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Manufacturing, Applications, Analysis and Design of Cold-Formed Steel in Engineering Structures: A Review

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***Abstract*— The concept of cold-formed light steel (CFS) framing construction has been widespread after understanding its structural behavior and characteristics through massive research works over the years. Application, manufacturing, design, and optimization of cold-formed steel structures continue to see significant improvements and refinements. The objective of this paper is to provide a comprehensive brief review of recent advances in different aspects of cold-formed steel structures. Therefore, in this review, the latest efforts and researches related to cold-formed steel structures are highlighted and discussed.*
Keywords*— Application, Cold-Formed Steel, Connections, Direct Strength Method, Optimization, Manufacturing.

I. INTRODUCTION

Due to rapid growth in the construction industry, there is a need for more advanced structures. The consideration of the construction material is an essential aspect in order to fulfil the advantage, quality, and economy of the construction. Therefore, decreasing the quantity of the material in many construction industries has been the priority for sustainable development. For that, the steel has been considered as a preferable option in the construction area due to its untold advantages over other materials, where the superior sustainable performance of steel members minimizes the environmental impacts when measured through the whole life cycle. Moreover, steel is a basic material for construction in the evolution chain, where it is considered as an effective material for any local energy producing, transportation as well as commercial and residential construction [1].

In steel structures, essentially, there are two types of steel to make the structural members: hot- rolled steel (HRS) and cold-formed steel (CFS) [2]. HRS is formed at high elevated temperature (up to 1400 °C in blast furnaces or electric arc furnaces), while the CFS is produced at room temperature. The differences in the properties of CFS and HRS in terms of structural performance, strength, and failure modes are influenced by the manufacturing method. For example, the HRS type is very well known among designers as it can accommodate heavier load than the CFS [1].

1.1 What are the Cold-Formed Steel Structures?

Cold-formed steel structures are light-weight structural products that are made by forming flat plane sheets or panels with different shapes which can meet the structural and functional requirements and support more than the flat sheets themselves. The produced shapes are thin-walled and can offer high value of capacity-weight load ratio among the various structural components. Therefore, the CFS members also called “light gauge steel members.” Reducing labor costs and producing a valuable economy can be achieved by using such light- weight components as well as easy handling of that product [3], [4].

1.2 Historical Overview:

Producing of the CFS sections has been initiated for more than a century since the first steel flat sheets were made by the steel mills. Great Britain and the United States began using the CFS members in buildings construction in the 1850s. In the 1920s and 1930s, there was not a wide acceptance of CFS to be as a construction material, because there were inadequate design guidelines and a lack of building codes information. Virginia Baptist Hospital, which constructed around 1925 in Lynchburg, Virginia, is considered as early applications used CFS in building materials [5]. In the past few decades, more development of CFS has been achieved by aesthetic architecture projects or light weight steel buildings [6]. The usage of CFS members as a structural frame is increased not only in residential structures but also in multi-story commercial structures, e.g., roof systems, wall studs, girts, and steel-framed housing [7]. This is because of the advantages of cold formed steel, which get over the disadvantages of conventional products. Therefore, the interest of CFS in both research and construction aspects increased rapidly, especially in, USA, Canada, China, Australia and some European Countries which are considered Industrialized Countries [1], [3], [8].

1.3 Why a Review?

Due to:

a. The unique features and advantages of CFS, which makes its range of applications wider.

b. CFS member's issues and disadvantages such as structural stability (primarily due to their large width to thickness) and other issues [1].

c. The lake of design guidelines related to this type of steel structure [9].

Massive research works over the years were done on the CFS in order to get more investigation on the advantages of the CFS element and improving its properties as well as understand its structural characteristics [9].

The researches focused on several disciplines like building performance, design methods, wind and seismic design, durability, fire resistance, construction safety, framing method and sections strength and behavior, e.g., compression members, distortional and elements buckling, curved and corrugated panels, purlins and flexural members, torsion and distortion, mechanical properties, web crippling, storage racks, composite and plasterboard construction, design optimization, etc. So, from the beginning of this millennium, several reviews have been conducted on the development of CFS structures such as Hancock [3], Schafer [10],Camotim et al. [11], Yujie et al. [12], Schafer et al. [13], Yeong et al. [9], Rondal [14], etc. [4]. However, as a result of the extensive researches which are conducted every year in several disciplines related to CFS, a literature review for these new researches should be done frequently in order to summarize and link these researches with previous studies for more understanding of CFS structures behavior, improving design codes of CFS structures, and also serving as guidance for future researches. Thus, our review coming in this context.

1.4 Review Content:

The main objective of this review is providing a new review of references on CFS research, as found in high quality journals in the last few years. Which clarify the development and current progress in different CFS research disciplines. This review covers both introductory and advanced topics that may the structural engineers, students, and researchers are interested in it. Section 2nd of this review briefly describes the manufacturing and construction methods, while sections 3rd and 4th covers the CFS structural members and their applications in engineering structures. Connections types and issues are discussed in section 5th. The behavior of CFS structures is reviewed in section 6th. Sections 7th and 8th discuss the development in design, and optimization of CFS, respectively. Finally, in section 9th, the review is ended up with conclusions.

II. MANUFACTURING AND CONSTRUCTION METHODS.

2. 1. Manufacturing Methods:

Generally, CFS members are essentially made from steel plate, sheet, or strip materials, which have a thickness from o.5 to 6 mm, where sheets or coils of CFS can be accommodated with a wide up to 60-inces and 3000 feet long by specific machines. Cold-formed steel can be made by different methods: 1. Cold Roll Forming, 2. Press Braking, 3. Bending Brake Operation.

Cold Roll Forming is widely used by the automotive industry for mass production of building components (structural members, roof truss, wall panel, corrugated sheets, frames of windows and doors, etc.).

In this method, the metal is forming through a specific process, where a sheet of metal is compressed through a pair of rolls to increase strength, reduce thickness, and improve surface finish. The rolling process happens with the temperature ambient condition below the steel's recrystallization temperature. Moreover, any desired shape with any length can be produced in a cold rolling process. In fact, more rolls will be used in case of more complex shape design. To minimize the residual stress formation in both the edge and notch of the steel section, therefore the speed rate of rolling is slow within the range of 6 m/min to 92 m/min, and that would affect the strength of the CFS sections [15], see figure 1. Simple shapes with small quantities can be created by the press-braking process, for example, roof sheets, decking sections, etc. The Press-braking method uses a beam as equipment that is moving over a stationary bottom bed and having the dies for the desired product, as shown in figure 2.

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Fig.1: Cold Roll Forming Line.
Source: Believe Industry Website [133].

Fig.2: Hydraulic Press Brake.
Source: Wikipedia Website [134].

2. 2. Construction Methods:

2.2.1 Penalization Method of Framing versus Conventional Field Assembly Method:

The typical projects of CFS structures are configured of a large number of individual pieces that compose a repetitive framing to get the final structure. There are lightweight pieces and easy for handlings, such as joists, clips, studs, and tracks, which is considered as one of the advantages of this system over others. However, significant time is required to assembly these large numbers of pieces. Thus, to minimize the duration of the construction process and labor efforts, these individual pieces are fabricated into subassemblies before transferring to the construction site. Because the subassemblies resembling a panel, so this process is commonly called Panelization, see figure 3. The panels are common wall (containing tracks, studs) or floor elements (containing joists, tracks).

Fig.3: Example of erection of panelized floor.
Source: FORTECO Website [135].

In addition, the panels may have the floor, wall, or roof sheathing built-up before shipment to the construction site. The advantages and disadvantages of the Panelization Method of Framing against Conventional Field Assembly Method are shown in the following table (Table 1) [16].

Table.1: Advantages & Disadvantages of Panelization Method of Framing against Conventional Field Assembly Method

Advantages	Disadvantages
Some construction can be occurred indoors and avoid the weather conditions because of the interior environment where the assemblies are done and controlled.	Special consideration of construction tolerances is required in case of larger dimensional tolerances of panels, foundations, and the other parts of the building and which may be a problematic issue.
Efficient assembly can be achieved since the set-up jigs are used to construct the repetitive sub-assemblies.	In the Fast-track projects, the design and preconstruction time required for panelization may not be allowed.
High quality control of the assembly comparing with in-field.	Difficult modifications of designs if panels have been fabricated early.
A significant reduction of the erection time can be achieved assembly in the field, especially if designs are done prior to being constructed on-site.	More transportation and crane costs are required over the structures which can be built in the field because of the size and weight of subassemblies units, despite that CFS panels are still lighter than other construction materials.

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2.2.2 Framing Options:

The available primary alternatives in CFS structures are namely; ledger framing, platform framing, and balloon framing system (rarely used) see Figure 4.

- In the platform framing, the joists work through the intersection between stud/joist, and the joists interrupt the studs. In this configuration, the axial load was transferred from the upper stud into the lower stud by the floor joist web and web stiffener [16].

In CFS construction, there is a common of the platform framing in case of existing any rigid panels in the floor system or steel joists and/or metal deck with concrete, hollow-core panels. In addition, clear separation in construction elements can be achieved with these floor systems where the CFS-framed walls are separated in construction, and it can provide an efficient combination of components. With respect to the tolerances between systems, more tolerance is with the combination of CFS wall framing with non-CFS floor framing [16].

