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Prefabricated Hybrid Wall Panel System for Lightweight Steel Construction in Seismic Prone Regions

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Abstract

A new lateral force-resisting wall panel is presented for applications in mid-rise prefabricated lightweight steel construction in seismic prone regions. This panelised system is composed of a hot-rolled frame and cold-formed studs and tracks, which works as a lateral force resisting system in lightweight steel framing. The proposed hybrid panel system exhibits proper ductility and energy dissipation behaviour. The hysteretic responses of full-scale panel experiments demonstrate that the system can safely resist high cyclic loads. The hot-rolled steel part, on the other hand, can significantly improve the initial lateral stiffness of the total system that will control the maximum allowable drift of multi-story buildings. Finally, in a case study, by applying the proposed system to the design of a mid-rise building in a high seismic area, the performance of the hybrid panels, are compared with those of fully hot-rolled systems (moment resisting frames) and fully cold formed systems. The findings indicate that applying hybrid panels will result in lower weights and better performance in seismic prone regions.

Keywords: Panelised construction; Lightweight frames; Hybrid systems; Cold formed steel; Hot rolled steel; Design for earthquake, Lateral force resisting system

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1. Introduction

The great progress in the knowledge of cold-formed steel (CFS) structures achieved in the past two decades, together with the modern design and fabrication methods supported by progressively improved technologies, have prepared the industry of the lightweight steel construction to play an important part, with confidence, in the future of building construction. Yet, despite the increasing hopes of expanding the use of CFS framing into more complex, robust and taller structures, the lateral performance of CFS framed structures has remained one of the major concerns, in particular with the applications in mid-rise construction.

In building construction CFS products are being used in three forms: members, panels, and fully prefabricated assemblies. Typical CFS members such as studs, track, purlins, girts and angles are mainly used for carrying or transferring loads between structural elements, while panels and decks constitute surfaces such as floors, roofs and walls for resisting in-plane and out-of-plane surface loads. Fully prefabricated cold-formed steel assemblies such as pods, roof trusses, panelised walls or floors, are composed of structural members and/or panels manufactured offsite. Prefabricated wall systems are one of the most popular modular systems in offsite construction industry [1-3].

Light Steel Framed (LSF) systems made of CFS components are suitable candidates for prefabrication and modular construction, and have proven their applications in the residential and commercial building industry. They bring efficiencies to the process by enabling assembling on site rather than building. Their shorter construction cycles lead to saving costs, earlier return on investment and reduced interest charges. Furthermore, the computer controlled formation of CFS products makes them very suitable for 3D modelling using BIM software, which enables accurate integration of services in advance. In seismic prone regions, their high strength-to-weight ratio allows for greater design freedom and a lighter frame that can result in lower weight and consequently lower damaging earthquake forces acting on the building.

While most CFS wall systems are intended to resist gravity loads, their performance as a lateral force resisting system can be of great importance, in particular in seismic prone regions and high wind areas. Yet, thin-walled CFS sections lack sufficient rigidity and suffer from many types of instabilities such as local, distortional, global and restrained distortional buckling which reduces the load bearing capacity of the elements considerably. A bare standard LSF panel with studs and tracks, is quite insufficient to withstand earthquake induced lateral loads [4]. Furthermore, since the close spacing of vertical members provides an efficient gravity loading arrangement in CFS framing; concentric bracing through the webs becomes more complex. Consequently, the bracing of LSF follows more of the traditions found in timber construction compared to methods used for bracing in hot-rolled steel construction [5]. Recent advances in the understanding of their behaviour, and ongoing design related research on lateral force resisting systems (LFRS) are quite promising to guarantee the use of CFS framing into more complex, robust and taller structures [6].

