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An Overview of Numerical Studies on Flexural Performance of Built-Up Cold-Formed Steel Beam (CFSB) Filled with Concrete

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ABSTRACT

Cold-formed steel (CFS) built-up sections have been recently introduced with other materials such as concrete connected by means of bolting and screws to avoid the problems of the CFS sections buckling. The flexural analysis of CFS-concrete composite beam is more complicated in terms of design and failure mode. Therefore, this paper attempts a short review on the numerical studies of CFS section with and without concrete under the flexural load. In particular, the CFS buckling failure modes were critically reviewed. Furthermore, the important considerations such as material properties definition and interactions during the numerical simulation were discussed. The review presented in this paper highlights considerable potential on how the nonlinearities of the concrete material, CFS-concrete interaction and connection types affect the level of simulation accuracy in predicting the flexural behavior of the composite beam. Moreover, the connections type, the nonlinear simulation methods and strategies and findings for the CFS-concrete flexural behavior were critically reviewed. The directions of the future research were provided through the concluded remarks and recommendations in achieving a higher accuracy of simulation results as well as more effective design philosophy in future to promote the utilization of CFS composite beam in construction industry.

Key words: CFS sections, bolting connections, concrete, flexural behavior, interactions, numerical simulation.

1. INTRODUCTION

The recent advancement in the construction industry has opened the engineers' insights to another alternative materials and designs to fulfil the needs of the construction industry. Cold-formed steel (CFS) is one of the materials that has been recently introduced alongside with other materials such as concrete into the construction industry. Historically, the use of cold-formed steel (CFS) in civil engineering structures can be traced back to the 1850s in the U.S. and U.K. However, it remained low-key up until the 1930s due to absence of construction code, insufficient knowledge, and lack of understanding on the design and behavior of CFS structures. Nevertheless, with the advancement in construction industry, the significance of CFS became more visible in the construction field with noticeable advantages such as cost-effectiveness, lightweight, easy installation, low maintenance and corrosion resistance, easily transportable, recyclable, and easy fabrication. CFS is introduced to the construction industry through its high strength to weight ratio, long-lasting versatility, stability, safety and cost-effectiveness [1]. In addition, CFS have been known to contribute significantly to the environment and maintain green construction in the formation of low-rise residential and medium-rise commercial structures [2].

Several studies have been dedicated to the CFS sections and concrete as composite elements. Smith and Couchman [3] conducted a study that focused on the strength and ductility of headed stud shear connectors within the profiled steel sheeting, and found that through the increase of slab depth, the shear connector's resistance showed an increase. Similarly, based on study done by Pavlović et al. (2013) [4] ,the behaviour of bolted shear connectors and stud connectors in push-out tests were examined to provide insight into the failure modes of shear connectors of different kinds (bolts and studs). Further, Wehbe et al.,(2011) [5] delved into the development of concrete and cold-formed steel (CFS) composite flexural members, entailing experimental and analytical steps in order to assess the structural performance and failure modes of concrete and CFS track composite beams. The authors developed optimum configurations for using light-gauge steel (LGS) construction.

The cold-formed steel (CFS) sections made of galvanized strip steel are normally ranging in the thickness from 0.9 mm-3.2 mm [6]. Therefore, these sections are hyper sensitive to the local buckling effects compared to their hot rolled counterparts [7]. Basically, the failure of CFS in the beam or column sections can be categorized into four failure modes namely local, distortional, lateral-torsional, and global buckling as shown in Figure 1. According to Dar et al.,(2018) [8], the buckling failure experienced by the CFS section could be resolved or eradicated through a suitable modification of design, improved strength and stiffness performance. The CFS section building calls for different fasteners in the form of screws, bolts, nuts, and welding. The connection requires a robust technology and an expert and for a stronger built, higher temperature is used through welding. Studies have also recommended the use of other connection methods like laser welding to speed up the connection process.

Most of studies have mainly concentrated on the performance of CFS sections in terms of compression, with flexural aspect largely ignored. More importantly, the CFS beam's flexural analysis is more complicated in terms of design and failure mode [9]. Built-up CFS closed sections are often expected to have a higher load-carrying capacity with simple connection. In this regard, limited studies focused on flexural aspect compared to compression aspect. In the study conducted by Wang and Young (2018) [10], the moment capacities and failure models of built-up open and closed CFS beam section were examined and it was found that the effect of screws arrangement was insignificant in the open section beams while it was a significant factor on the closed beam sections. Therefore, the researchers are also looking for alternative methods to overcome buckling failure in CFS structures which has led to the introduction of concrete filled CFS.