In panelized systems, the platform framing designs can be useful since the tolerance is increased because of placing the floor panels over the bearing walls rather than placing them onto the side of the wall. During the construction and while the ledgers are connected, the floor panels can be easily placed over the walls rather than of holding in place [16].

- Balloon Framing of CFS structures is parallel to balloon framing of wooden-frame, which is the original system for light wooden-frame structures that were used in the 1800s. With Balloon framing and by using two-story-high studs, a two-story house was built. In timber construction, this system was common to be used when long timbers were easily available [16].
- Ledger Framing: this option is similar to the previous one (Balloon option), but the difference that the CFS floor joists are hanged from a ledger connected to the inner face of the wall or studs, and the entire floor has sheathing.

Ledger framing is available for simple floor-by-floor construction, and it can reduce the cost by maximizing the spacing of wall stud and the spacing of floor joist. The load path of the horizontal diaphragm forces can be transferred directly to the vertical walls. Anyway, when the CFS joists are used for the floor framing, then the method is considered as a wide-use method [16].

Additionally, increasing axial loads in the studs with height leads to the more desired use of Ledger framing for multiple-level structures. Therefore, that forces must be transferred by the intersection of stud/joist at the floor levels. But these axial forces cause a web crippling in case of using a platform system, so the stiffeners are required in joists to avoid this phenomenon [16].

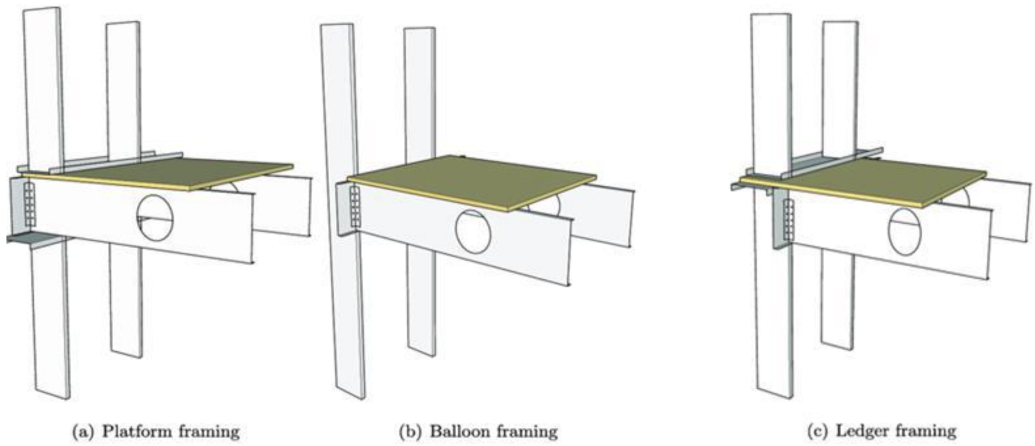

Figure 4. Constriction Framing Options. Source: Reference [17]

III. COLD-FORMED STEEL STRUCTURAL MEMBERS.

There are two major types of CFS structural members 1. individual structural framing members, 2. panels, and decks. Each one of them has a different cross-section, thickness, and properties [1]. CFS sections are generally thin-walled members with a thickness between0.4 mm to 6.5 mm and they offer a very high ratio of load capacity-to-weight over the other structural component [18]. In the past few years, due to the features of CFS which allow for a wide variety of shapes and procedures, cross-sections innovations have started exploiting advanced manufacturing technology and begun to expand the limits of available design methods [13].

3. 1. Individual Structural Framing Members (Bar Members):

Usually, the CFS sections have a depth ranging from (50-70mm) to (350-400 mm) for bar members and with typical thickness from about (0.5 mm) to (6 mm) [1]. For section thicknesses, which typically range from (1.0 mm) to (3.0 mm), yielding stress of the fabricated CFS members is (350 MPa) for normal steel and recently was increased to (550 MPa) for high strength steel [19]. The strain hardening and type of steel used are the reasons for increasing of yield stress. While, the increasing of the ultimate strength is directly related to the strain aging and depends on the metallurgical properties of the material, but with decreasing in the ductility [1]. Another factor that influences the mechanical properties of the CFS members is the availability of various cross-sections for CFS structural members. The most common CFS sections of bar members are:

3.1.1 Single Open Sections [20], [3]:

CFS open section members amenability for torsional deformation is high because of their low torsional rigidity resulting from their thin walls. In addition, the sections are probably exposed to eccentric loading from their shear centers, so they are subject to essential torques, as shown in figure 5. The common CFS open sections are:

- Channel Sections (C-sections) with and without lips (the lipped and plain channel [16]). Where the CFS framing industry has provided some modern variations of typical C sections to be used as studs, headers, jambs, distribution members, and even bracing [13]. In general, it was found that the lipped-channel section has more efficiency than the channel section regarding all the applied load.
- Z-Sections, typically with sloping lips.
- Angles Sections.
- Sigma sections: According to several studies, sigma sections are beneficial for their high load-carrying capacity. Sigma sections have torsional rigidity higher than standard channels. They are light in weight and have a smaller blank size.
- Perforated Sections which are similar to the aforementioned sections but with holes in order to provide room for services. These sections can be used in floor joists and storage rack structures [3], [13], see figure 6.
- Other open sections see figure 7.

Lipped C and Z sections are the most common sections with thickness varying from (0.9mm) to (3.2mm) [9],[21]. The yield strength of these sections is generally between 280 to 450 N/mm2 [7]. They usually used as flexural members in cold-formed design (purlins, girts, etc.) [3]. Other novel sections were developed, such as sections that used in trusses like wide flanges sections, narrow webs sections, sections with intermediate stiffeners, and return lips to be used as chords of the trusses [13] (see figure 8). For non-load-bearing applications sections, cold-formed from knurled steel has been developed (figure 9) which has the advantages of improving the thermal, fire and acoustic performance [13].

3.1.2 The hollow flange beam (LiteSteel Beam):

It was developed in Australia as a unique cold-formed section for use in particular as a flexural member. The typical sections are shown in figure 10. Usually, the flanges are fully welded or fastened to form tubular sections. However, there is another type has the flanges unwelded, and it is much weaker than the welded one [3],[22],[23]. This type of section is highly researched, where it was found that by using closed tubular sections for the flanges of a channel, this section is able to give capacities more associated with hot-rolled, than cold-formed [24][25]. However, as was concluded by the researchers that a high torsional rigidity concentrated in the flanges, while overall extremely beneficial, does lead to specific behavior and interactions more-notably lateral-distortion [26]. The Australian Cold Formed Steel (CFS) Specification provides a novel treatment of this unparalleled CFS building product [13].

3.1.3 Open Built-up Sections:

Some of the aforementioned sections can be joined together to form compound members with open built-up sections such as Wide Flange section (back-to-back lipped channel sections), T-section (back-to-back angle sections), etc. [1], see figure 11.

3.1.4 Closed Built-up Sections:

Some of the aforementioned sections can be joined together in order to form compound members with closed built-up sections such as tubular sections [1], see figure 12.

3. 2. Panels and Decks:

Decks and panels (Corrugated or curved) are made from linear trays (cassettes) and profiled sheets, the depth of panels often ranges from 20 to 200 mm, while thickness ranges from 0.4 to 1.5 mm. A variety of open sections can be used, such as “hat-shaped” deck sections [3], [13], see figure 13.

For increasing the stiffness of both CFS sections and sheeting, intermediate and edge stiffeners are used. These stiffeners act as out-of-plane supports for the flat plate elements; therefore, it can improve the strength of sections.

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The stiffeners can enhance the efficiency of the CFS by up to 50%, according to the study was conducted by [27]. After all, the performance of CFS sections varies with the grade, slenderness ratio, temperature, etc. and it is considered as a popular and effective field of research.

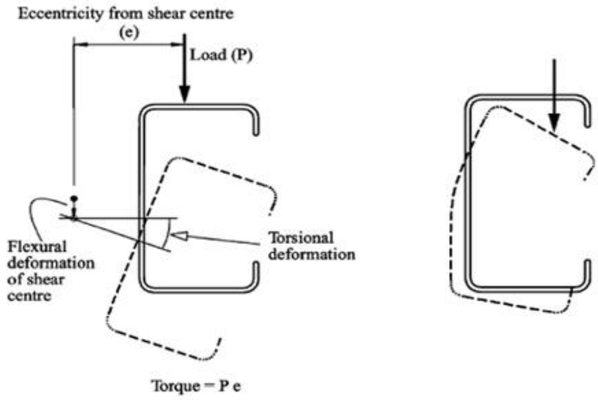

Fig.5: Torsional and Distortional Deformations of Single Open Sections Source: Reference [3].

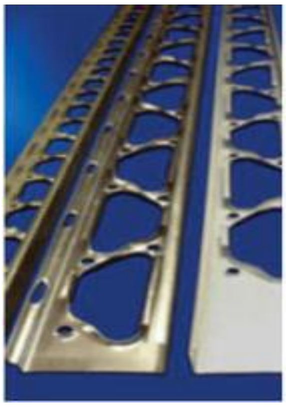

Fig.6: Perforated Sections (SteelForm DEltaStud) Source: Reference [13].

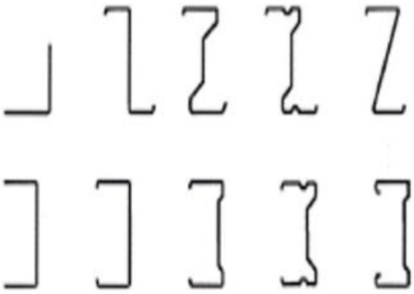

Fig.7: Single Open Section (Source: Reference [1]).