In this study, an innovative hybrid steel panel is introduced that can be widely employed in the prefabricated mid-rise construction of lightweight steel frames. In this panel, some CFS chord studs are replaced with hot-rolled square hollow section (SHS), in order to achieve a higher load bearing capacity and stiffness. Each hybrid wall panel (HWP) consists of a hot-rolled SHS frame, laterally incorporated in a cold-formed panel; while a CFS top chord acting as a load collector, and the hot-rolled steel frame acting as a lateral load resisting system.

2. LSF Latrell Load Resisting Systems

LFRS are defined as the structural elements and connections required to resist racking and overturning actions, because of wind, earthquake, or other predominantly horizontal forces, and/or combinations thereof, imposed upon the structure in accordance with the applicable codes [5]. Nowadays, there are several provisions for lateral design of LFRS, such as FEMA-450 [7], TI 809-07 [8], ASCE 7 [9], which refers to AISI standards for lateral design [10, 11], AS/NZS 4600 [12] and IBC [13].

A comprehensive review on the LFRS in LSF systems was carried out by Sharafi et al. [6]. As per their classification, LFRS for LSF systems typically fall into one of the following categories [6]: (1) shear walls clad with face sheathings such as plywood, plasterboard or steel sheets; (2) CFS frame strap-braced wall systems; (3) some frame-connection systems such as special bolted moment frames; (4) podium-type structures, where a complete load bearing CFS lightweight frame is built atop lower levels of other structures; and (5) mixed (hybrid) systems where CFS joists, trusses, and load-bearing walls are used for the primary gravity system, while shear walls, braced frames or moment frames are used for the vertical offsets of the LFRS. Determination of an appropriate LFRS for a given building depends on architectural and structural considerations. Moreover, other factors like the hold-downs, shear bolts, strap anchorage details (for example gusset plates), and bearing of panels on the foundation beam may also influence the overall shear resistance of the light-gauge steel framed walls [14].

Gad et al. [15] classified the factors impacting LSFs behaviour under lateral loading, as well as factors influencing the behaviour of CFS wall panels. They included factors such as properties of frame (material properties of frame and hold down, aspect ratio, stud spacing, etc.); cladding (material, thickness and orientation, number of cladded sides, type and

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configuration of fasteners); bracings (material, type of bracing and member properties, fixity details and initial tension level); cladding and bracing interactions; boundary conditions (set corner joints, ceiling cornices, skirting boards and vertical loads); and size and location of openings.

In the design of LFRS for a seismic region, an important consideration is the distribution of lateral load demands in proportion to the in-plane relative stiffness of diaphragms and wall bracings, thereby restricting the inter-story drift ratios within an acceptable range. Serrette and Chau [16] had a review and a discussion on the AISI provisions in order to estimate lateral displacement of conventional CFS shear walls. In parallel with some attempts for the efficient use of CFS frames in mid-rise construction [17], in 2012, Cold Formed Steel Network for Earthquake Engineering Simulation (CFS-NEES) project incorporated full scale shaking table tests together with advanced modelling of CFS framed buildings in an effort to address multi-story CFS lateral force resisting systems for modern performance-based seismic design. Some outcomes of this project have been published in [18-22].

In multi-story prefabricated construction, an efficient force resisting system can be a mixed mechanism, where CFS joists and loadbearing walls are used for the primary gravity system, diaphragms and collectors; and structural steel moment-resisting frames (e.g. with hot-rolled sections) are used for the vertical elements of the LFRS. Such mixed systems are allowed in codes [23], but efficient performance and connection details are not properly investigated.

3. Design Characterisation

In this study an innovative hybrid steel panel is proposed, which performs as an LFRS system in modular LSF construction. In this system, the structural lateral performance is affected by both horizontal and vertical elements as well as connections. As shown in Figure 1, the proposed prefabricated hybrid panel here is formed of two individual panels: a hot-rolled

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steel panel made of square hollow sections (SHS), and a CFS panel made of C-sections for top and bottom chords, studs and noggings. Each panel is 3.6m wide (2.4 m cold-formed, and 1.2m hot-rolled frame) and 3m height. The hot-rolled profile is made of an SHS89x89x3.5 rectangular hollow section, the cold-formed studs are WSL92-075-30 C-sections, and the bottom chord is a 94-055-30 C-channel. Two rows of noggings are connected to one-third (1/3) and two-thirds (2/3) of the studs' height on both sides to reduce the free buckling length of the studs to 1m.