Built-up CFS section filled with concrete has been extensively examined in several studies such as [2], [11]–[13]. Concrete-filled CFS provides several enhanced strength and ductility advantages. It is also capable of mitigating local buckling, has lower material cost and framework production, and is fire-resistant. Besides that, there is lack of information on the suitable connection between concrete and steel of concrete filled CFS beam in regard to its flexural performance. Therefore, studies need to be carried out to provide better understanding on the flexural performance of concrete filled CFS beam. Owing to that, this paper aims to provide a state-of-art review on the flexural behavior of CFS-concrete filled beam focusing the numerical studies that have been conducted previously.

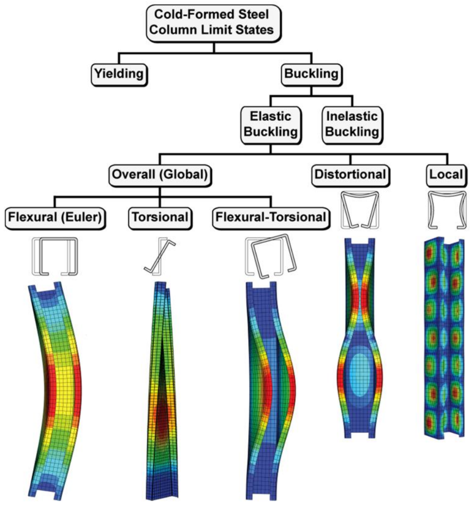


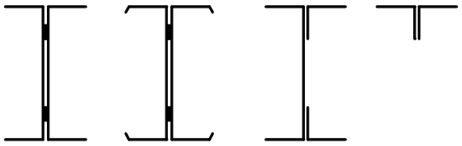
Figure 1: Failure modes for CFS C-section [14]

2. CFS BUCKLING FAILURE MODES

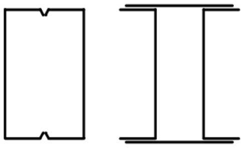
Typically, CFS sections under compressive actions may experience three different modes of buckling failure which are local, distortional and global buckling [15] as shown in Figure 1. These possible modes of failure along with the different connection types of built-up CFS sections are very important to be understood as it is the basis of analysis and design of CFS members under different loading conditions. CFS members may experience a local buckling due the fact that they are thin in respect to their width which cause them to buckle at a localized areas at a stress lower than the yielding when being subjected to either pure compressive, bending and shear load or to their combination [16]. On the other hand, the distortional buckling failure is characterized by the rotation of the flange member at its flange-web junction with edge stiffnesses and this failure mode is associated with presence of the stiffeners [17]. The critical stress of the distortional buckling failure does not depend only on the dimension of the CFS cross section but also on the type of load being subjected to [18]. This mode of buckling is common to occur in the short columns. The global buckling has three failure modes which are flexural, torsional, and flexural-torsional buckling. These failure modes are associated with long columns. The flexural bucking is characterized by the deflection caused by the bending or the flexure and usually occurs about the axis with the largest slenderness [19]. This type of failure is common in long column and beams. Due to the thin-walled nature of most CFS members that are vulnerable to buckling issue, researchers all over the world are looking for methods and materials to minimize the buckling failure of CFS sections.

3. BUILT-UP CFS SECTIONS

The built-up CFS sections can be either open built-up section or closed built-up section as shown in Figure 2. These built-up sections can be attached together using either conventional connection method such us bolting and arc-welding or long-lasting method such as blind rivets, self-drilling, or self-tapping screws. Several studies on the behavior of the built-up CFS columns as can be seen in works done by [20]–[23]. On the other hand, the flexural behavior of built-up section beams were investigated in some studies such as [24]–[27]. These studies focused mainly on the built-up CFS sections behavior under compressive actions and how the buckling problems can be reduced comparing to single open sections. As mentioned earlier that the small thickness of CFS sections compared to its width can make them more vulnerable to local and global buckling and with this the CFS would not be good in resisting the bending alone [28]. For this reason, CFS sections have been recently introduced into the construction industry together with other materials such as concrete or soil. In the CFS-concrete composite beam, the CFS has high tensile strengths which provides good ductility while the concrete provide compressive strength, fire resistance and floor surface [29].



