling of the flanges and the web was observed, as shown in Fig. 6d. However, this failure was observed at a much higher loading, clearly indicating better performance over the other specimens. No failure was found any of the specimens at the fastener level.

Table 1: Comparison of test results and design strengths

Specimen	Test results	Design strengths	
	P_{Test} (kN)	P_{Des} (kN)	P_{Des} / P_{Test}
CS	72.25	88.20	1.22
SSS	101.32	112.80	1.1
GSS	118.77	145.87	1.23
TSS	155.31	187.75	1.21

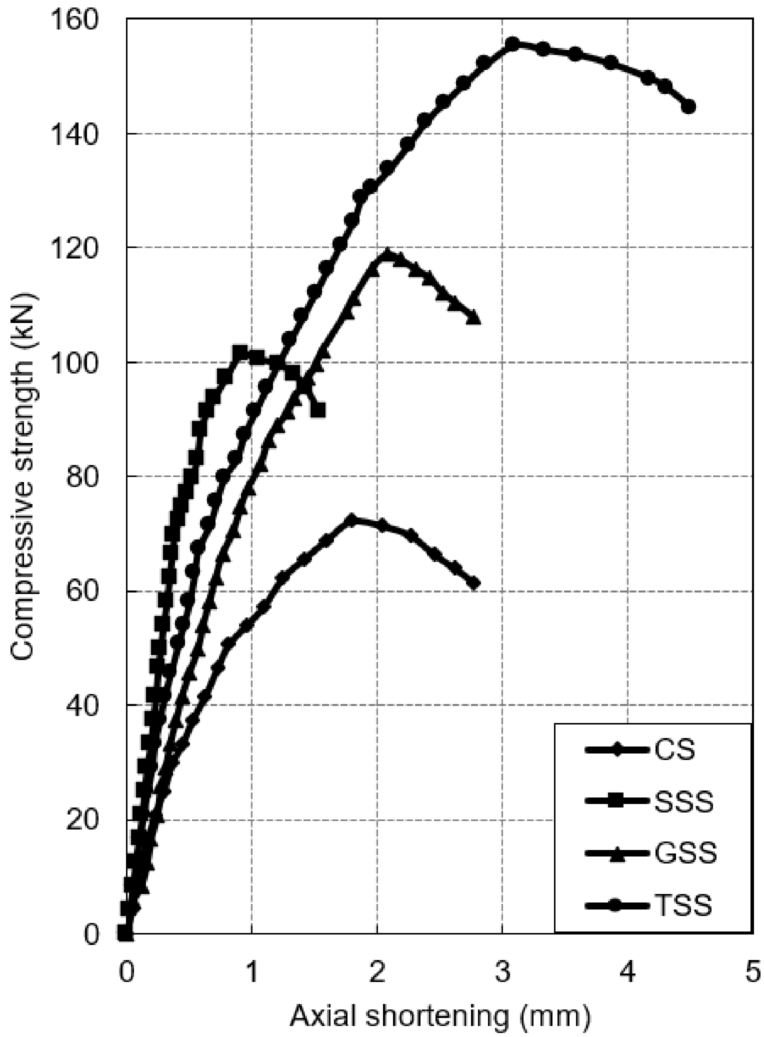
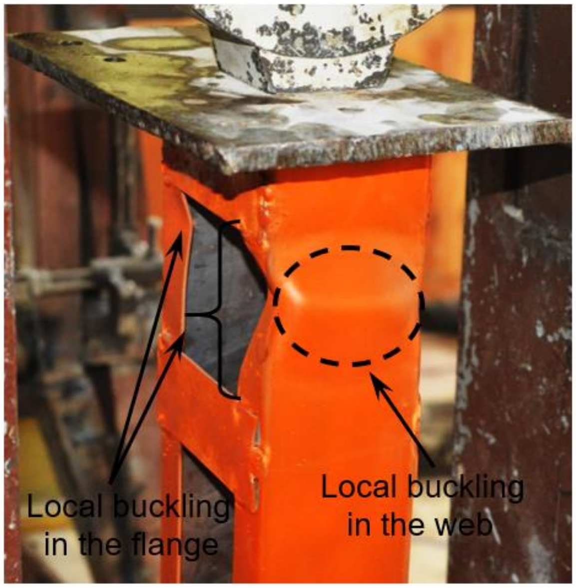
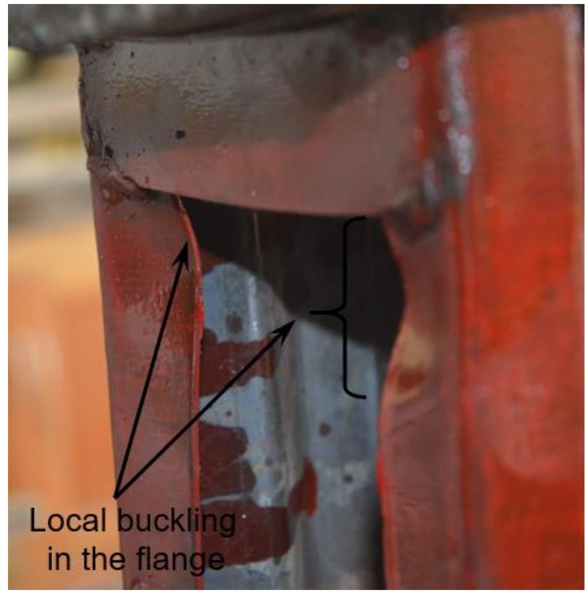


