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Reuse design of CFS columns subjected to interaction buckling for the application of circularity in construction

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Abstract

The embossments in cold-formed steel sections are a breakthrough to inhibit the buckling deformations. The embossments are minor corrugations in thin steel sections which are formed by a cold rolling process. This paper presents the test results of embossed cold-formed steel (CFS) angle sections. A total of 24 stub column tests were performed with various thicknesses, embossment patterns, embossment thicknesses and material strengths. The CFS columns are of constant length of 700 mm. The test results indicate that the local buckling capacity of the CFS sections increased and, in some sections, the local buckling deformations can be fully inhibited due to the presence of embossments. The results also indicate that the increase in embossment thickness increases the local buckling capacity while the yield strength decreases due to the change in material properties. This paper also discusses the appropriateness of using the Direct Strength Method (DSM) for the design of the embossed CFS section against local buckling. A new approach to modify the DSM method for accurately predicting the design strength is proposed.

1. Introduction

Innovations will replace fossil fuel with hydrogen and electrical batteries to implement carbon capture to meet the net zero goal by mid-century. However, a large portion of the carbon emission is from the construction industry (21% from material extraction and processing) and it takes the maximum share of 59% from natural resources (including metals, sand, gravel, crushed rock, and non-metallic minerals) [1], which should be controlled. To control such inevitable and continuous damage being done by the construction industry, several policies have been proposed [2]. One of the revolutionary themes is to develop a circularity in construction, that is recycle or reuse the construction materials as long as possible. The term recycle is simple and common in construction, but direct reuse of structural members requires a different set of design methods and an overall change in the construction methods. To enable direct reuse of structural members, firstly the connections must be demountable rather than conventional monolithic, secondly, the building construction method and systems should suit for member reuse [3].

However, it should be acknowledged that in temporary structures like shoring, scaffolding, and event tents, the direct reuse of load-bearing members is already in practice. Those structural

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components are designed for heavy loading with simple demountability but for temporary use. Similar features should be used for the development of reusable long-term structural members. Developing constructable and reusable building components is difficult because of the requirements like simple, aesthetic, and cost-effective. The latest design guidelines for reuse suggest that the structural members can be designed elastic (by using the higher safety factor) [4]. A recent investigation suggests that they can be classified for reuse based on the use history after a preliminary assessment, however, there is a need for establishing a relationship between the history and reuse after comprehensive research [2 and 5]. Therefore, this research investigates the feasibility of the reuse of thin-walled cold-formed steel (CFS) structural members that are typically slender and prone to instability failure. Although some research design codes and proposals suggest that they can be reused until they are at an elastic limit, designing a thin-walled CFS structural member is tricky because they typically fail within the elastic stress limit (instability failure). This research attempts to develop a preliminary suggestion for the reuse of cold-formed steel sections.

2. Present Investigation

In the present investigation, the CFS columns are tested under axial compression. The CFS column cross-sections are of unequal angle sections with varying thickness and embossment patterns. The cold-formed steel columns were fabricated by the press brake process from steel sheets to form unequal open-angle sections. The steel sheets were cut to a specified length before the press brake process. The moderate strength 350-grade steel with zinc coating was used to fabricate the CFS open unequal angles. The column ends were welded to a 12 mm thick plate to ensure uniform distribution of load and to restrain the major and minor axis rotation of the supports, warping, and translation of the support end (fixed end condition) [6-11]. The embossment process, embossed steel plate, cross-section of the angle section, 3D view of the column member, and test setup are shown in Figure 1. The flatness of the 12mm thick base plate was ensured by the grinding process for full contact between the loading platen and plate surface.