This panel can be fully prefabricated and transported to the construction site and assembled using the same fastener options as for pure CFS systems. The weight and size of the panels are kept in a range that can be safely handled i.e. lifted, transported, installed and assembled by two workers. The length of the CFS part of the panel can vary according to the architectural demand, while the hot-rolled part maintains the same size according to the amount of shear force required to be resisted.

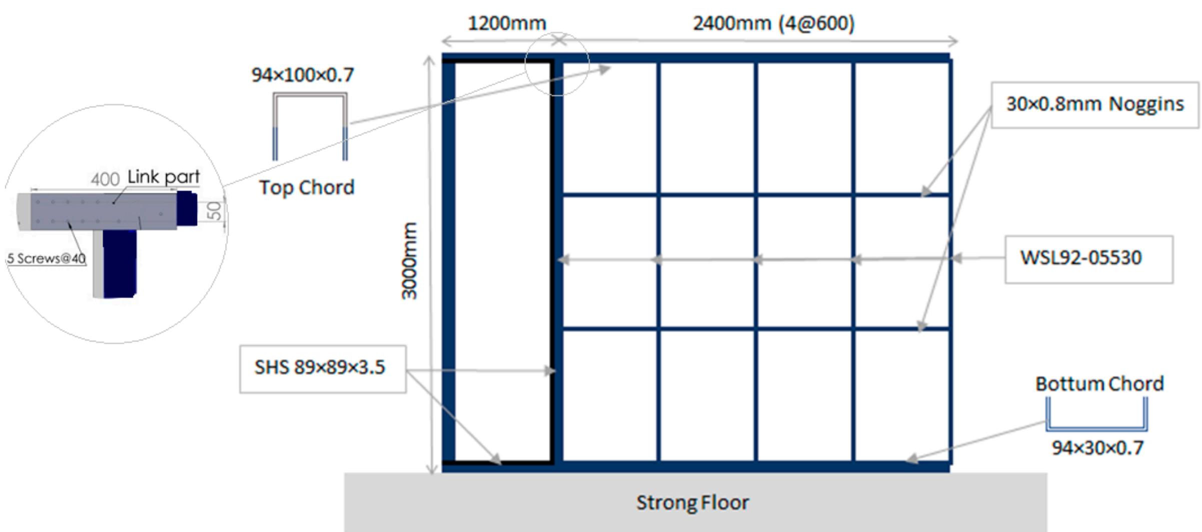

Figure 1. Prefabricated hybrid steel panel design

In case of high lateral excitation, the CFS parts of the panel, which are mainly designed for carrying vertical loads, can contribute through buckling and plastic deformations, while the

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hot-rolled panel is primarily designed to resist the entire lateral load. Screw connections provide the energy dissipation through hysteresis, essentially combining to make up the total panel hysteresis. The hot-rolled panel behaviour, collectors and connections therefore, govern the seismic behaviour of the hybrid system. The hot-rolled frame is designed to carry the lateral load both in tension and compression, while one side of the hot-rolled panel is connected to the CFS panel. This design allows the hot-rolled panel to dissipate energy for the entire system. The high elastic capacity of the hot-rolled panel provides relatively small residual displacements under lateral cyclic loading. This is suitable for controlling the drift.

Reversed cyclic tests were performed to investigate the behaviour of the hybrid panel to provide an accurate model of its hysteresis for integration at a structural system. In this study, the behaviour of bare panels is investigated and the effect of sheathing elements on the lateral behaviour of the wall is not considered. Figure 2 shows the test set up.