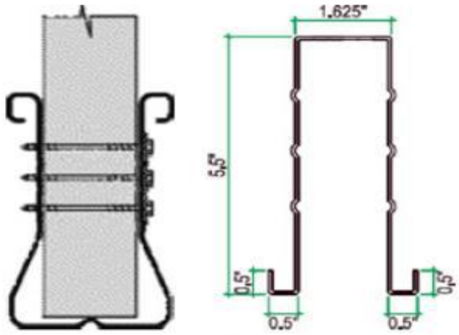

Fig.8: TrusSteel® Dyna Truss Chord and Nuconsteel NUTRUSS® Source: Reference [13][28].

Fig.9: ClarkDietrich UltraSteel® Stud Source: Reference [13]Reference [13][28].

Triangular Hollow Flange Rectangular Hollow Flange (LightSteel Beam)

Fig.10: The Hollow Flange Beams Source: Reference [23].

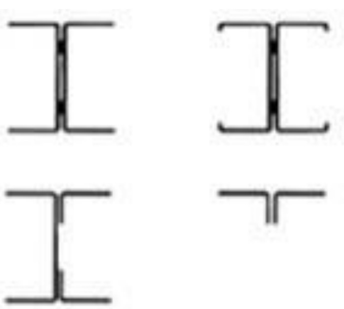

Fig.11: Open Built-up Sections (Source: Reference [1]).

Fig.12: Closed Built-up Sections
Source: Reference [1].

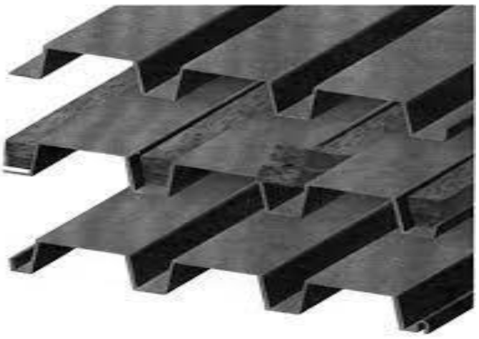

Fig.13: Panels and Decks Sections
Source: Reference [29].

IV. APPLICATIONS OF COLD-FORMED STEEL STRUCTURAL MEMBERS IN ENGINEERING STRUCTURES.

In general, HRS sections are used as primary structural members while CFS sections are used as secondary members to support claddings in forming external building envelopes [19], and these CFS secondary members are connected onto the primary structural members through web cleats as moment or pinned connections, depending on the configuration of connections [30]. Nevertheless, over the past three decades, there is a growing trend to use CFS sections as primary structural members in buildings construction for low to medium-rise residential houses, multi-story commercial buildings and portal frames of modest span [7] (e.g., roof systems, wall studs, girts, purlins, side rails and steel framed housing [7],[4]). It is also being used as minor structural elements in tall buildings and in the construction of infrastructures such as transmission towers, bridge, storage, and drainage facilities, bins, etc. [4],[30],[31], (see figure 14). That is due to the inherent features of CFS which overcome the downsides of conventional products. CFS features such as high weight to strength ratio, adaptability, versatility, non-combustibility, and ease of production have encouraged architects, engineers, and contractors to expand the using of CFS products, that can improve building performance and structural function, in addition, to provide aesthetic appeal at a lower cost [30]. The application of CFS members in the engineering structures can be divided into the following categories:

4. 1. CFS Primary Load Bearing Members:

The primary areas of load-bearing CFS applications are:

4.1.1 Framing:

where CFS used to make the primary structural elements such as columns, beams, roof truss members [9]. CFS members are commonly in lightweight houses and prefabricated structures as load-bearing components [12]. Steel frame buildings constructed with galvanized sections of CFS are usually named as Light Steel Framing. The former system is considered as one of the industrialized building systems, and it has a lot of advantages over the traditional construction methods. As a result, it becomes a common construction choice for medium and low height buildings (see figure 15) as well as residential house constructions [9]. However, various researches have been conducted to reinforce the safety issue and increase the use of cold-formed steel members as primary structural components [9].

4.1.2 Composite sections:

CFS structural members can become even more effective as primary structural members when used in conjunction with other materials, particularly with wood and cementitious materials [3],[31]. For this purpose, there are two common ways which are; 1. use CFS composite beams in concrete slab systems, 2. as wall studs lined with gypsum plasterboard in residential buildings [3]. For example, in residential structures where light steel roofs and floors can be used with light steel composite members, as follows [31]:

- ‘Open’ roof systems using steel-timber composites.
- Light steel-timber floor beams
- Light steel slim floors.
- Gypsum composite floors members with steel lattice joists.

The primary use and benefits of these composite members are in residential buildings or medium-rise constructions, where the advantages of lightweight and longer spans availability can be realized [31].

4.1.3 Lateral Loads Resisting System (LFRS):

CFS can be used for some or all parts of the lateral load systems in some of the construction types. for example [16]:

- Structures with light-frame bearing walls where the gravity systems are constructed by using CFS joists or trusses and supported by CFS load-bearing walls in addition to the lateral load resisting systems using CFS strap-braced walls or shear walls.

- Podium-Structures with CFS light-frame, where there is the ability to build the load-bearing structure atop lower levels of different constructions, such as steel or concrete structures.
- Hybrid structural systems where the primary gravity systems, diaphragms, and collectors have CFS trusses, joists, and load-bearing walls. Whereas for the vertical components of the lateral load resisting systems, moment resisting frames, concrete shear walls, structural steel braced are used.
- Penthouse structures that are used at the top levels of steel or concrete buildings; the penthouse structure is generally considered as an architectural component instead of considering as a part of the building's lateral load resisting system, and it is designed under ASCE 7 Chapter 13.

CFS framing resisting systems are typically considered as one category of the following [16]:

- Shear walls with wooden panels (oriented strand board (OSB) or plywood) connected CFS tracks and studs.
- Shear walls with steel sheet sheathing connected to CFS tracks and studs.
- Wall systems of CFS light-frame strap-braced member (tension braced walls, diagonal).
- Special Bolted Moment Frames (SBMF).
- The products which are not recognized by American Standard for Seismic Design of CFS Structural Systems (AISI 2015b), and AISI S400-15, in addition to shear walls with steel sheet connected to other sheathing materials, for example, gypsum board.

4. 2. CFS Secondary Load Bearing:

Generally, in the steel buildings, the secondary system can be provided by the CFS members [3],[9],[13],[19]. For instance, CFS decks and corrugated panels were used for a long period, but recently more development has been obtained on corrugated curved panels, and they are widely used in steel arch kinds of buildings e.g., farm building. They serve as both the secondary structural system and the building envelope providing economic designs and duct facilities for the electrical, heating and air conditioning system.

These curved and corrugated panels usually contain transverse corrugations that serve to bend the thin-walled steel sheet into a curved shape and simultaneously act as a stiffener. However, assessment of the strength of these corrugated and curved panels is difficult. Furthermore, researches that work on these secondary systems remain active (particularly with purlins) [3], [13].

Another usage of CFS sections as secondary members is providing lateral restrictions of the braces by cold-formed steel studs (CFSS), see figure 16. Oguz et al. [32] investigated the performance of CFSS by conducting an experimental study and the cyclic inelastic performance of concentrically braced frames with and without CFSS infills designed to laterally restrain braces and delay their buckling. The results showed a significant increasing in the cumulative energy dissipation of the braced frames at the same level of ductility when CFS members are used for laterally restraining the braces against buckling.

4. 3. CFS Application in Storage Racks:

Steel storage racks are one of the major applications of cold-formed steel. CFS storage racks are remarkably efficient structures with novel cross-sections (usually perforated sections) and connections in their design. Although the connections and members have not changed significantly in the last few years, understanding of behavior and translating that understanding into improved designs have been very active. The down-aisle strength and stability are very important factors in storage rack design. Beam to column joints significantly affects this stability, since the structures are usually unbraced in the down-aisle direction to allow for loading and unloading of pallets [3], [13].

Some studies on storage racks provide valuable information related to the sway and seismic behavior of racks, such as Baldassino and Bernuzzi [33], Bernuzzi, and Castiglioni [34], etc.. Moreover, Significant new testing has been conducted on uprights [35], [36], upright to shelf beam connections [37], [38], and base plates [39]. Testing protocols have become formalized [40], as well as analysis protocols, particularly in the use of second-order analysis [41], [42].

Other concerns, such as impact forces [43], [44], and progressive collapse [45], have also been studied. Standards organizations supporting the CFS rack industry are active and progressive, that because of the complicated nature of rack structural performance. For instance, the Australian rack standard (AS 4084) provides complete codified guidance on performing material and geometric nonlinear analysis on the imperfect structures (GMNIA), similar in spirit to Eurocode for shell structures [13].