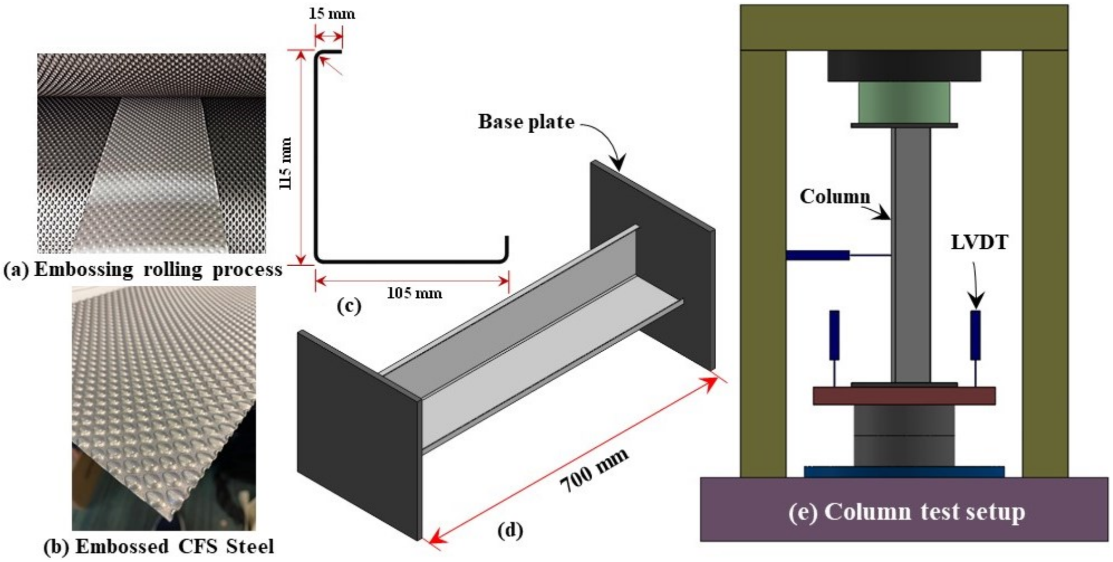

Figure 1: (a) Embossment process; (b) Embossed steel plate; (c) Cross-section of the angle section; (d) 3D view of the column member and (e) Test setup.

Series of CFS angled section columns were tested, each having different cross-sectional and different thicknesses of 1 mm and 0.5 mm. Four types of embossment pattern CFS angled section columns; (1) plain surface (no embossment); (2) thick embossment; (3) medium embossment; and (4) thin embossments for each thickness were tested. The cross-section dimensions and corresponding angle section dimensions and the slenderness (λ_l and λ_e) of the CFS unequal open angle sections are summarized. The local (λ_l) and global (λ_e) slenderness of the CFS angled cross-sections were determined from Eqs. (1) and (2), respectively. The cross-section slenderness of the sections was designed such that the cross-sections will fail predominantly in local buckling (λ_l>1) [12-18]. The critical elastic local buckling stress (σ_{crl}) and critical elastic global buckling stress (σ_{cre}) were obtained respectively from finite element software Thinwall [6] and the analytical method prescribed by sections E2.1 and E2.2 AISI (S100 2016).

$$\lambda_l = \sqrt{\frac{\sigma_y}{\sigma_{crl}}} \tag{1}$$

$$\lambda_e = \sqrt{\frac{\sigma_y}{\sigma_{cre}}} \tag{2}$$

where λ_l and λ_e are local and global slenderness, respectively; σ_y is the yield stress of the CFS sheet; and σ_{crl} and σ_{cre} are the critical elastic local buckling stress and critical elastic global buckling stress of the column cross-section, respectively.

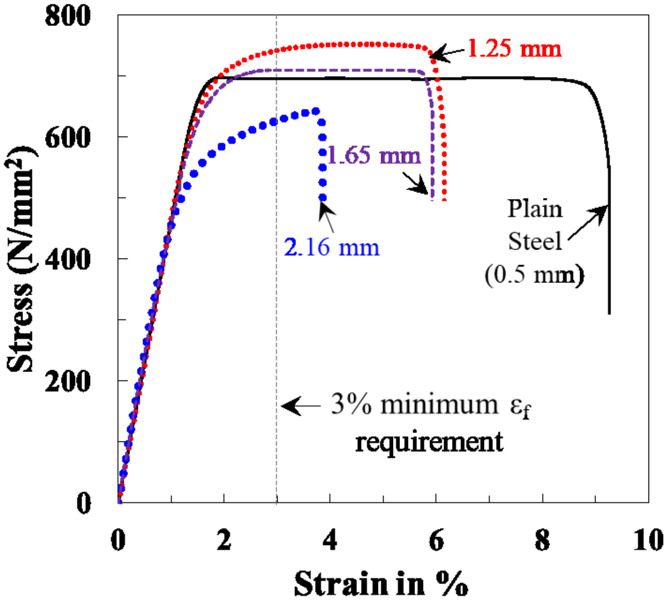

Figure 2: Material property rest results for 0.5 mm thick plain steel and corresponding embossment pattern steel sections