a) Open built-up sections



b) Closed built-up sections

Figure 2: Typical built-up CFS sections [30]

The CFS built-up sections were introduced with other material such as soil, concrete and ground granulated blast furnace slag and then been examined under compressive or bending actions. Sani et al. [31] examined experimentally built-up bolted CFS column infilled with concrete and it was found that the column with concrete on shortest end bolt spacing has increased 68%-78% in its load carrying capacity comparing to its counterpart column without concrete infilled. In another study, Sani et al. [32] investigated the flexural behavior of built-up CFS beam filled with compacted soil (CFSBCS) under four-point bending test and the findings showed that the CFSBCS has recorded higher values of the ultimate moment comparing to non-infilled CFS beam. Grisilda and Ligoria [33] studied the effect of concrete filling and GFRP wrapping on flexural behavior of cold-formed steel beams and the authors found that the infilled-beam wrapped with GFRP has better load carrying capacity. These studies have opened up the potential of CFS filled with other materials to enhance its performance and minimizing buckling failures.

4. NUMERICAL SIMULATION OF CFS BEAM FILLED WITH CONCRETE

Finite element modelling (FEA) is numerical method used to solve the engineering problems and mathematical physicals. Hence FEA is a method to compute the approximation of real solution for partial differential equations (PDEs) in the bounded domain [34]. It is a useful method when dealing with solving engineering problems that are having complicated geometries, loadings and material properties and their analytical solutions cannot be obtained. The finite element approach involves dividing the physical structure into small elements connected to each other through shared nodes in which these elements with nodes are called mesh. This mesh approximates the geometry of the physical structure. The computed variables (e.g., stress, displacement, forces, etc.) of each element of the body can be locally computed on each node and in which these values for a respective variable will be summed for all elements to give the global response of the body. The finite element modelling on CFS-concrete composite beam is still very limited. To numerically simulate the flexural behavior of the CFS-concrete composite beam, some considerations have to be considered before initiating modelling process such as the software tool to use, material property definition, CFS-concrete interface bond interaction, load type, and boundary conditions, just to name a few.

4.1 Material Consideration

In the non-linear finite element analysis, the definition of the materials plays very important role in achieving reasonable level of simulation accuracy. In the numerical modelling of CFS built-up sections filled with concrete to simulate the composite beam behavior under monotonic flexural load, crucial attentions have to be given during the definition of the material properties models for concrete and steel. Therefore, this section aims to shed light into the relevant consideration in the concrete and steel material models.

Concrete material is one of the most complex materials to be modelled especially under severe loading. That is due to non-linearities of the concrete such as micro-cracking, bond slip, tension stiffening, compression softening and crushing [35]–[37]. In the past four decades, there have been tremendous efforts to develop analytical models that can predict the concrete behavior under different load conditions. Theses analytical models were based on three most commonly known theories which are plasticity, fractur-based approaches and continuum damage mechanics [35]. Early stage of these models was mainly relied on the theory of the plasticity. Some of the research works adopted plasticity in the concrete are done by [38]–[41]. However, the stiffness degradation was not captured by these models. Therefore, in order to improve the accuracy of the model, the plasticity was coupled with damage mechanism theory to capture the shortcomings of the plasticity theory. These models considered the plasticity with isotropic hardening and enriched by either isotropic damage (scalar) parameter or anisotropic damage [42] . The isotropic damage coupled with plasticity was used by several researchers in their studies [43]–[46]. On the other hand, the combination of plasticity and damage models were also grouped into two categories based on the way they were formulated which are effective stress space formulated plasticity [47], [48] and nominal stress space formulated plasticity [49], [50].

