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Comparison of the behaviour of steel, pure FRP and hybrid shear walls under cyclic seismic loading in aspect of stiffness degradation and energy absorption

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HIGHLIGHTS

- Hybrid and pure FRP shear walls have improved behaviour under seismic loading.
- Pure FRP shear walls have excellent load capacity and resistant to stiffness loss.
- FRP shear walls have good energy absorption and potential for increased durability.

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ABSTRACT

Introducing of light-weight lateral load resisting systems, such as steel shear walls (SSW) is very beneficial for multi-storey buildings. Further improvement of such elements via introducing fibre reinforced polymer (FRP) materials is expected to allow increasing of their ultimate load capacity, stiffness and energy absorption. The aim of presented research is to compare the behaviour of modified SSW via inclusion of FRP in infill plate design. Produced and tested shear wall specimens are three different types: with steel infill plate (control), with FRP infill plate and with hybrid steel/FRP infill plate. All samples are loaded under quasi-static cyclic seismic loading as defined in ATC-24 protocol. The highest ultimate load capacity and lowest stiffness degradation is achieved for sample with glass FRP infill plate, followed by hybrid (carbon FRP/steel and glass FRP/steel) specimens. Highest cumulative energy absorption for predominant part of the investigated amplitudes was achieved for hybrid specimens. The obtained results indicate that the innovative shear walls with FRP and hybrid infill plates offer excellent load carrying capacity and energy absorption, relatively small loss of stiffness and potential for increased durability in comparison with conventional SSW systems.

1. Introduction

Steel shear walls (SSWs) have become popular lateral resisting system in the last three decades.

SSW consists of horizontal and vertical boundary elements bounding a thin steel infill plate inside. The resulting system is a stiff cantilever which acts as a vertical plate girder where columns can be treated as flanges and steel plate as web. Advantages of SSW system such as substantially large displacement ductility, high initial stiffness, large energy absorption capacity, fast pace of construction, small wall thickness and small seismic mass have made them preferable in seismic design in many cases in comparison to other lateral load resisting systems [1–3].

SSWs are often used in earthquake resistant design for tall structures in Japan and North America. The first building incorporating the SSW system is the Shin Nittetsu Building in Tokyo, Japan completed in 1970. Five continuous H-shaped shear walls were built for 20-storey office tower [4]. The first important building with SSWs, which experienced two significant earthquakes and damages occurred only to non-structural elements, was built in USA is Sylmar Hospital in Los Angeles [1].

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Fibre reinforced polymers (FRP) are often used as a strengthening material for structures which undergo substantial damages or require additional capacity due to change of design brief [5,6]. Structural elements with carbon FRP (CFRP) and glass FRP (GFRP) are becoming popular in thin walled structures, sandwich panels and shear walls due to the combination of benefits from different materials. Initial research about FRP repair and straightening of damaged SSW and hybrid SW indicates opportunities for fast and effective recovery of the capacity of the damaged shear walls of this type [7].

The aim of this research is to investigate the performance of the shear wall system via inclusion of pure FRP as well as a combination of steel and FRP as one of the main structural components for the infill plates of the innovative shear walls. In total three types of infill plates for shear wall were investigated – one type of infill plates was hybrid of steel and FRP, the other was made of pure FRP and infill plate for control specimen was made from steel. The shear wall specimens were tested under cyclic sinusoidal loading with horizontal displacement loading increasing from 0.2 mm up to 30 mm in accordance with the ATC-24 protocol [8]. The results of ultimate load capacity and energy absorption within the testing interval for different shear wall systems were measured and compared. The degradation of stiffness values at peak load of each cycle for all specimens and dynamic stiffness of all specimens through entire loading were estimated and the results were analysed.

2. Background

2.1. Steel shear walls

The effectiveness of the steel shear wall for seismic design under laboratory conditions were investigated by many researchers in the United States, Japan, Canada and the United Kingdom. The first analytical models were developed by Thorburn et al. [9] who investigating the effects of varying the thickness of infill plate and the angle of the inclination of the tension field for different height/width ratio on post-buckling capacity.

