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Lateral behaviour of hybrid cold-formed and hot-rolled steel wall systems: Experimental investigation

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ABSTRACT

The seismic design of light steel frames (LSF) can not only rely on the application of cold-formed steel (CFS). Some mixed systems and integrated solutions such as hybrid systems can offer new possibilities, in particular with regard to applications in mid-rise construction. A hybrid solution is to replace some CFS chord studs with hot-rolled square hollow section SHS, in order to achieve higher capacity. This paper provides the results of experimental studies on the lateral behaviour of a hybrid light-weight steel panel and investigates the implication of any further system improvements for mid-rise construction. Each hybrid wall panel (HWP) consists of a hot-rolled SHS frame, laterally incorporated in a cold-formed panel. The study includes investigating the lateral performance of HWP, while a CFS top chord acting as a load collector, and a hot-rolled steel frame acting as a lateral load resisting system. The behaviour of specimens is investigated under monotonic and cyclic loads, and the step-by-step enhancement is implemented according to the results. The outcomes revealed that although the hysteretic behaviour of the HWP represents pinching effect, mainly due to poor performance of the cold-formed steel collector, by strengthening the top chord design the behaviour is improved. Relying on the cold-formed part to resist the major portion of gravity loads, while the hot-rolled collector transfers the entire lateral load to the hot-rolled frame, results in significantly improved hysteretic behaviour.

1. Introduction

Lightweight Steel Frames (LSF) made by framing thin gauge cold-formed steel (CFS) into different structural elements such as walls, trusses and joists are commonplace many parts of the world. The great progress in the knowledge of CFS structures achieved in the past two decades, together with the modern design and fabrication methods supported by progressively improved specifications, have equipped the industry of the lightweight steel construction with tools and confidence to play an important part in the future of building construction. During the past few decades, the use of cold-formed steel frames as the main load bearing system of low to mid-rise structures has become a common practice. Due to its light weight, construction flexibility, prefabrication options and ease of installations, in comparison with hot-rolled steel frame; this structural system is becoming a popular option for residential construction [1,2].

Despite the ever-increasing demand on the use of cold formed steel framing into more complex and taller structures, the lateral load resistance capacity of lightweight steel frames has proven to be a major hindrance and a major concern. Unlike hot-rolled steel structures, it is well recognised that the implication of CFS for lateral bearing systems have been challenging. Low rigidity of CFS sections alongside partially restrained screw or rivet fasteners leads to limited or no lateral resistance for CFS frames [3]. There have been various efforts to combine other structural systems with CFS frames that improve its seismic performance and remedy the existing deficiencies. Relying on face sheathings is the first common approach to improve the lateral load performance of CFS wall systems. Face sheathing elements such as steel, plywood, oriented strand board (OSB) and gypsum wall board (GWB) are the most popular bracing elements being evaluated to improve the lateral behaviour of CFS frames [4–8]. The second approach being developed to improve the CFS lateral capacity is to apply strap bracings through lateral load bearing spans. Different configurations of strap bracings such as K bracing, knee bracing or diagonal bracing have been considered in a number of research studies [9–11].

Lateral force resisting systems for LSF typically fall into one of the following categories: (i) shear walls clad with face sheathings such as plywood, plasterboard or steel sheets; (ii) CFS frame strap-braced wall systems; (iii) some frame-connection systems such as special bolted moment frames. Mixed shear walls can be the next alternative for CFS lateral load resisting systems. A combination of face sheathing panels with strap bracings have been investigated by Moghimi and Ronagh [12]. They evaluated the lateral behaviour of strap braced walls with and without gypsum boards and brackets and concluded that adding brackets at the corners rectifies the lateral performance. They also

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showed that double-sided bracing does not show any further improvement to the overall behaviour unless straps are prevented from developing full plastic capacity. Mixed shear wall system can also include face sheathing boards accompanied by sprayed light-weight mortar to act as bracing element [13].

The primary aim of using LSF systems is to minimize the amount of labour and material resources to reduce construction costs and time. One way to minimize labour and the duration of constructional process is panelisation, in which panels are common elements containing tracks and studs. Assembly is done in a controlled interior environment with higher quality control; repetitive and efficient assembly, and reduced erection time are some advantages of such panelised systems [14–16]. Although the CFS structural wall panels are lightweight and easy to handle, their behaviour as a structural element is still not reliable enough to justify their application as the sole load resisting system for mid- to high-rise construction [10].

In earthquake-prone regions, CFS structures are expected to withstand lateral loads, during seismic events. In the current literature, CFS shear walls with various face sheathings (wood, steel and other materials) and strap braced wall systems or a mix of both are experimented as effective lateral load resisting systems for CFS structures. Regarding seismic design of bare LSF shear walls/panels however, where the effects of sheathing are not considered, strap bracing is the most common system being used for resisting lateral loads. The results of studies have shown that strap braced walls often have large residual displacements, which could be undesirable due to permanent deformation resulting from severe damage and an inability to re-centre [17]. Such large residual displacements and very probable slacks in the wall and rather poor energy dissipation during cyclic loading make the existing strap bracing systems quite ineffective in earthquake-prone regions [9–12].