The following are the observations from the material tests shown in Figure 2. The embossments increased ultimate tensile strength for thin embossment by 7.8% (1.25 mm) and reduced for thick embossment by 7.9% (2.16 mm thick) while the percentage of elongation reduced with the increase in embossment thickness (Figure 2). The thickest embossed pattern 2.16 mm has an elongation of 3.75% at the ultimate strength of 643 MPa, however, this is higher than the minimum required elongation (3%), according to AISI (2022) for the design of structural members with resistance factors. The decrease in the percentage of elongation should be attributed to the strain-hardening effect throughout the steel plate. It was also observed that the tensile test samples from thicker embossments of 1.65 mm and 2.16 mm ruptured on the line of embossment due to higher strain hardening, however, such failure mode was not observed in the 1.25 mm thin embossment. Therefore, as a preliminary conclusion, it can be deduced that the thickness of the embossment should not be more than 2 times the thickness of the plain steel. Similar material characteristic was observed for the 1 mm thick steel plates. It is anticipated that this material property will have a significant effect on the axial strength of the columns.

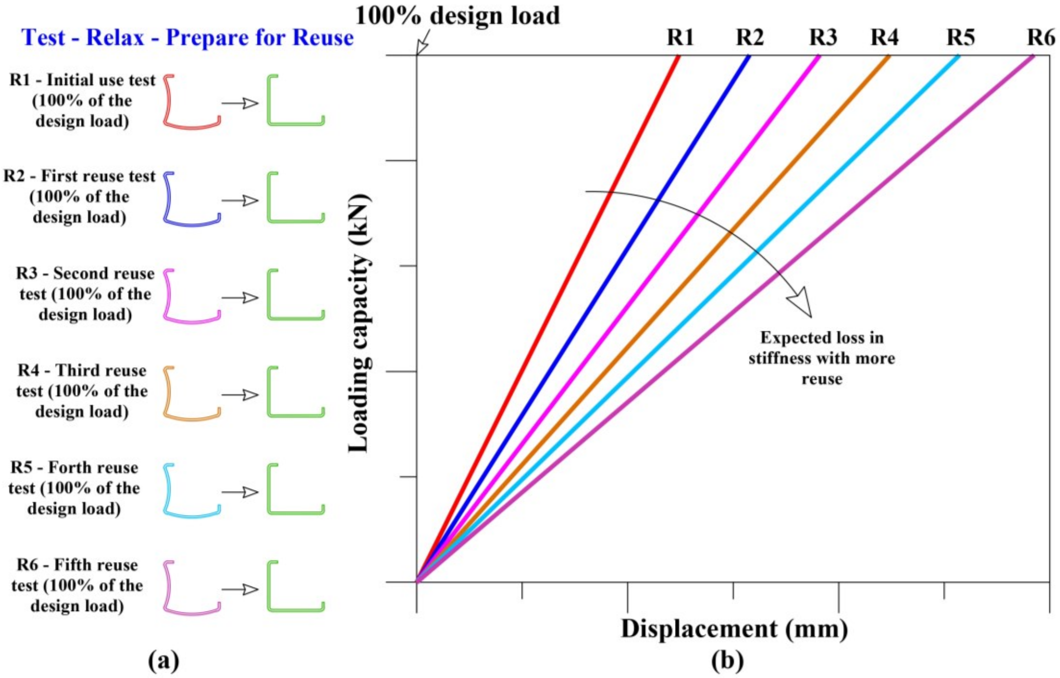

Figure 3: Reuse testing protocol for the axial compression tests on CFS columns

3. Testing Methodology for Reuse Application

As the cold-formed steel sections were not investigated before for the applications of reuse, a new reuse cycle test method is proposed. Prior to the test, the design strengths of CFS unequal angle columns were determined using the Direct Strength Method of AISI [7], concerning their material and geometric properties. During the test, the CFS columns were loaded up to their axial compression design strength then the load was released. This cycle is repeated up to 6 times. The first test is called as initial use test and the second test is called the first reuse test, similarly, the other reuse tests are named. The reuse testing protocol is explained in Figure. 3. After each cycle of the reuse test, the column sample is rested for a minimum of 48 hours before the next test. During each test, the full deformation of the column samples including local and global deflections were recorded for comparison and analysis. It is anticipated that the specimens will have a loss in stiffness with more reuse due to the presence of residual deformation (from buckling modes).

4. Results and Discussion

The test results including the maximum load taken by the column at each cycle of reuse test, corresponding load versus displacement curve, lateral displacement, and failure modes are summarized in Table 1 and Figures 4-6. It was observed that the columns with a thickness of 1 mm failed in local-global interaction buckling while the columns with 0.5 mm thickness failed in local-distortional buckling failure mode. This should be attributed to the design slenderness of those corresponding sections. In general, it was found that the thin steel sections and thin embossments have a higher possibility of reuse. However, future research should be towards optimizing the embossment pattern type to improve the buckling displacement pattern.