Figure 2. Fabricated test frame and specimens setup

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4. Experimental Program and Results

A total of 5 specimens were tested under the monotonic and cyclic loads to evaluate the maximum capacity and hysteretic behaviour of the panels. The overall behaviour of the panels under monotonic horizontal loads can be represented as a relationship between the lateral shear resistance and the lateral displacement. In the tests, the first yield was observed at the displacement of 60 mm and the lateral load of 8.7 kN. The lateral load was applied to the CFS top chord to study its ability and performance for a proper load transfer. The failure happened, where the screws connecting the cold-formed top chord to the cold-formed stud, and directly attached to the hot-rolled column were pulled out. The hot-rolled steel panel remained in the elastic deformation zone (Figure 3).

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Figure 3. Local deformations and screw failure under monotonic pull load

The results of the monotonic push and pull tests revealed that an adequate connection between the hot-rolled and cold-formed part needs to be provided to increase the lateral capacity of the panel. As shown in Figure 1, a strong configuration was employed, so that the connections between the cold-formed and hot-rolled parts attachment point become the governing factors of lateral load strength. Therefore, having determined the maximum lateral load capacity and ultimate displacement of the hot-rolled panel, the panels are designed so that they can achieve the hot-rolled panel maximum capacity. The details of the experiments and the improvement process are discussed in [24].

For the cyclic test stage, the specimens are subjected to a cyclic load based on method B of ASTM E2126 [25]. This loading protocol includes: (1) Five fully reversed cycles of 1.25%, 2.5%, 5%, 7.5%, and 10% of the ultimate displacement, form the first pattern; (2) three equal cycles of 20%, 40%, 60%, 80%, 100%, and 120% of the ultimate displacement. The hysteretic response of the specimens shown in Figure 4 indicates that the maximum lateral load resisted in compression mode is 13.3 kN (at the lateral displacement of 182.3 mm) and for tension mode is 12.56 kN (at the lateral displacement of 147 mm).