Hot-rolled steel frames on the other hand, are reliable lateral load resisting systems, supported by a wide range of studies on their seismic behaviour in low- to mid-rise structures. Therefore, hybrid shear wall panels including CFS and hot-rolled steel to accommodate the advantages of both structural systems are an interesting field for investigating the implication of CFS structures for mid- to high-rise construction.

In the current study, a hybrid wall panel (HWP) system is introduced which consists of a hot-rolled steel framed panel laterally connected to a CFS panel. The CFS panel transfers its share of lateral load to the hot-rolled panel, while the hot-rolled panel is responsible to resist the transferred lateral load. The proposed panel provides the advantages of a light-weight structural system as well as the reliability of a hot-rolled steel structural frame. In this study, the lateral behaviour of the proposed system is investigated through experimental studies.

2. Panelised hybrid cold-formed-hot-rolled steel system

There has been a great deal of research studies on the lateral load resisting capacity of LSF systems [18]. Different factors such as sheathing properties [19], framing details, fastener types and spacing [20,21], geometry and construction approach might be considered as the main contributing factors. In a CFS structural system, the structural lateral performance is affected by both horizontal and vertical elements as well as connections.

The proposed prefabricated hybrid panel here is formed of two individual panels: a hot-rolled steel panel made of square hollow sections (SHS) and a CFS panel made of top and bottom chords and studs. The panels can be transported to construction site separately and assembled on site 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, installed, transported 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.

In case of lateral excitation, the CFS parts of the HWP carry the vertical load while the lateral load is primarily resisted by the hot-rolled panels. Screw connections provide the energy dissipation through hysteresis, essentially combining to make up the total panel hysteresis. The hot-rolled panel behaviour, therefore governs the seismic behaviour of the HWP.

As shown in Fig. 1, 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 HWP. The high elasticity of the hot-rolled panel provides relatively small residual displacements under lateral cyclic loading. Reversed cyclic tests were performed to aid in understanding the behaviour of the hybrid panel to provide accurate modelling of its hysteresis for integration at a structural system, such as a building level. 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.

3. Testing arrangement and specimen details

The lateral behaviour of the proposed HWP system is investigated using full-scale physical experiments. The general configuration of the testing rig is illustrated in Fig. 2. It consists of longitudinal and lateral frames, a strong floor, top beam, bottom track beam, hold-down devices and clamps, and lateral struts with roller heads. The longitudinal frame is an inclined frame designed to mount horizontal hydraulic jacks for imposing loads in the longitudinal direction of the wall panel. The three lateral frames are designed to support the hydraulic jacks responsible for vertical loads. It should be noted that the testing rig is designed for both lateral and vertical loading. Yet, in this study only the effects of lateral loads in the absence of vertical loads are investigated. These frames are complemented by a multi-configurable strong floor of 16 m × 8 m. A strong hot-rolled channel section is used as the top beam to cover the top chord, in order to restrain the out of plane deformations at the top of the panel. A strong bottom track beam is used to prevent any out-of-plane displacement at the bottom of the panel (Fig. 3-c, d). In addition, the bottom chord is clamped to the strong floor using the bottom rigid beam to prevent any possible uplift (Fig. 3-d). Cyclic loads is applied to the top chord, which is bolted to top beam in three points (Fig. 3-a). Likewise, cyclic load is imposed to the hot-rolled beam, which is fixed at both ends to allow for push and pull loads to be applied (Fig. 3-b). Lateral struts hold the top chord in the right track and prevent any overall out-of-plane movement. A horizontal roller is attached to the tip of the struts to allow horizontal displacement. A hydraulic jack is installed to apply horizontal loads as shown in the fabricated test set-up (Fig. 2).

Hex flange head self-drilling screws of 12-gauge diameter with 14 thread/in. are used as fastener elements for the CFS parts and also between cold-formed and hot-rolled steel parts. Lab View Signal Express software [22] is used to analyse and transfer the data obtained from LVDTs and load-cells. The experimental program proceeded in the Structures Laboratory of the Centre for Infrastructural Engineering of Western Sydney University using the specifically designed and fabricated testing rig illustrated in Fig. 2.

3.1. Specimen fabrication and test materials

The specimens were designed to accommodate the panelised system characteristics; each HWP is 3.6 m wide (2.4 m cold-formed, and 1.2 m hot-rolled frame) and 3 m height as shown in Fig. 1. The hot-rolled profile is made of a rectangular hollow section (SHS89 × 89 × 3.5). The cold-formed studs are WSL92-075-30 C sections and the bottom chord is a 94-055-30 C channel. The top chord is not chosen from currently existing products since it should accommodate enough space for a higher number of screws with a wider flange, in case any improvements is required. Therefore, a 94-075-100 C channel was bent out of a CFS coil for this purpose. Two rows of noggins were connected to one-third (1/3) and two-third (2/3) of the studs' height on both sides to reduce the free buckling length of the studs to 1 m.