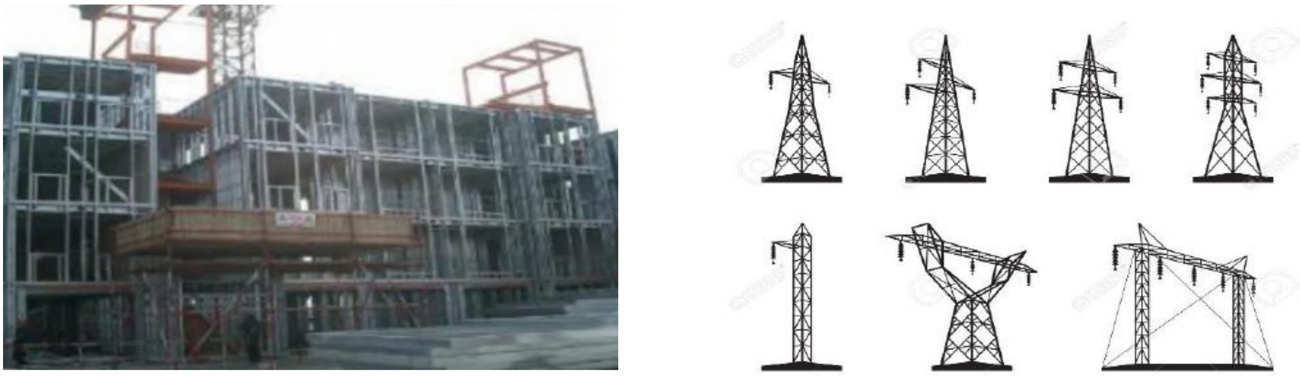

Fig.14: Some of CFS Applications Source: Reference [30] + 123RF Website [136]

Fig.15: Mid-rise CFS Framing
Source: Reference [127]

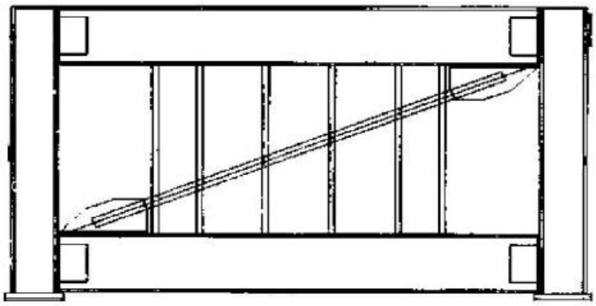

Fig.16: Lateral Restrictions of The Braces by CFS Studs
Source: Reference [32]

V. COLD-FORMED STEEL CONNECTIONS.

The connection is the physical component that mechanically fastens the structural components and located where the fastening action occurs [46]. Therefore, the connection transfers the forces from the structural member to the supporting elements [9]. Accordingly, structural joints are classified into several categories by referring to its strength and stiffness to be able to transfer that forces [9].

Connections serve as important elements for light steel framing in order to achieve its structural stability. Compared to HRS sections, CFS connections perform dissimilarity [9]. As known, CFS sections are typically made of thin-walled elements, which consequently reduces the stiffness and ductility capacity of CFS structures because of the buckling behavior, resulting in limited structural applications in seismic areas [47]. Furthermore, relatively low strength and stiffness of the joints of the conventional CFS stud-wall frame systems [48] highlights the need for more investigations and improvements in CFS structures' connections [49].

There are nine types of joints which are commonly used in the construction industry of CFS structures [15], namely, bolts, blind rivets, self-tapping screws, powder actuated pins, puddle welding, spot welding, clinching, nailing, and self-piercing rivets [9].

In this section, the current researches on the CFS connections will be discussed, particularly for bolted connections, screwed connections, piercing connections as well as the application of CFS in slotted track connections, steel roof truss end-connections, and portal frames (eaves, apex, and base) connections. The investigations of the structural behavior, strength, ductility, energy dissipation, seismic performance, failure mode, and other issues over the last few years will be reviewed, but because of the wide research area of the CFS connections, limited number of researches has been selected to clarify the importance of CFS in the structural engineering application as follow:

5.1 Bolted Connections:

The bolted connection is widely used as a fastener in steel constructions of both HRS and CFS [9]. In CFS structures, bolted connections provide ductility, energy dissipation capacity, and resistance to the moments, tensile, and shear loading [49]. Nevertheless, the development of a bolted

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connection with a targeted design performance requires addressing many types of uncertainties. These include both physical and design deficiencies such as frictional coefficient, bolt pre-tension, positioning of bolts within their holes, instantaneous center of rotation (ICR) as well as precise force distribution within a bolt-group [49].

Shahini et al. [49] and Jun et al. [50] presented a detailed investigation on a new configuration of CFS bolted moment MR-connections, where the dissipated energy is mainly through bolted connections. The aim of incorporation of a friction-slip mechanism into a slotted bolting type of connection is to; postpone local buckling, improve ductility and seismic energy dissipation capacities [49],[50]. By means of validated finite element analysis, both cyclic and monotonic performance of CFS connections comprising two types of circular (CB) and square (SB) bolt group arrangements are studied comparatively without and with slip at various levels [49], see figure 17. Higher energy dissipation capacity is provided by the connections with slip comparing with the connections without slip by about 75% [49], see figure 18. CB connections produce more uniform bolt-group force distribution that is closer to the idealized method, while the SB connections encounter a significant delay of up to 30% in activation of bolt group slip that could lead to unfavorable beam local buckling [49]. By using a bolting friction-slip mechanism, the ductility, energy dissipation capacity and damping coefficient of the connections can significantly be increased (up to 200%) especially for CFS beams with thinner plates [50].

Jun et al. [51] studied the seismic performance of CFS connections by investigation of the effects of bolt arrangement, cross-sectional shape, and gusset plate thickness under cyclic loading. The results indicated that, for the same amount of material, increasing of ductility and energy dissipation capacity up to 100% and 250%, respectively, by using folded flange beam sections with diamond or circle bolt arrangements compared to conventional flat-flange sections with square bolt arrangement, see figure 19. In addition, reduction of the moment capacity of the connection is possible by using gusset plates with the same or lower thickness as the CFS beam.

Rinchen et al. [52] investigated the flexural behavior of apex, eaves connections for CFS single C-section portal frames by conducting a series of connection tests and analyses of finite element models. It was clear that the apex connections reached their ultimate load capacities after inelastic buckling near the compression flange-web junction of one of the adjecnt beams, while the eaves connections attained its ultimate load capacities upon ply bearing of M8 bolts on the C-section, see Figure 20. Lim et al. and Kwon et al. [53], [54] also studied the behavior of bolted connections in portal frames structures.

Yancheng et al. [55] Investigated the effects of end distance on thin sheet steel (TSS) bolted connections. It was found from the experiment that by increasing the end distances up to three times and five times the bolt diameter, the ultimate loads were increased for single shear and double shear, respectively. In addition to the behavior of bolted connection in multi-span of purlin was investigated by several studies [56], [57]. Many researchers investigated different aspects of bolted connections from various viewpoints such as:

1. the behavior of beam-to columns connections to predict the strength and stiffness of the connection [58],[59], [60],[61],[62]. 2. the stainless CFS bolted connections [63]. 3. the carbon steel bolted connection [128]. 4. the failure mode of the bolted connection [64]. 5. The tensile strength of bolted CFS channel section [65]. 6. Lateral-torsional buckling and plastic behavior of single CFS channels bolted back to back bolted connections [129].

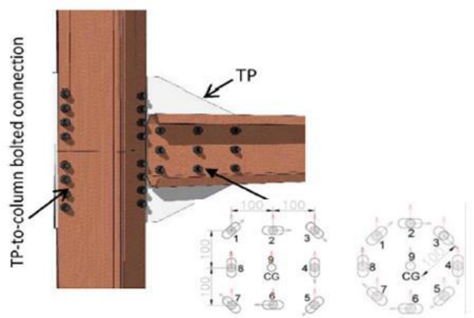


Fig.17: CFS joints with SB and CB bolting. Source: Reference [49].

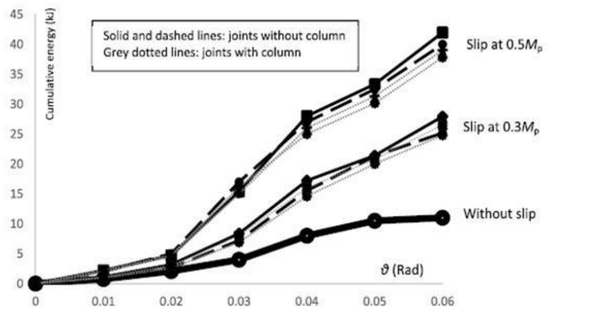
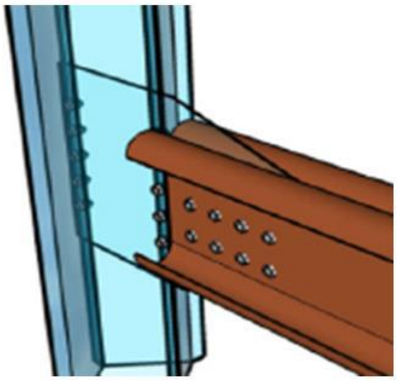
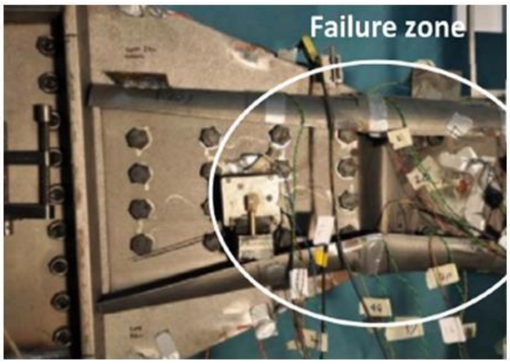


Fig.18: Cumulative energy dissipation curves of SB (solid line) and CB (dashed line) connections without slip and with slip levels Source: Reference [49].