In the commercial finite element software packages particularly the Abaqus software, the concrete damage plasticity (CDP) which was initially developed by Lubliner et al.(1989) [51] and modified by Lee and Fenves (1998) [48] is one of the most widely used material model in modelling concrete material. This model can be used in both static and dynamic analysis and it can define the damage of the material based on the degradation in compressive and tensile strength. Although the Abaqus CDP model is very flexible, it is not simple to use. One of the reasons is the large number of the required input parameters. In addition to the compressive and tensile hardening behavior input data, there is a number of parameters that determine the shape of the initial yield surface and the flow potential. In particular, the sensitivity of the model output with respect to the tensile meridian to compressive meridian ratio and the angle of dilation are still under investigation [52].

On the other hand, Cold-formed steel is among a few martials such as aluminum alloys, stainless steels that exhibit rounded stress-strain response when subjected to the tensile test [53]. The most common model used recently to capture rounded stress-strain response of CFS and other similar material is Ramberg-Osgood model which is developed by Ramberg and Osgood (1943) [54] and modified by Hill (1944) [55]. Recently, Ramberg-Osgood model has been widely used in finite element application in order to obtain an accurate simulation of the CFS behavior under different load conditions. This model is generally defined using three parameters which are the Yong's Modulus (E), yield strength of material (f_y) and strain hardening behavior.

4.2 Interface Consideration

First, the bond between concrete and smooth plates depends on the chemical adhesion and friction and very small mechanical interlocking which is mainly due to the roughness of the plate [56]. According to FIB (2011) [57], the interaction between concrete and steel member can be classified into four groups as follows: (i) adhesion which is due to a pure bond between the concrete and steel, (ii) frictional interlocking which is due to the irregular shapes of the interface profile, (iii) mechanical interlocking due to such treatment and deformation at the steel interface and (iv) dowel action which is provided by anchor devices and systems. Further, the bond and friction between the steel and concrete are very important as they influences the composite response of the element and they are also the basis for learning the load mechanism of that element under the load [58]

The bond and friction are the key factors that affect the response of the composition action and they also form the basis to understand the load transfer mechanism though the interface of the two materials. With regard to the composite structure with concrete and metal sheeting (e.g., cold-formed steel), pure bonding is not suitable to transfer the shear forces to develop composite actions [57]. The insufficient interaction between CFS and concrete can lead to the flexural strength reduction [59]. The simulation of the composite action for concrete-steel sheeting interface in FEM is surfaced-based interaction that has a contact pressure model in the normal direction and a Coulomb friction in the tangential direction [60]. Based on Coulomb friction model, the shear stress can be transferred through the two material interfaces until it reaches a greater value limit shear stress, τ_{cri} in which the bond slip will take place between the two surfaces. The τ_{cri} can be determined based on Equation (1).

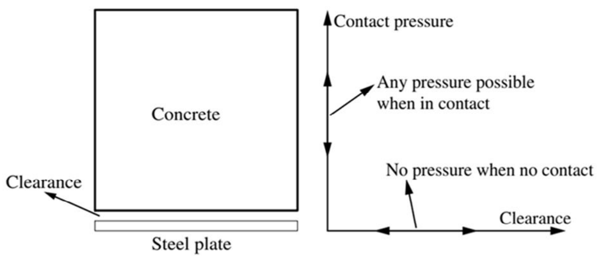
$$\tau_{crit} = \mu p \geq \tau_{bond} \qquad (1)$$

Where μ is frictional factor, *p* is confinement stress between steel and concrete core. The τ_{bond} is the average surface bond stress and according to [61], it can be determined for square cold-formed steel stub using Equation (2).

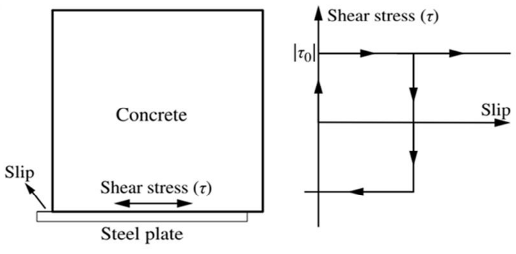
$$\tau_{bond} = 0.75\left[2.314 - 0.0195\left(B/t\right)\right] \qquad (2)$$

Where, *B* is outer dimension of square steel tube and *t* is thickness of the steel tube.