Stiffened and unstiffened steel shear walls have been introduced in many buildings around the world. In some cases heavy stiffeners are used in order to increase the buckling capacity of shear wall and to obtain high energy absorption during post-buckling [10,11]. In order to achieve higher stiffness and deformability of shear wall system, steel infill plates can be reinforced by addition of concrete layer using shear studs on one or both sides of the steel plate [12,13]. Other way for improving SSW performance is using hybrid shear wall by bonding FRP laminate to the steel infill plate.

2.2. Hybrid steel/FRP shear walls

Hybrid shear walls (HSW) are defined as steel boundary elements with infill plate either laminated with FRP material or made completely from FRP material. HSWs are innovative structural lateral load resisting system and have significant advantages in comparison with steel shear wall systems. These include increased in-plane stiffness and load carrying capacity of the system and more uniform distribution of the tension field resulting in reduction of out-of-plane deformations in the infill plate [14,7].

Maleki et al. [15] conducted experimental and numerical studies investigating behaviour of the medium scale hybrid steel/GFRP shear walls with and without openings. They concluded that when steel plate is laminated with GFRP material, during quasi-static testing following the ATC-24 protocol more uniform distribution of the tension field within infill plate is observed and out-of-plane deformations are reduced significantly. Application of GFRP material significantly improved the stiffness and the strength of the system in comparison with a control consisting of a steel shear wall. Similar conclusions were made by Nateghi-Alahi and Khazaei-Pul [16] when testing hybrid steel/GFRP specimens under fully reversed cyclic quasi-static loading. Hybrid specimens achieve higher ultimate strength and increase the cumulative energy dissipation.

For design optimisation, numerical studies investigating the one-storey hybrid steel/CFRP shear wall with different fibres orientation and lay-ups were carried out by Rahai and Alipour [17]. It was found that the optimum CFRP fibres orientation is the angle of inclination of the tension field in the infill plate. When this angle is applied, significant increases in strength and stiffness were noticed. It was also noted that application of the FRP does not change dramatically the stress distribution within the infill plate at initial stages of testing; however when the plate has yielded, FRP composites layer carries significant loads in the direction of the tension field. Hatami et al. [18] carried out experimental and numerical studies and developed equations and graphs regarding the influence of different inclination of CFRP fibres on shear capacity, ductility, energy dissipation and stiffness ratios.

Comparison between two types of steel/GFRP and steel/CFRP hybrid specimens were investigated by Petkune et al. [19]. Similar behaviour of the specimens was recorded when significant failure in the connection between fish plates and the infill plate occurred. Investigation of hybrid connections showed that the addition of an adhesive bonding significantly improved the connection's capacity. Another important damage mechanism for these specimens was the delamination of the FRP layers and debonding from the steel of the infill plate. The delaminations and deboning were monitored using the infrared thermography (IRT) following external heating of one side of the infill plate at the end of the loading cycles [20,21].

3. Methodology

3.1. Description of the specimens

The experimental protocol included testing of five single-storey medium scale shear wall specimens. These specimens consist of steel frames with the same dimensions for all specimens (Fig. 1) and infill plates with different design specifications depending on the type of the specimens. The steel frames were made from steel (grade S355), fabricated and assembled from Universal Beam Section $127 \times 76 \times 13$ mm. The frames were designed at Kingston University London, and then assembled and produced (Cannon Steels Ltd, Enfield, Middlesex, UK). Primary fish plates were welded to the steel frame.

Five tested specimens are differentiated by infill plates: control steel shear wall (SSW), pure CFRP shear wall (CSW), pure GFRP shear wall (GSW), hybrid CFRP/steel shear walls (HCSW) and hybrid GFRP/steel shear wall (HGSW).

The control SSW specimen was made from a steel frame of S355 grade and the steel infill plate with the thickness of 0.8 mm was made from S275 steel grade.

Group 1 pure FRP specimens (CSW and GSW) were made from eight layers of unidirectional (UD) CFRP or GFRP plies laminated on steel infill plates within steel boundary elements. For the CSW specimen, CFRP prepreg type MTM 28-1 series was supplied by Cytec Industrial Material Ltd (Derby, UK) and for GSW specimen GFRP prepreg with epoxy resin E722-02 was supplied by Tencate Advanced Composites Ltd (Nottingham, UK). The materials properties of prepreg CFRP and GFRP fabrics are shown in Table 2. For preparation of specimens, eight layers of the prepreg FRP were laid between steel cover plates at ±45° inclination angle of fibres