Table 1. Test results for the embossed steel column specimens

Thickness (mm)	Embossment patterns	R1 (kN)	R2 (kN)	R3 (kN)	R4 (kN)	R5 (kN)	R6 (kN)
1.0	Plain	20.11	20.09	20.02	20.19	20.22	20.09
	Thin	20.03	20.14	20.09	20.13	20.14	20.02
	Medium	20.04	19.66	19.34	19.88	19.58	19.52
	Thick	20.01	19.79	19.06	19.41	18.50	18.46
0.5	Plain	4.02	4.00	4.02	4.01	4.08	4.07
	Thin	4.02	4.05	4.06	4.05	4.02	4.02
	Medium	4.00	4.07	4.04	4.08	4.08	4.03
	Thick	4.01	4.02	4.01	4.06	4.00	4.02

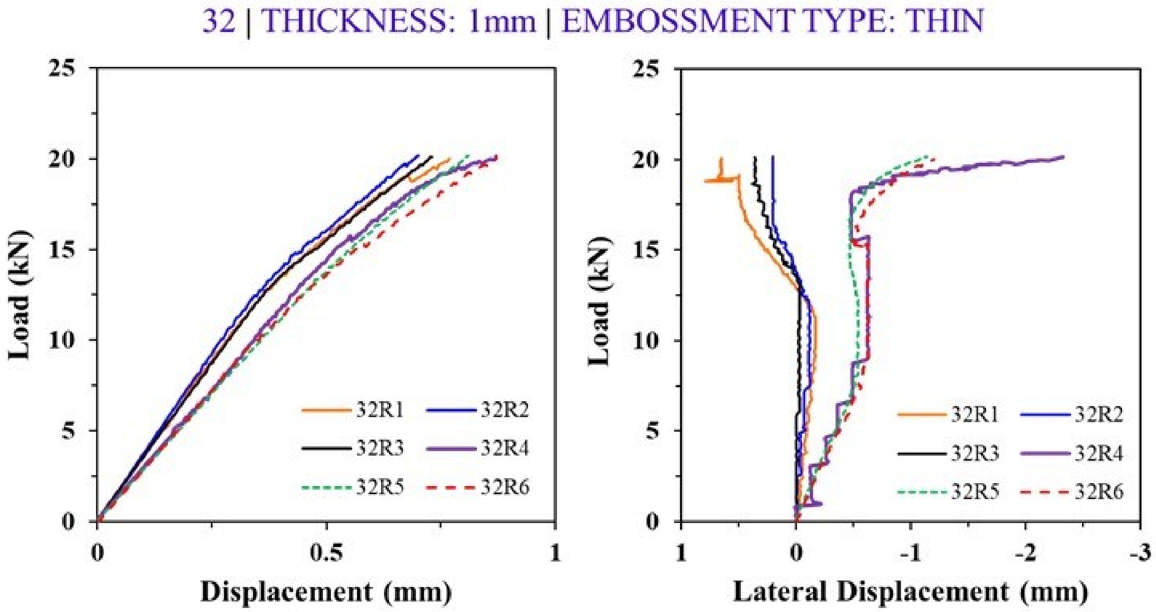

Figure 4: Load versus displacement response of the specimens with thickness 1 mm and thin embossment

4.1 Influence of Embossment Pattern

In general, it is observed from the 48 test results that the thin embossment has similar strength and stiffness compared to the plain sections while the thick embossment exhibited a strength degradation. This can be observed from Table 1 that the results of R1 strength are similar for all the embossments but when comparing the stiffness, the thick embossments have lesser stiffness than the thin embossments (compare Load versus displacement plots in Figure 4 and Figure 5). Figure 4 and Figure 5 show the load versus displacement response of thin and thick embossments in specimens with 1 mm thickness, while comparing, it is clear that the thin embossment has a lesser axial displacement than the thick embossment columns. Overall, the thicker embossment patterns have less influence or in other words, strength degradation on the axial strength and this may be attributed to the following facts; (i) both the 0.5 mm and 1 mm thick column specimens are vulnerable to buckle in interaction bucking while the embossment could only improve the local buckling [8]; (ii) the yield and ultimate strength of the embossed steel materials has significant difference compare to the plain steels (Figure 2).