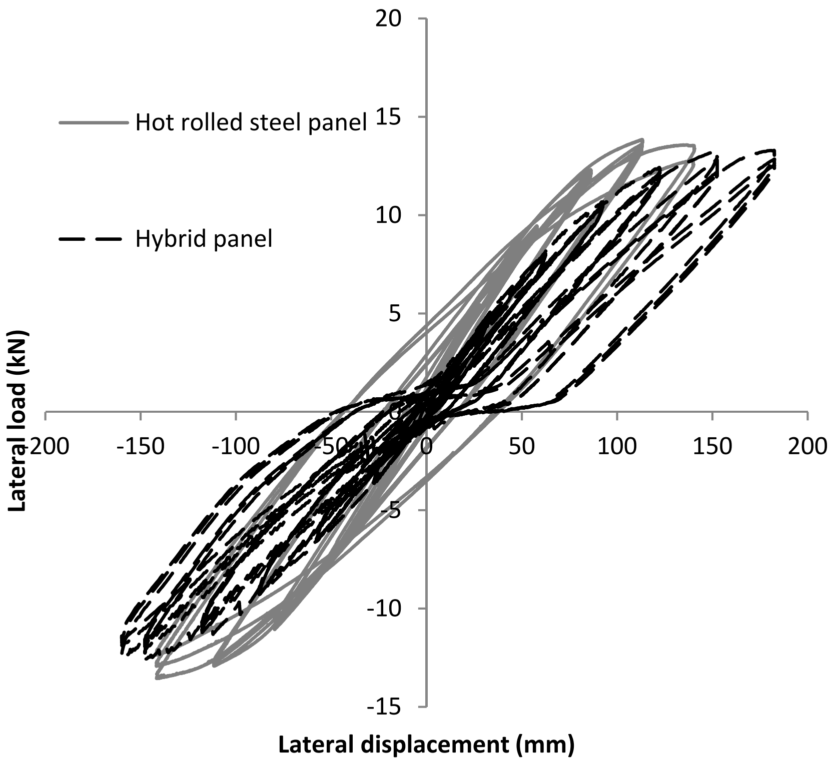

Figure 4. Hysteretic curves for panels without Gusset plate

CFS columns show a small contribution to the shear capacity of the panel, while performed well in energy dissipation due to deformation. On the other hand, the pinching behaviour of the cold-formed part governs the lateral deformations of the panel and results in a reduction in the energy absorbing capacity of the hybrid panel. The pinching behaviour is a result of local buckling of cold-formed studs, and the performance of fasteners. A stiffer hot role frame can improve the overall behaviour of the panel and to some extent address these problems. To that end, 350×350×4 corner gusset plates (Figure 5(a)) were added to the hot-rolled part, whose improved cyclic behaviour is shown in Figure 5(b).

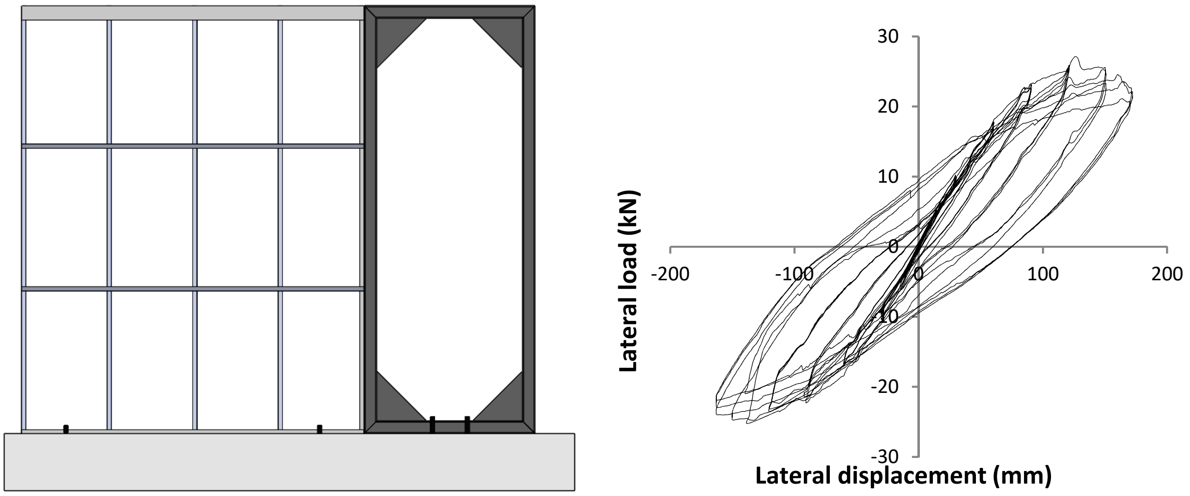

Figure 5. (a) Panel with stiffened hot-rolled section, and (b) the improved hysteretic curves

5. Case study

A four-storey residential building made of LSF systems in LA, USA, is studied in order to investigate the performance of the proposed panel in mid-rise construction in a high earthquake zone in the region [26]. As Figure 6 illustrates, each 21m by 16.2m level of this building accommodates four residential units in plan and 3m in height with the building's total height of 12m, and total seismic weight of 2400kN. The building is loaded and analysed according to ASCE7 [27] and designed according to AISC360-10[28], AISC341-10[29] and

AISI-S100 [30]. The building contains six divisions (plane frames) in the x-direction and three in the y-direction. The design objective for this system is to design the frame with the proposed panle so that minimise the number of hot-rolled steel parts, while maintaining the allowable storey drifts. Then, in order to evaluate the performance of the proposed panel for this case study, and compare the results with other systems, the steel frames are designed by three different systems: (1) fully hot-rolled steel frame (moment resisting frame), (2) fully CFS frame, and (3) the proposed hybrid system.