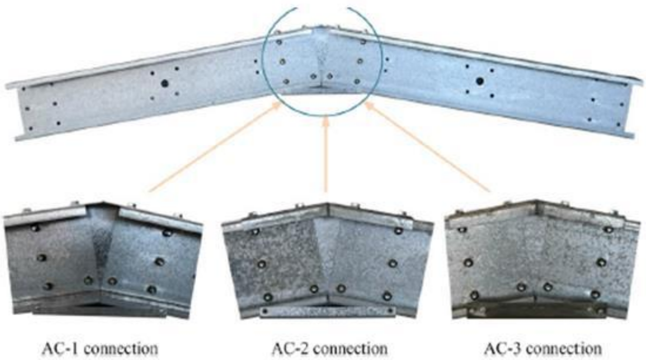


(a)

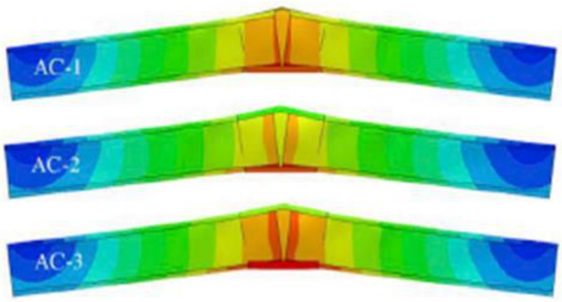


(b)

Fig.19: a) Folded-flange, b) Failure zone. Source: Reference [51]



(a)



(b)

Fig.20: a) Apex connections with fastener configurations, b) Deformation of specimens at ultimate moment.
Source: Reference [52]

5.2 Screwed connections:

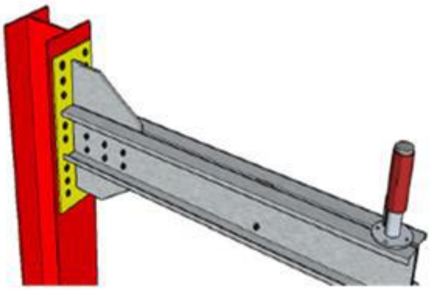
Screwed joints are effective and suitable when applying to the CFS sections with the condition that the total thickness should not give difficulties to the self-drilling process [9]. For steel-to-steel connections, although provisions exist to accommodate the use of screws in shear and tension, the predominant application of screws is in a shear mode [66].

Fiorino et al. [67] assessed the effect of screw diameter and thickness profile on the screwed connection response with reference to gypsum and cement-based solutions by conducting an experimental study of these connections for sheathed CFS structures with gypsum or cement-based panels. It was observed that the increment of the steel profile thickness and screw diameter did not produce an apparent increasing of strength. Bondok et al. [68] investigated the failure capacities and the energy absorption capabilities of roof truss end-connection with different screw configurations. It was found that the screw configuration and the direction of loading strongly affect the toughness (energy absorbed to failure) of the end-connection.

As known in roof battens and with multiple screw connections, the pull-out capacity cannot be calculated directly depending on the number of screw fasteners. Therefore, Mayooran et al. [69] investigated these capacities of two and four-screw fastener. The results showed 40% and 29% improvement of the total pull-out capacity of roof batten to purlin/rafter connection when two- and four-screw connections were used, respectively. Mahyar et al. [70] examined experimentally a beam-to-column connection by using a self-drilling screw in order to provide a failure mechanism for the CFS structure's connection. The results indicated a decrease of the plastic and maximum deformation while there was an increase in the maximum moment and stiffness when the profile thickness of the beam increased, see figure 21.

Ayhan et al. [71] conducted full-scale experiments to investigate the moment-rotation behavior of floor-to-wall connections which were used in ledger-framed CFS building. Pull-out of the ledger to joist screws has been only observed without floor sheathing present, see figure 22.

Screwed ridge joints were also studied under wind at roof pitch conditions [72]. In addition to the behavior of screwed connections was also studied from different viewpoints. [73].



(a)

(b)

Fig.21: Self-drilling screwed connection and failure mode
Source: Reference [70]

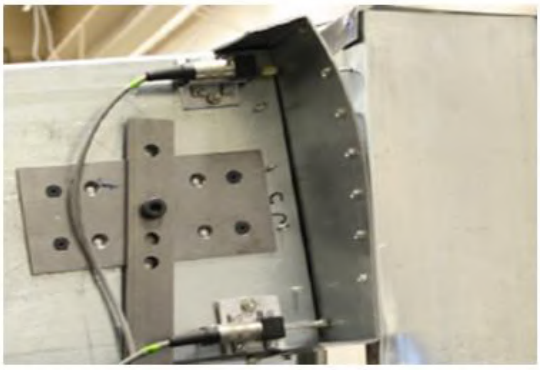


Fig.22: Fastener pull put failure mode.
Source: Reference [71]

5.3 Self-piercing riveted (SPR) connections:

SPR connection method is a practical and common method in the field of automotive and machinery industries. Furthermore, high strength, high stiffness, efficient installation, and anti-fatigue behavior are some advantages of SPR [74]. Most studies on SPR using numerical and testing methods concentrated on process parameters, mechanism of forming, fatigue, and mechanic performance [75].

Zhiqiang et al. [76], presented an experimental investigation of (CFS) shear walls with (SPR) and studied the effects of rivet spacing on mechanical behavior as well as failure modes of CFS shear walls. It was concluded that the rivet spacing at the sheet edges was a very important factor affecting the failure modes (see figure 23), and mechanical properties of CFS shear walls, where the relationship of shear strength and ultimate deformation decreased linearly with the increase of the rivet spacing.

In Zhiqiang et al. [75], tested 78 SPR joints to evaluate the quality and shear strength. The results indicated that the failure mode was greatly affected by the sheet thickness and sheet thickness (see Figure 24), and the rivet length was an essential factor that affects the shear properties of SPR connections.

Many types of research have studied the behavior of SPR connections from different viewpoints, such as 1. Rivet diameter and length effects [77],[78],[79]. 2. Fatigue performance of SPR joints [80],[81]. 3. Hybrid SPR joints made of aluminum alloy composite materials [82]. 4. the structural behavior of SPR connections [83].

5.4 Slotted track connections:

Slotted tracks are widely used in building constructions. These connections do not require additional materials to reach the desired performance [84]. Espinoza et al. [84], proposed equations depending on mechanics. These mechanics-based equations can estimate the design strength of cold-formed steel slotted tracks for out-of-plane loads resulted from connected studs. Testing suggested that under the maximum differential displacement of the adjacent floor, the equations in the paper predicted lower values of the slotted track flange deflection. But, the strength of the slotted track flange may be greater.

Slotted tracks which have similar material properties and cross-sectional shapes, are produced by many manufacturers (Bailey Metal Products Limited [137], Brady Innovations LLC [138], CEMCO [139], Clark Dietrich [140], SCAFCO [141], and Steeler [142]) [84].

5.5 Other types of Connections:

5.5.1 Welded Connections:

Welded joints offer rigid joints between CFS members. In this case, welding operation requires skilled workers. It is also served with extra care as compared to other joints. Many types of research conducted on laser beam welding (LBW) [85], stainless steel welding [86], and other welded joints [87], [88], are listed in this review but not discussed in details.

5.5.2 Storage Racks Connections:

CFS members are the main components of Storage rack structures. As a result of the similarity between the storage rack systems and the light steel frames, the design parameters have an equivalent value [9]. The behavior of the main members of racks was investigated, in addition to

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the assessment of the performance parameters in terms of beam-column connections [34]. Many other studies have been conducted on the Storage Racks Connections from many structural viewpoints [33], [89].

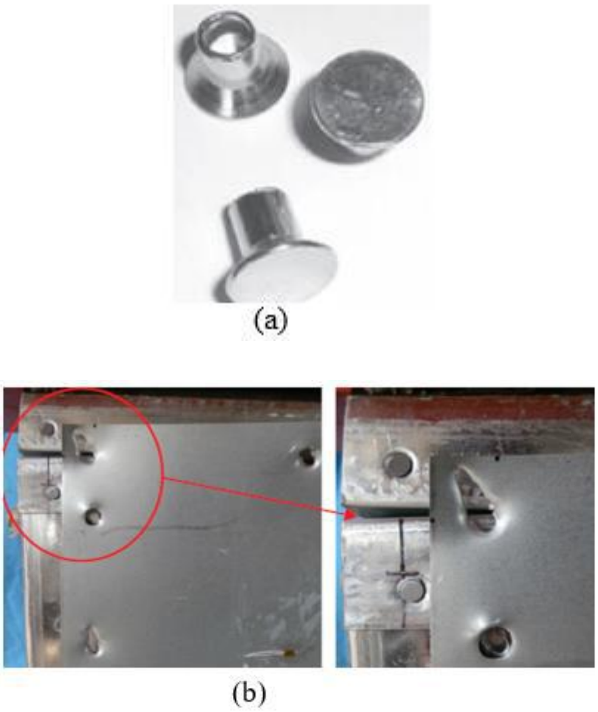

Fig.23: a) Real products. b) Failure mechanisms of SPR connections in walls.
Source: Reference [76]

Fig.24: Failure mode of SPR connections.
Source: Reference [75]

VI. THE BEHAVIOR OF CFS STRUCTURES:

Understanding the behavior of CFS is very critical in order to obtain a safe and economical design. The behavior of CFS structures is more complicated compared with the conventional HRS structures due to 1. The thin-walled nature of the CFS sections which make them be highly influenced by the interaction of different types of buckling (failure patterns). 2. The post-buckling behavior of CFS structural members which is different from HRS structural members. 3. The changes in the mechanical properties of CFS members due to the cold work of the formation of the CFS sections.