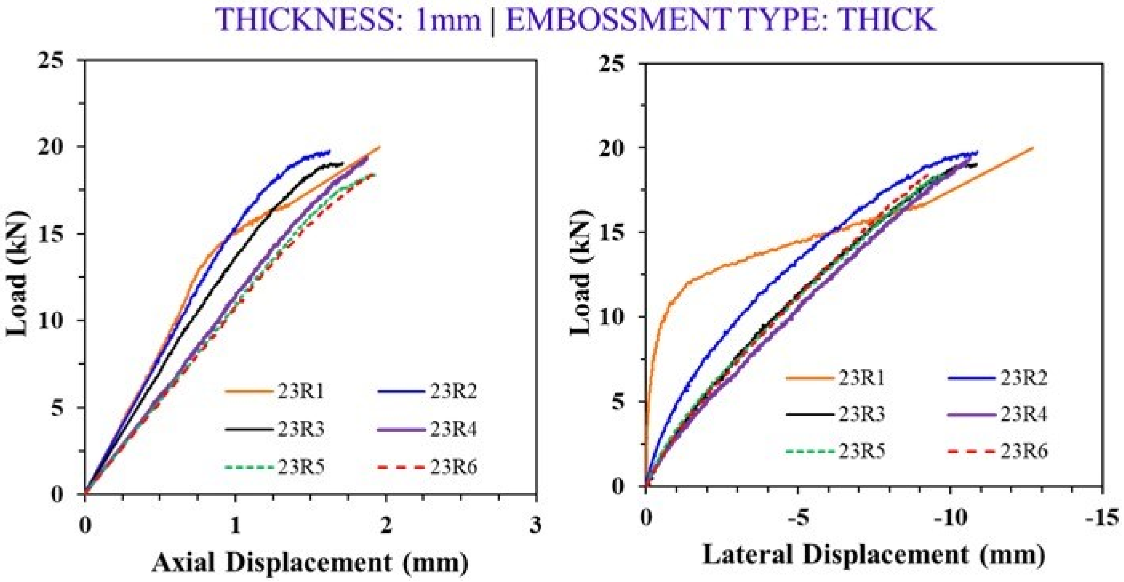

Figure 5: Load versus displacement response of the specimens with thickness 1 mm and thick embossment

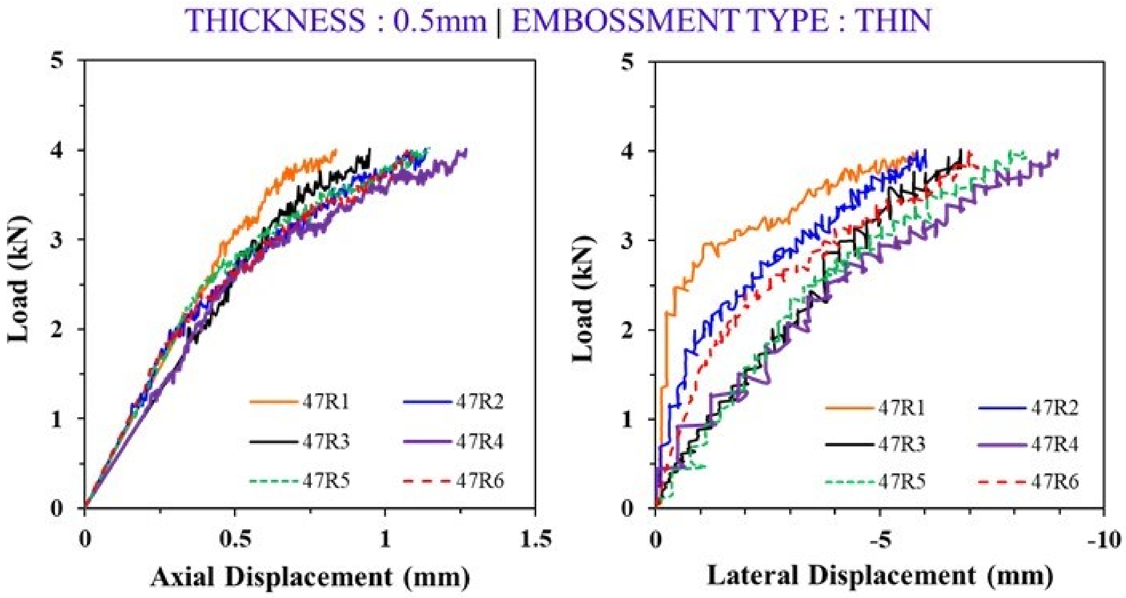

Figure 6: Load versus displacement response of the specimens with thickness 0.5 mm and thin embossment