In the numerical simulation of the interaction between the CFS and concrete, the most common method used is surface-based interaction with hard contact model in normal direction and friction penalty model in tangential direction as shown in Figure 3. The normal interacting action is due to the load perpendicular to the surface and the tan tangential interaction due to the likely relative sliding between the two adjacent surfaces.



a) Hard Contact Model



b) Penalty Friction Model

Figure 3: CFS/steel -Concrete interaction models [13]

4.3 Concrete Filled CFS Numerical Studies.

The existing literatures on the numerical analysis of the flexural behavior of CFS built-up section beams with and without infill concrete are very limited. Table 1 summarized a total number of 10 existing numerical studies on the CFS section under the flexural load between years 2013 to 2019. A total number of seven (7) studies [10], [25], [62]–[66] were mainly focused on the flexural capacity of built-up open/closed sections that are connected or attached to each other through the webs or flanges by the means of screws and bolts. Most of the CFS sections in the above-mentioned studies were in the shape of I, U and C sections to ease the building process of the desired open or closed sections. Most of the numerical findings of these studies were in acceptable agreement with experimental results. As a general conclusion, it was found that the capacity of the built-up sections is mainly influenced by the arrangement of the bolts.

On the other hand, the CFS sections were introduced with other material such as concrete to avoid the buckling problems. There are three (3) studies [33], [67], [68] using CFS single section and filled with concrete. Palanivelu (2019) [67] and Sudharsan and Vinoth Kumar (2018)[68] used the shear connectors to strength the bond between the concrete and CFS. The numerical and experimental studies confirmed that the shear connectors can lead to better performance of the CFS-concrete composite beam under the bending test. However, for the CFS built-up section with concrete, only one study was reported in the literature by [65] in which the built-up section was filled with polystyrene aggregate concrete and tightened by bolts .

Furthermore, from the numerical analysis method perspective, all the summarized studies used nonlinear finite element analysis to evaluate the flexural behavior and validate the experimental results. Furthermore, five out of ten studies [10], [25], [62], [64], [66] used Abaqus software as a tool to perform the finite element analysis while the remaining studies used Ansys software. For the element type, the CFS single or built-up sections were modelled as shell element type in some of the studies such as [10], [25], [62]–[64], [66]. On the other hand, some researchers studied CFS filled with material such as concrete used the 3D solid element for CFS concrete discretization during the modelling process [33], [65], [67], [68]. To conclude, most of the studies modelled CFS as shell or solid elements while concrete is only modelled as solid element.

In the modelling of the interaction between the CFS to CFS and CFS to concrete, the surface-based method was used by most of the studies with frictional contact in the horizontal direction and hard contact in normal direction. For the CFS built-up section, bolts or screws used to connect theses section together were modelled as connector element as per study done by Ye et al.(2018) [69] or coupling method as per Manikandan and Sukumar’s study [25].

Based on the numerical analysis in all of the previous reported studies, it can be seen that there is still lack in the definition of the material properties of CFS and concrete. Further, the numerical modelling of interaction between the concrete and CFS section under flexural behavior in these studies lack of the sufficient knowledge on how the interaction behavior can affect the load transfer mechanism. Hence, it limits the exploration of the concrete filled CFS structure to be used as flexural member.

5. CONCLUSION

This article paper presents a state-of-art review on the related research findings for the numerical simulation of CFS single and built-up sections with and without the concrete analyzed nonlinearly. Some conclusions and recommendations are summarized as follows:

I. Most of studies mainly concentrated on the performance of CFS sections in terms of compression, with flexural aspect largely ignored.
II. The built-up CFS sections mostly were connected by means of bolting and screws. Such connections were used to connect back-to-back webs or lip-to-lip to form either open or closed built-up sections to improve the flexural capacity loading. Further, built-up CFS section filled with concrete provides several enhanced strength and ductility advantages. It is also capable of mitigating local buckling, has lower material cost and framework production, and is fire-resistant. However, the lack of knowledge on the suitable connection between concrete and steel of concrete filled CFS beam in regard to its flexural performance has hindered its applications in the construction industry.

Therefore, further investigation on the connection types and configuration is recommended to provide better understanding on the flexural behavior of concrete-filled CFS beam and the influence of the connector's configuration towards the overall performance of concrete-filled CFS beam.