6. 1. Failure Patterns:

6.1.1 Buckling:

In CFS members, bucking is an essential design criterion which should be taken into consideration. Compression, shear or bending loads cause the buckling of CFS members. The basic modes of buckling are [3],[30]:

- Local Buckling: is a buckling mode that involves only the plate flexure regardless of the line transverse deformations or lines of intersections of the adjacent plates.
- Distortional buckling: this buckling mode is essential in the stability when high strength thin steel sections are used. In this buckling mode, a change in cross-sectional shape is involved, excluding local buckling.
- Global buckling mostly occurs in columns and beams without any observation of cross-sectional distortion. Flexural and lateral-torsional buckling may also exist in the member [90].

The previously mentioned buckling modes are also able to interact with each other. Yu and LaBoube's book [15] discussed these buckling modes as well as the thin-walled nature of these cross-sections.

6.1.2 Web Crippling:

Web crippling is an essential failure criterion for cold-formed steel members. The rounded corner of the CFS members is one of the causes of loading eccentric from the web centerline resulting in the occurrence of the web crippling, in addition to the slender and unstiffened webs which differ than the hot-rolled design where the web is often strengthened by stiffeners [3],[30].

6. 2. Post-Buckling Behavior:

Although the CFS members would deform and subject to different types of buckling, the substantial post-buckling load can be taken by these members due to the transverse membrane stresses, which developed with deforming of the plates [16], see figure 25. It is well known that there is a significant post-buckling reservation in the local buckling, a modest post-buckling reservation is in the distortional buckling, and a minimal post-buckling reservation is in the global [16],[11]. Therefore, new thinking is required for the post-buckling capacity, accompanying a new design approach and conducting experiments for validation of these approaches, for example, the effective width method (Winter 1947) [16] or the more recent Direct Strength Method (DSM) [11].

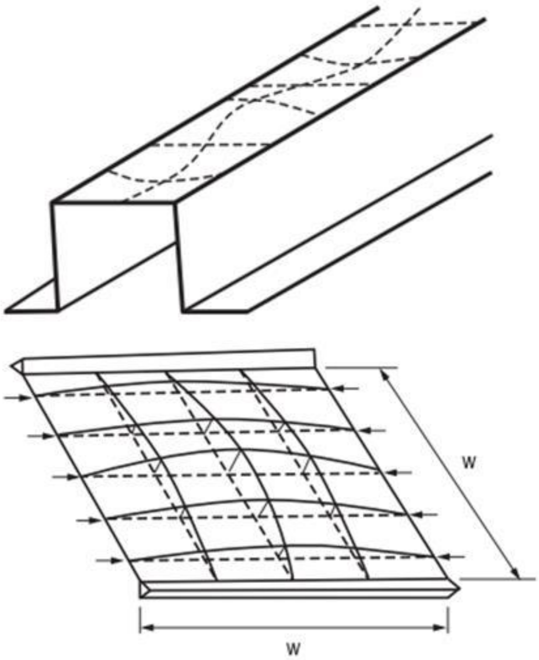

Fig.25: Winter's depiction of local buckling in the compression flange of a hat-shaped cold-formed steel beam and his grid model for explaining how transverse membrane stresses create the source of post-buckling strength in plates under load.
Source: References [16].

6. 3. Mechanical properties:

The manufacturing process and chemical composition of steel strongly affect the structural behavior of steel. In Hot rolled Steel (HRS), design standards accurately provide the mechanical properties of normal and high temperatures. However, the mechanical properties of CFS are different than HRS; that is because of the forming process. Generally, the yield and ultimate tensile strength of CFS are increased because of the forming procedure, but the tensile elongation capacity is decreased. The mechanical properties of CFS are also affected by the available and various cross-sections. In fact, there are three main reasons that change the CFS mechanical properties during the forming, which are: 1. Strain hardening, 2. Strain aging, and 3. Bauschinger effect. Strain hardening is considered as a steel strengthening since the plastic deformation results in changing the crystal arrangement of the materials. When steel is subjected to aging, its maximum load-carrying capacity increases after the elastic range stressing, this is called Strain aging. Bauschinger is considered such a phenomenon in (1887) [3],[90].

Actually, the mechanical properties of CFS are mainly affected by the strain aging and strain hardening. From figure 26, it is obvious that there is increasing in tensile strength and the yield strength after pre-straining and aging of the steel, but there is a reduction in elongation or ductility [30].

At high temperatures, the fire resistance of CFS is mainly influenced and controlled by the mechanical properties of CFS, such as the yielding strength and modulus of elasticity. Therefore, the affected mechanical properties make the CFS elements more sensitive to buckling. Important guidelines and codes take the effect of fire on CFS structures into consideration by assigning specific reduction factors as temperature increases. These reduction factors of CFS are higher than that of HRS due to the effects of molecular surface metallurgical composition [12],[90].

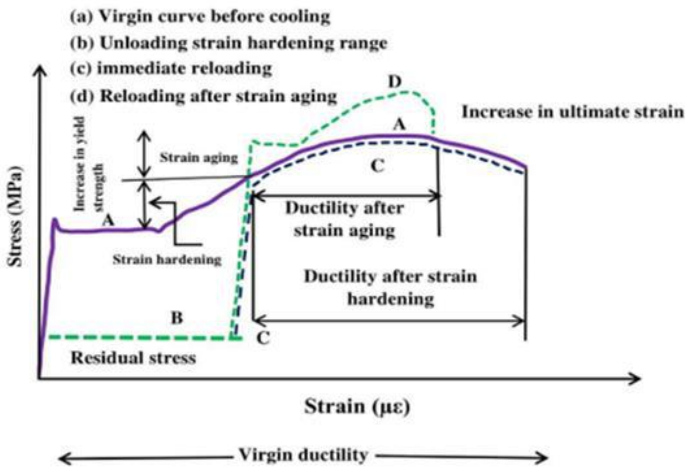

Fig.26: Effects of strain hardening and strain aging on typical stress-strain characteristics of structural steels.
Source: Reference [90].

6. 4. Review of the Related Researches:

Over the past three decades, massive researches have been conducted on the CFS structures due to its increased applications in the construction industry. These studies investigated the reliability and stability of the constructed steel structures. This section reviewed the investigations of the CFS behavior, failure mode of the CFS members, and mechanical properties (strength and stiffness) of the CFS members, as follow:

Martins et al. [91] studied the buckling, and the distortional failing modes of CFS simply supported beams under uniform bending. This article also investigated the factors that influence the distortional post-bucking behavior and ultimate strength, such as the flange-web ratio, lip-flange width ratio, and the critical distortional half-wave number. The results showed that the previous factors, in addition to the end support conditions, play essential roles in the behavior of the analyzed beams.

Zhou et al. [92] established a new formula of buckling by presenting an analytical approach, where this formula can take into consideration both of the effects of end condition and column length. The results showed that for both fix and pin-ended columns with practical length, this formula successfully estimated the distortional buckling load. Also, the consideration of column length and end condition effect in this formula could make the formula estimate the buckling strength reasonably.

Gardoso et al. [93] studied the distortional buckling critical stress of the lipped channel columns under uniform compression and presented rational explicit formulas. The results showed that some cross-sections are usually not practical in applications. For example, sections that have bf/bw < 0.3 usually display very low global buckling critical loads, whereas sections which have bf/ bw > 0.8 and bs/ bw < 0.1 do not have a high efficiency against distortional buckling, which causing lower critical loads.

Ajeesh et al. [94] studied the contribution of the buckling modes, including the primary (global, distortional, local) and secondary modes, by presenting a mode identification technique depending on the spline finite strip method (SFSM). The results showed that the proposed technique successfully quantifies the participation of various buckling modes. In addition to the availability of comparison between the mode participation and mode identification with the aid of generalized beam theory (GBT) and finite strip method (FSM).

Martins et al. [95] characterized the post buckling behavior and the ultimate strength of beams subjected to the interaction effects of severe local-distortional (L-D) buckling by carrying out a systematic numerical investigation. The results showed a high qualitative similarity between the local-distortional coupling effects in columns and beams. Also, two types of L-D interaction were discovered – "true L-D interaction" and "secondary (local or distortional) bifurcation interaction."

Cheng et al. [96] investigated the buckling behavior of CFS beams with channel section and plasterboard protection, and these beams are exposed to fire on one side with uniformly distributed loads. Three phases are involved in this work, namely buckling analysis, pre-buckling analysis, and heat transfer analysis. The results indicated the significance of the temperature variations in fire exposed flange, web, and lip. Also, a different effect was observed on the buckling behavior of the beam between the cases of the temperature variation and the constant uniform temperature on the beam section. When the beam is exposed to the fire only on its tension side, then the compression zone will be reduced, with increasing of maximum compressive stress on the flange, which is not exposed to the fire.