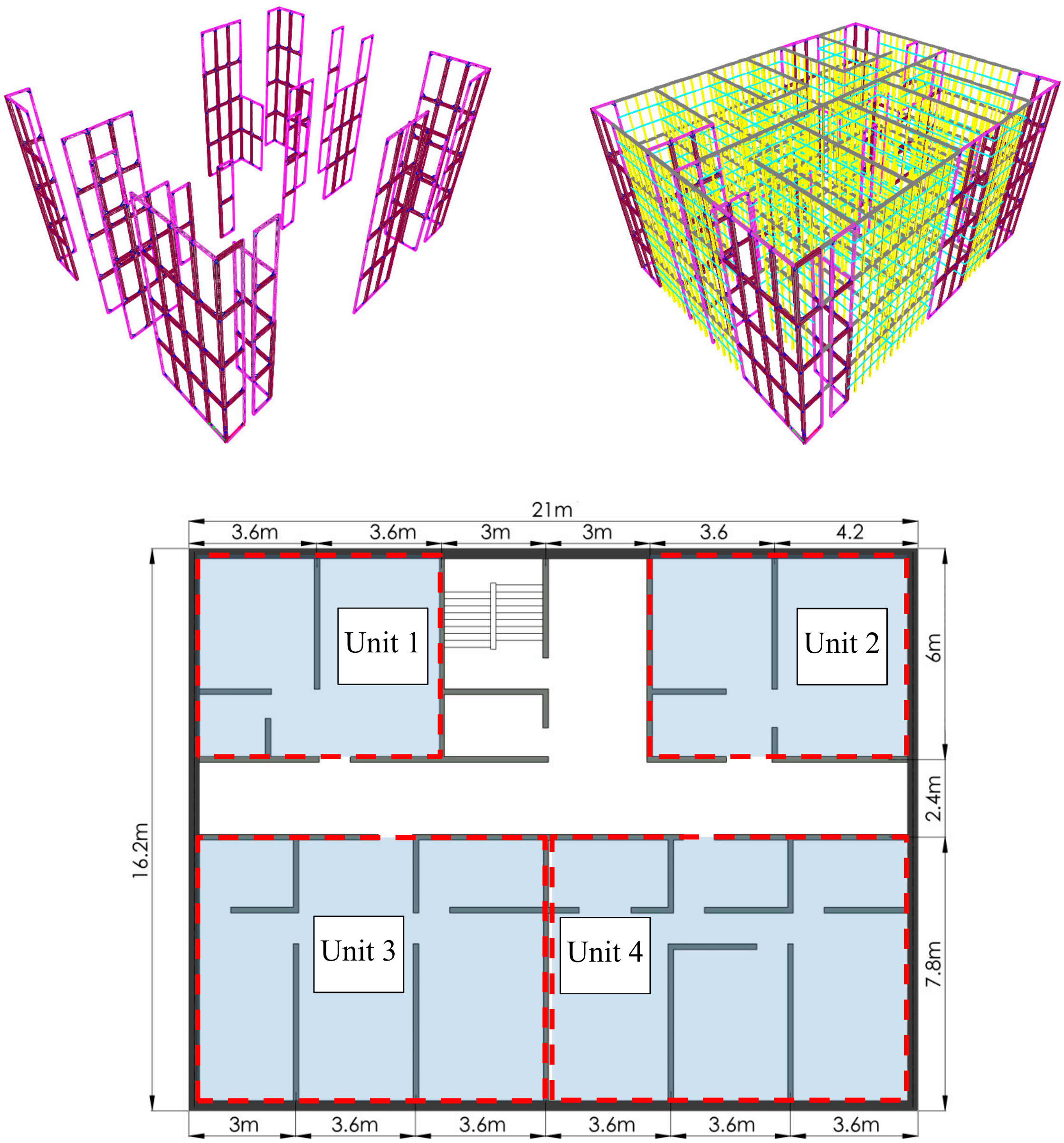

Figure 6. Layout and framing of the building

For a complete analysis, in addition to determining forces and moments in an elastic and perfect profile, the imperfection effects are taken into account in the linear elastic analysis, through explicit modelling. To address this concern, codes consider notional loads to be applied to the lateral framing systems to account for the imperfections. The magnitude of notional loads is calculated according to [28]. Furthermore, a second order analysis, taking the P-delta effect into account, is performed for this preliminary design in order to evaluate the sensitivity of the structure to change of geometry in the system and the member curvature [31, 32]. Figure 6 shows a comparison between the weights for each system, obtained from the design. Results demonstrate that using the prefabricated hybrid system for the design of the building in high seismic regions, a total of 39% save in steel material and 51% save in the hot-rolled steel frame can be achieved compared to moment resisting frames. It should be noted that the changes in the structural system from moment resisting frames to the prefabricated hybrid system, will change some other structural systems such as flooring due to the constructional consideration. This will in turn affect the total weight of the building. These changes are shown in Figure 6.