III. The nonlinear finite element studies on the flexural behavior of the CFS built-up sections with concrete are very limited. This is mainly due the complex nonlinearities of the concrete material (i.e., microcracking, cracking, tension stiffening, compression softening and crushing), high possibility of the slip between CFS sections and infilled concrete under flexural load, and the connection interaction. Therefore, the proper definition of the concrete material model and CFS-concrete interactions are the key steps in the implementation of the finite element analysis in CFS-concrete beam under flexural load.

IV. The impact of using bolt connections for the CFS-closed sections filled with concrete in transferring load mechanism and in controlling hardened concrete from possible brittle cracking or shear failure need to be further investigated.

Table 1: Numerical studies on the flexural behavior of CFS built-up section beams

Study		**Methodology**							**Main Findings**
					Finite element analysis method				
No.	**Reference**	**Material**	**Connection type**	**Test Type**	**Analysis type**	**FEA Tool**	**Elements**	**Contact model**	
1	[62]	CFS channel built-up I-section	Two rows of bolts connected back-to-back webs	Four-point bending test	Linear & nonlinear	ABAQUS	CFS: Shell element	-	The mean and standard deviation between of the moment capacity obtained by FEA and by DSM were 0.96 and 0.07, respectively which shows an acceptable agreement.
2	[63]	CFS built-up sections beams (channels or Sigma section)	Self-tapping screws		Non-linear Analysis	ANSYS		Surface-to-surface frictional contact friction coefficient taken as 0.25 and normal behaviour	- Higher yield strength and steel thickness lead to higher bending capacity. - Strengthening web with stiffeners can lead to better performance of the beam flexural capacity
3	[67]	CFS U-section beam attached with shear connections and filled with concrete	-	Three-point bending test			3D Solid elements for CFS and concrete	Surface-to-surface	- The numerical and experimental results for deflection and carrying load capacity differed by ratio from 1.04 to 1.27 which indicates an agreeable match. - Shear connectors led to better performance
4	[10]	CFS built-up open/closed section beams	Different arrangement of screws on webs /flanges	Four-point bending test		ABAQUS	CFS: Shell element	Surface-to-surface contact with frictionless tangential behavior and normal hard contact	- Impact of screws spacing on the moment capacity of built-up closed sections was more than built-up open sections.
5	[69]	CFS back-to-back lipped channel beams	Two rows of screws on webs with four screws in each row					Bolts: Connector element CFS-CFS: surface-to-surface contact	- Ultimate capacity of the sections predicted by the FE models was varied with 2% less than the experimental results

Study		**Methodology**							**Main Findings**
No.	**Reference**	**Material**	**Connection type**	**Test Type**	**Finite element analysis method**				
					Analysis type	**FEA Tool**	**Elements**	**Contact model**	
6	[33]	CFS square hollow section beams with and without GGBS*and GFRP**	-			ANSYS	3D Solid elements for CFS and infill material	Surface-to-surface contact with frictional behavior (friction coefficient = 0.2)	- GGBS concrete in-filled models did fail not under the local buckling but under flexure. - Load capacity of concrete in-filled beams wrapped with GFRP increased by 42.7 % more than the hollow CFS beam.
7	[68]	CFS composite beams with shear connectors	-	Four-point bending test	Non-linear analysis	ANSYS	3D Solid elements for CFS &concrete	-	- Deflection obtained by FEA was slightly higher than the one obtained from the experimental investigation.
8	[65]	Built-up open / and closed sections (I-section) and filled with polystyrene aggregate concrete	Bolts on webs/lips	Single point loading			3D Solid element	-	- A closer match to the experimental results. - Failure modes for experimental and numerical investigation were in acceptable agreement.
9	[25]	Built-up CFS sections stiffened at the flange/web junction and at the edge	Bolts on the webs	Four-point bending test	eigenvalue elastic buckling analysis and static nonlinear buckling analysis	ABAQUS	CFS: Shell element	Bolts: coupling method	- FEA has acceptable level of accuracy in predicting the strength and behaviour of the built-up CFS beams
10	[66]	CFS open and closed section beams	Bolts on either webs/ flange		non-linear		CFS: Shell element. Screws: 3D solid elements	Surface-to-surface contact with frictional behavior (friction coefficient = 0.2) for CFS-CFS and CFS-screws interaction	- Similar buckling mode of failure was observed in both in numerical and experimental investigation.

GGBS*: Ground granulated blast furnace slag
GFRP**: Glass fiber reinforced polymer

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