Chen et al. [97] carried out an experimental and numerical investigation to study the structural performance of pin-ended CFS columns with the elliptical hollow section buckled about the minor axis. The parametric study also was performed though out developing a finite element model (FEM) to replicate the main test results. Furthermore, more improvement was proposed by modification of the Direct Strength Method to obtain more accurate design strength predictions. The validation results showed that the model gives an accurate prediction of the behavior of CFS columns with the elliptical hollow section buckled about the minor axis.

Jun et al. [98] studied experimentally the interaction between the local and overall flexural behavior in CFS lipped channels subjected to axial compression. The results were used to evaluate the accuracy of the design procedures in Eurocode 3 predictions by comparing it with the experimental results. It was clear that a combination of the effective width approach with the P–M interaction equation, which was proposed in Eurocode 3 for taking into account the eccentricity of the effective centroid, provided consistent and safe results.

Yuan et al. [99] investigated the distortional buckling behavior of the perforated CFS beam with channel-sections and circular holes in its web. The effects of those holes on the distortional buckling, corresponding critical stress, and the moment of perforated CFS beams were also discussed. The numerical and analytical results showed a decreasing in a critical moment of distortional buckling of that beams with increasing of the hole size, but there was an increasing in the half-wavelength associated with the critical moment with increasing of the hole size.

Xu et al. [100] investigated the influence of corrosion degrees and types of CFS thin-walled on the mechanical properties. The results showed that pitting corrosion has a flat fracture mode, whereas the overall corrosion has various fracture modes, such as staircase, circular, and oblique fracture. Also, it was observed from all the pitting specimens that the necking segment and yield platform disappeared. Whereas only at 36.14% of corrosion rate, the overall corrosion specimens were occurred, in addition to decreasing the strength and elongation by 21%, 70%, respectively.

Kesawan et al. [101] conducted experimental studies to figure out post-fire mechanical properties of CFS hollow sections of different grades and thicknesses. Yield strength, post-fire stress-strain curves, elastic modulus, ultimate strengths, and their reduction pattern were provided by the results. The results showed that the post-fire mechanical properties of CFS hollow sections differ from that of open CFS channel and hot-rolled (HRS)

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sections. When the hollow sections exposed to temperatures of 600,700 and 800 °C, they would be able to retain 74, 66, and 55% of their ambient temperature capacity, respectively. Whereas, the elastic modulus remained with the same value even after heating up to 500°C. After 800 °C, the steel could recover more than 80% of its ambient temperature elastic modulus value.

Li et al. [102] carried out coupon tests to present the material properties of high strength CFS at elevated temperatures up to 1000 °C. Therefore, both steady state and transient state methods were used to obtain elastic modulus, yield stress, thermal elongation, ultimate strain, ultimate strength, and fracture strain as important material properties. It is found that the retention factors of EC3, AISC Specification, and BS 5950 derived for hot-rolled steel (HRS) materials for the yield stress are not applicable for the high strength CFS materials discussed in this research. Furthermore, it is clear that the design proposals for the ultimate strength, elastic modulus, stress at 2.0% strain, and 0.2% proof stress at high temperatures are mostly conservative for both high strength CFS and high strength HRS materials.

Matsubara et al. [103] derived the design rules of CFS members subjected to axial compression after reaching the modes of local-distortional buckling (L-D). A wide range of (L-D) slenderness ratio was taken into consideration to obtain the strong and weak interaction conditions of L-D through the numerical results. The results showed that for the structural design of lipped cold-formed steel columns, the direct strength method is applicable to be applied as a design concept.

VII. DESIGN OF THE COLD-FORMED STEEL STRUCTURES:

AS prementioned, most of the CFS members exhibit slender cross-sections and are typically thin-walled. Therefore, the CFS members are more vulnerable to various individual buckling phenomena. In fact, the instability phenomena which take the member geometry and loading into consideration may be critical and leads to complicated design [10],[91]. Moreover, in some codes, the CFS sections are largely restricted to be treated as individual members under typical and ideal conditions. Therefore, it is very necessary and essential to handle the difficulties of the CFS element's behavior by establishing safe and accurate design approaches. [104].

7.1 Design Approaches to CFS Structures:

In past years, many countries have built national design specifications of CFS structures due to the extensive research efforts and product development. Basic design methods such as Effective Thickness, Reduced Stress, the Q-factor approach, the Erosion of Critical Bifurcation Load approach championed by Dubina for CFS members are currently available in that specifications, but they are not detailed here [10]. In this section, the Direct Strength Method (DSM) and the Effective Width Method (EWM) and will be explained, as they are considered the most efficient and recent used methods.

7.1.1 Effective Width Method (EWM):

The effective width concept is considered as the base of investigating the local and distortional buckling of thin walled members subjected to bending and compression for unstiffened and stiffened members of the design standards and specifications. The effective width method depends on forming the cross section of the element as an isolated cross-section, so this method is considered as an elemental method [3]. In 1932, it was originally proposed by Von Karman et al. [130], and then it was modified by Winter [131]. The main idea of the effective width method is that the effectiveness of the plates which comprise a cross-section is reduced due to the local buckling [3],[10].

- Advantages and Disadvantages of the (EWM):

The effective cross-section 1. illustrates the locations in the model where the carrying load capacity of cross-section is ineffective, 2. clarifies the local buckling effect on the concept of neutral axis shifting and 3. provides sufficient and clear ways to take the local-global interaction into consideration where properties of the reduced cross-section affect global buckling (some standards usually simplify this interaction) [10].

Further, the (EWM): 1. disregards the equilibrium and compatibility of the inter-element (e.g., between the flange and web) in determination of the elastic buckling behavior, 2. incorporation of competing for buckling modes, e.g., distortional buckling can be unsuitable, 3. heavy iteration process is required for determination of the basic member strength and 4. more complicated determination of the effective section associated is needed with the need for more attempts to optimize the section. The EWM is a useful design method, but it is strongly tied to the stability of the classical plate and creates a special design methodology that differs from the design of conventional HRS. Therefore, it may prevent the use of some materials by some engineers in different situations [10].

- Codification:

(AISI-S100 2010) North American specifications for the design of CFS structures and Australian/New Zealand standard for the CFS structures (AS/NZS4006 2005) both consider an effective width method in the design as well as Eurocode 3 (1) Parts 1-3 and 1-5 (EC3-1e3 and EC3-1-5.

Chinese technical code of CFS thin-walled structures (GB50018-2002) [132] also uses the effective width method.

7.1.2 Direct Strength Method (DSM):

The designation "Direct Strength Method" (DSM) was first mentioned in the pioneering work of B.W. Schafer1 and T. Peköz2 (1998) [105] related to developing new design approaches for cold-formed steel beams. Twenty years ago, the (DSM) alternated the traditional design methods and became as an effective alternative for CFS thin-walled members. DSM may be considered as one application of methods that are used in structural design depending on generalized slenderness concept [106]. The importance of the DSM to design the thin-walled members in general (not necessarily CFS) and structural systems spread quickly around the world and leads to an abundance of numerical and experimental investigations aiming to validation, codification, and development of the design methodologies based on DSM for various structural problems [107].

The DSM provided a consolidated approach for CFS members design subjected to bending (columns) and compression (columns) exhibiting distortional, global, and local interactive failures [107].

- Advantages of DSM:

After comparing DSM with EWM, four major advantages of DSM can be concluded, all stemming from the concept that viewed the cross-section as a whole. Indeed, DSM (1) automatically takes the wall-restraint effects into consideration, which is different than EWM, where the wall-by-wall approach is used. (2) no cross-section classification or effective width calculations are needed, (3) there is the possibility to provide the strength estimation for members which fail in distortional modes (distortional buckling is considered as an independent limit state), and (4) can directly take into consideration the interactions of the buckling mode. Additionally, the DSM can provide a systematic and rational framework to design the structural systems comprising of thin-walled (not only members) made of different materials (not only CFS) [106],[107].

- Codification:

In 2004, North America (AISI, 2004) codified the DSM, then simultaneously considered in the Australian/New Zealand standard (AS/NZS, 2005). After a few years, it was also adopted in Brazil (ABNT, 2010) [107]. AISI S100-16 also codified DSM by moving DSM provisions from the Appendix and combine them with the main specification [106].

7.2 Application and reliability of the Design Approaches.

7.2.1 Design of CFS members (Beams and columns):

In this section, the review will show many types of research are implemented to design CFS members in the last few years, particularly with DSM and EWM, but the former has more researches recently. The majority of the new researches in this review, which related to the Design methods, is based on the DSM.

- Beams and Purlins:

Starting with the EWM studies which are related to the buckiling design of CFS sections (Beams-Channels), Yu et al. [108] proposed a design method depending on the Effective Width Method (EWM) in order to determine the nominal distortional buckling strength of CFS members shaped as C and Z sections under bending load. More comprehensive limit states were covered by the conventional design approach because of the proposed method. The former proposed method is calibrated by the flexural distortional buckling strength, which predicted by the DSM, and it presented the same accuracy level and reliability of the Direct Strength Method.

Xingyou et al. [109] proposed a method in order to improve the efficiency of the effective width method EWM by using the energy method and deflection theory aiming to find the distortional buckling strength of cold formed steel lipped channel members. In the Chinese Technical code of CFS thin-walled structures (GB50018-2002), a comparison conducted between the effective width method and the energy method to get the post-distortional buckling strength. The comparison results indicated the efficiency of the energy method and concluded that the EWM formula in Chinese code could calculate the post distortional buckling strength, it is also accurate and reliable in evaluating the load-carrying capacities regarding the distortional-buckling and design of the CFS lipped channel members.