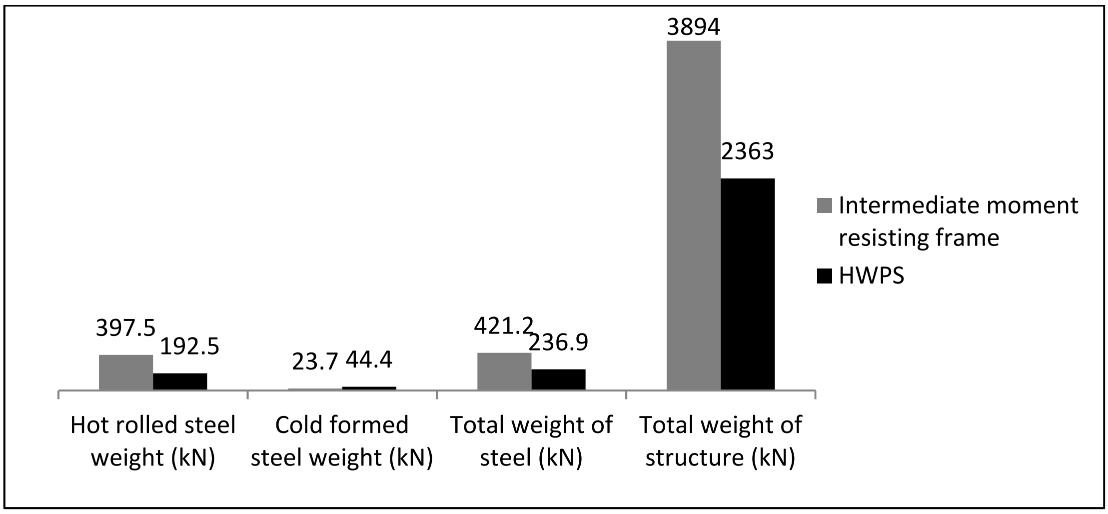

Figure 7. A comparison between the weight of structural steel, and total weight

6. Concluding Remarks

The increased demand for mid-rise lightweight steel frames has resulted in various research activities being undertaken in order to enhance the performance of these systems. This paper investigates the performance of a prefabricated hybrid wall panel system made of a hot-rolled steel panel and a cold-formed steel panel for mid-rise construction in seismic prone regions. In this design, the hot-rolled steel panel resists the shear force, while the gravity load is distributed proportionally between the hot-rolled and cold-formed panels. In this study, the behaviour of bare panels is investigated and the effect of sheathing elements on the lateral behaviour of the wall panels is not considered. The experiment results were employed for a case study design of a four-storey residential frame in a high seismic region. Results of the case study reviled that the hybrid system is more efficient than regular moment resisting frames and fully cold formed systems, and can save 39% the weight of structural steel, and 51% weight of hot rolled section compared to the moment resisting frames, for the project.

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