4.2 Reuse test - observations

In general, it is observed from the 48 test results that it is feasible to reuse the cold-formed steel structural members. As can be observed from Table 1, the plain CFS columns without embossments did not exhibit a decrease in strength while the medium and thick embossments exhibited a 10%. decrease in strength. This should be again attributed to the fact that the thicker embossment significantly affected the material characteristics of the cold-formed steel. Besides, all the column sections with 0.5 mm thick CFS steel sections have similar strength and stiffness, including the thick and thin embossments as shown in Figure 6. It should also be noted that the buckling pattern of the thin embossed sections is better than the thick embossed sections. This can be observed by comparing the Lateral displacement plots in Figures 4 and 5. However, there is an increase in lateral displacement of all the sections as the number of reuses increases. This should be due to the fact of residual deformation from previous tests.

4.3 Discussion on reuse strength predictions - preliminary suggestions

The test results indicate that the CFS sections can be reused for at least up to 6 cycles, even the structural members were used for their full strength. Moreover, it should be noted in the present investigation that the column specimens are tested up to their 100% nominal design strength (without using any factors for safety), even then the column specimens do not exhibit a significant decrease in load during reuse tests. This may be attributed to the fact that the CFS sections were usually designed well within the elastic limit however, the column specimens resisted the load even after the significant lateral buckling deformation (Figure 7). Therefore, it is proposed that the CFS column sections may be reused with a resistance factor of 0.8 (80% of their nominal design strength).

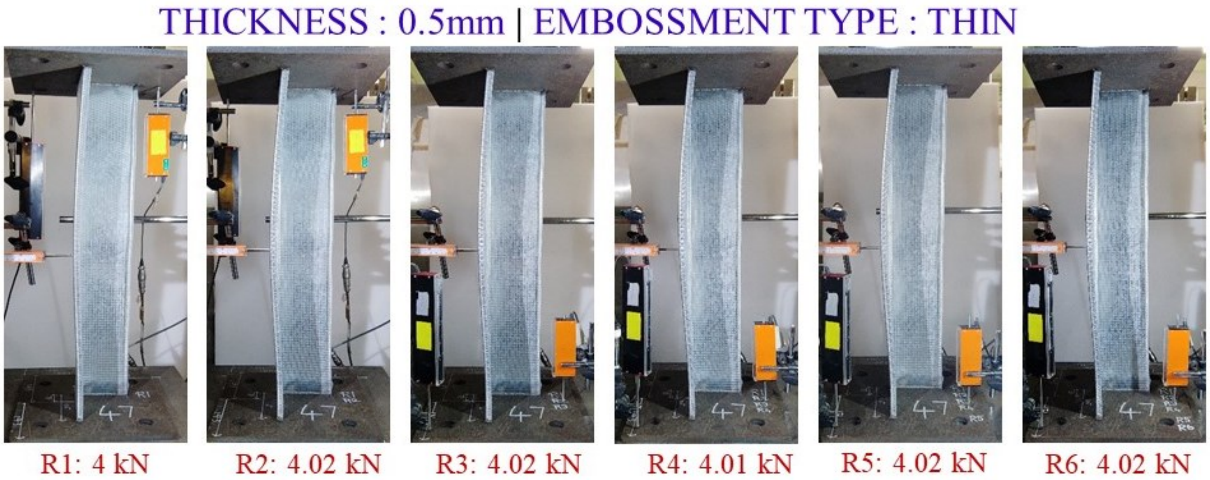

Figure 7. Buckling displacement profile of columns specimens – reuse cycles R1-R6.

5. Conclusions

This paper investigated the influence of embossments in CFS columns with interactive buckling modes subjected to axial compression. A total of 48 axial compression test results including repeated tests are presented. A detailed analysis of the effect of embossments on material properties is presented. Based on the limited test results, the following conclusions can be drawn

1. The material tests show that the thickness of the embossment should not be more than two times the thickness of the plain steel.
2. The column specimens with thick embossments have a lesser axial stiffness compared to the thin embossed sections.
3. Thin embossed column specimens also had a lesser lateral buckling displacement which is more suitable for the applications of reuse.
4. It is preferred to use the thin embossments as the thick embossed sections have exhibited a decrease in strength with an increase in the number of reuses.
5. Based on this preliminary investigation it is suggested to use the resistance factor of 0.8 for the reuse applications up to six cycles.

Acknowledgements

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