In the design of cold rolled purlins, Nguyena et al. [110] studied the design of new cold roll-formed C and Z sections to be used as purlins members, and they are namely as UltraBEAM™2 and UltraZED™2, which were developed by Hadley Industries plc. The results presented a high agreement between the values of the test and Direct Strength design and concluding that the DSM is a sufficient tool to optimize and design of the new cold roll-formed C and Z purlins.

Hadjipantelis et al. [111],[112] investigated the design of Pre-stressed CFS beams. Design failure criteria of the CFS beam and cable are developed through employing interaction equations integrated with the DSM. Subsequently, a reliability analysis was conducted in order to illustrate that the developed design recommendations are valid to obtain a safe design of the studied prestressed CFS beams.

Anbarasu [113] investigated the design of CFS closed built-up beams which composed of two sigma sections aiming to study the local buckling behavior. The predicted flexural resistances obtained by the current DSM were compared with those predicted by the proposed DSM for built-up beams. The results indicated that the predictions of current DSM are not safe, and they dispersed for slenderness (low and moderate local) which is less than 1.5. The proposed DSM regarding the local buckling is more efficient for prediction of the moment capacities for cold-formed steel closed built-up beams. Many other studies have been conducted on the CFS beams design using DSM such as Kyvelou et al. study [114], Camotim et al. study [107], etc.

- Columns:

Martins et al. [104] proposed an efficient design approach based on DSM in order to investigate the L-D interactive failures of columns. It was also indicated that the distortional design curve of DSM, which is currently codified, can adequately predict the failure loads of columns which subjected to secondary local bifurcation L-D interaction (SLI).

Roy et al. [115] conducted a comparison between the column strengths (back-to-back CFS channel sections) and the design strengths calculated using the Direct Strength Method, AISI & AS/NZS, and Modified Direct Strength Method. Both the experimental and FEA results were higher by 53% than the design standards when λc (nondimensional slenderness) was used for calculating the design capacity of those columns.

Chen et al. [97],[116] conducted an experimental and FE study on the elliptical hollow section EHS members subjected to compression loads (no design rule is available or codified currently) (see figure 27). Modification on the Direct Strength Method was proposed in this study, aiming to predict more accurate design strength and reach more improvement of that predictions. As a result, the adoption of the Modified Direct Strength Method design equations to predict the nominal strength of CFS columns with an elliptical hollow section and pin-ended support, and they buckled about the minor axis.

Also, Cai et al. [117] conducted an investigation to design the columns with steel elliptical tubular stub sections. The results showed conservative and reliable values of the strengths, which were predicted by the Modified DSM and DSM. The Modified DSM provided the smaller scattered and higher accurate predictions over all of these design methods. Therefore, the Modified DSM is mostly recommended in order to design the CFS and HFS (hot-rolled steel) elliptical tubular stub columns.

7.2.2 Seismic Design of CFS structures (Shear walls, Portal Frames):

Generally, the CFS structural systems are used for mid-rise and low height constructions. Shear walls are used in the design of CFS-framed buildings for providing the resistance of seismic or wind loads. From the viewpoint of structural systems properties, CFS-framed shear walls are considered as small systems. However, various studies have been conducted recently to investigate the reliability of CFS-Framed shear walls -for steel structures-in general and CFS structures in particular.

Bian et al. [118] examined the reliability of CFS framed shear walls sheathed with wooden panels. Chung et al. [119] provided modern design and analysis techniques as well as guidelines with practical consideration to investigate the performance of CFS structural systems.

Xie et al. [76], conducted an experimental investigation on CFS shear walls with self-drilling screw connections. They concluded that there is an ability to use the safety factor and resistance factor proposed in AISI (Lateral Design Standard) to design the CFS shear wall with SPR connections for both wind load and seismic load. Jun et al. [51] also investigated an efficient design of CFS frames for earthquake resistance through bolted-moment connections. Also, Shahinia et al. [49] clarified that the DSM could be used to predict an appropriate initiation level for the connection slip moment before introducing the beam buckling moment, particularly in seismic areas. Furthermore, Jun et al. [50] improve the cyclic response of CFS connections subjected to strong earthquakes by identification of the best design configurations.

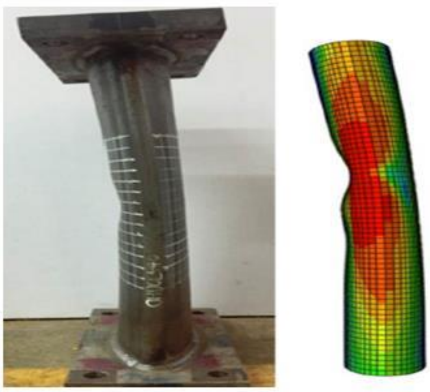

Fig.27: Failure mode of EHS.
Source: Reference [97]

VIII. OPTIMIZATION:

Higher load carrying capacities of the CFS sections can be achieved due to the flexibility of the CFS cross-sectional shape resulting in more efficient members. Therefore, more economical and sufficient design can be obtained by applying the optimization process on the CFS sections. However, the challenges of design issues of CFS elementsiated with buckling behavior (local, global, distortional) can lead to a complex optimization task. Several studies suggested and applied many methods aiming to obtain the optimum design solutions of CFS structural members, for example:

Parastesh et al. [120] used the Genetic Algorithm in order to present a practical optimization method for symmetric CFS beam-column elements. In this study, they investigated the effect of element length (short, long, intermediate beam-column) on the optimization results. The results showed that better design solutions are not necessarily obtained from more complexed shapes. Generally, when the distortional buckling mode is predominant, then increasing the eccentricity will lead to more spread optimum sections, particularly in short and intermediate-length beam-columns elements.

Wang et al. [121] developed an evolutionary algorithm by introducing manufacturing constraints for the optimization of CFS shape profiles. The algorithm considered as “self-shape optimization,” and it uses the Augmented Lagrangian together with the Genetic Algorithm (GA). Column lengths range from (500mm) to (3000mm) were used as well as various numbers of roll-forming bends were investigated and optimized to obtain the optimum cross-sections. The results showed that the effect of introducing manufacturing constraints into shape optimization algorithm is not so essential from the viewpoint of the performance of the resulting section. Also, there was a similarity in the manufacturable cross-sectional shapes.

Wang et al. [122] used Augmented Lagrangian Genetic Algorithm (GA) to optimize the cross-sectional shape of open-section, singly-symmetric, and simply- supported CFS beams and beam-columns elements. No constraints of manufacturing are used. This study optimized beams which are unrestrained or fully restrained against twist and lateral deflection, as well as optimization of unrestrained beam-columns elements is conducted. The results showed that the shape optimization of CFS beam-columns or beams elements depending on the unconstrained algorithm leads to obtain cross-section that can freely be able to converge to any shape.

Mojtabaei et al. [123] studied the optimum design of CFS sections of beams by developing a practical methodology depends on Population-based Big Bang-Big Crunch method with simultaneously maintaining the following conditions: 1. maximum flexural strength, 2. minimum deflection under ultimate and serviceability load, 3. consider the manufacturing and end-use design constrains in Eurocode. It is shown that the optimized sections depending on serviceability limit state (SLS) can provide up to 44% higher effective stiffness, and the ultimate limit state (ULS) can provide up to 58% higher value of bending moment capacity after comparing with a standard lipped channel beam section with the same plate thickness and width.

Jun et al. [124] used the Particle Swarm Optimization method to optimize different prototypes of the CFS channel section, and the optimization process was with respect to their flexural strength. Particle Swarm Optimization method was determined in Eurocode 3 (EC3) part 1-3, the provisions which were based on the effective width method. From the results, if the material amount is not changed, then the optimum sections provided up to 25% more flexural strength laterally braced CFS beams and 75% more flexural strength for the unbraced beam while they also satisfied the constraints of design and manufacturing.

Li et al. [125] proposed a two-level optimization framework in order to decrease the weight of CFS lipped channels and produce a family of light channels with the minimum number of independent cross-sections. The optimization efforts are expanded to a wide set of axials (P) and bending (M) demands against distortional and local buckling modes only. While Madeira et al. [126] investigated the optimal design of CFS columns to maximize both the local-global and distortional buckling strengths. The optimization problem was solved by using the method of Direct Multi-Search (DMS), where there are not any derivatives of the previous objective functions. Results showed the decreasing in maximum distortional strength due to the maximization of local-global strength.

IX. CONCLUSION:

Significant developments continue to take place in the structural use of Cold-Formed Steel, and many types of research have been growing rapidly across the world revealing the importance of CFS structures with respect to various engineering viewpoints. As this extensive research lead to more understanding of the CFS behavior, efficient design, perfect manufacturing, applications, and improving the design codes, therefore the authors of this paper aimed to review most of the studies conducted on the CFS members recently related to many disciplines which mentioned before. This paper showed the features of the CFS structures, and it is very useful for interested researchers, designers and students who need to discover many aspects of CFS to get the last updated references. Despite all the advantages of this comprehensive review, but the authors strongly recommend to accomplish more reviews that might have deep details about the CFS structures in general and CFS members in particular, such as special reviews about the CFS manufacturing, connections, behavior, design, and many other important issues. Therefore, if these reviews conducted, it would improve the understanding of each point related to CFS and link many ideas that have been published separately to build more worthy guidelines about the CFS design for higher codification.

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