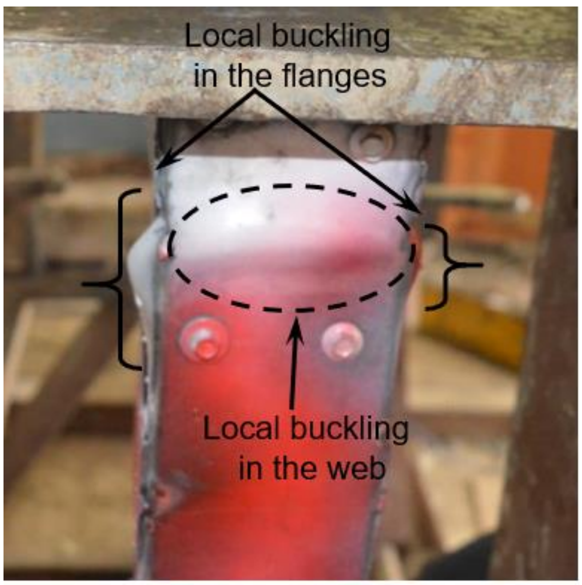
Figure 5: Compressive strength *vs.* axial shortening behaviour



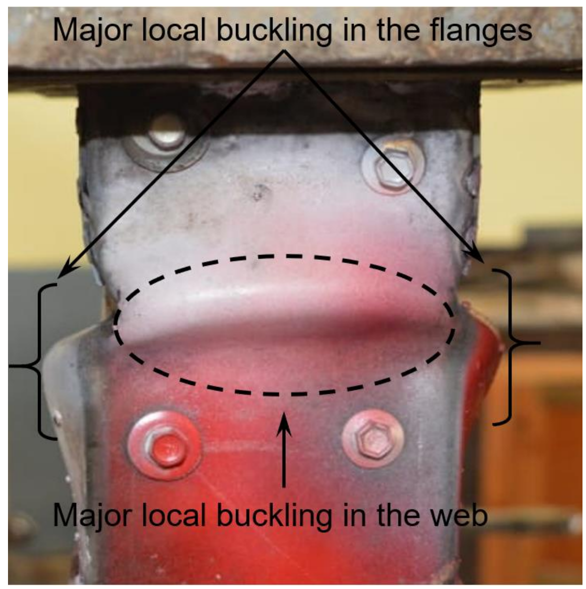
(a) CS



(b) SSS



(c) GSS



(d) TSS

Figure 6: Failure in the test specimens

Currently, no guidelines are available to predict the axial strengths CFS battened columns with composite chords. Therefore, European Standards EN1993-1-3 (2006) and (EN1994-1-1 (2004) was used to quantify the design strengths of the various specimens. The predicted strength of the CFS part was determined using EN1993-1-3 (2006) while as the same of the remaining parts, by (EN1994-1-1 (2004). Table 1 presents the comparison of test and design strengths. It was noted that the design strengths were higher than the test strength by approximately 10-20%. This clearly indicates the unreliability of these design standards, and calls for more research on such members to develop large pool of data for developing reliable design guidelines for CFS battened columns with composite chords.

5. Summary and Conclusions

An experimental research on CFS battened columns comprising composite channel sections was addressed in this study. Arrangements for fixed end support were adopted for all the column specimens which were categorized as short columns. The impact of various strengthening schemes using conventional stiffening and various light-weight packing materials for the web of the channel sections was examined. The impact of these variations on CFS battened columns' axial compression capacity and stability response was evaluated. The structural efficiency of the built-up columns was measured in terms of their resisted peak loads, load-displacement responsiveness and modes of failure. Finally, to assess the design strengths for comparison, the North American Specification and Eurocode for CFS structures were used. In their accuracy, the forecasts of each of these standards demonstrated inconsistency. All the specimens failed by local buckling of the web and the flanges, except the one with web stiffened channels. No failure at the connection levels were observed. Also, the local buckling failures were focused towards the top of the built-up columns. The lateral displacements of all the column specimens were very small, and substantiated their short column type of behaviour. All the three strengthening schemes adopted were able to improve the compressive strength of the battened columns.

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Notations

CFS	: Cold-formed steel
CS	: Control specimen
SSS	: Sigma-section strengthened specimen
GSS	: GFRP strengthened specimen
TSS	: Timber-GFRP strengthened specimen
E	: Modulus of elasticity
f_u	: Ultimate strength
f_y	: Yield strength
P_{Des}	: Design strength
P_{Test}	: Ultimate test strength
ε	: Strain at fracture