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Performance of pristine and retrofitted hybrid steel/fibre reinforced polymer composite shear walls

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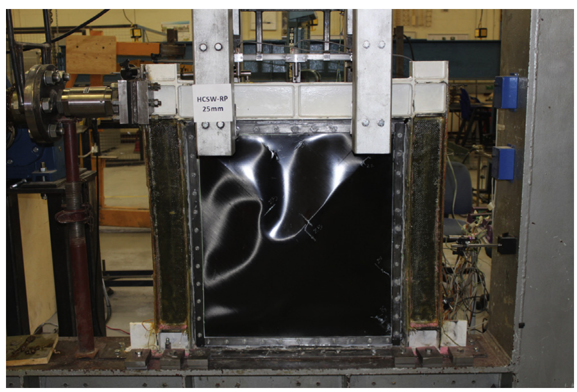
HIGHLIGHTS

- Specimens consisting of steel frame and hybrid steel/FRP infill plates were tested.
- Quasi-static cyclic loading following ATC-24 protocol was applied.
- The damaged specimens are retrofitted with FRP materials and retested.
- Ultimate capacity, deformability and energy dissipation for specimens was compared.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study new types of advanced hybrid shear wall systems using steel/fibre reinforced polymer (FRP) composites are being developed for deployment in the construction of buildings. The hybrid steel/FRP shear walls made from laminates of steel with either carbon FRP (CFRP) or glass FRP (GFRP) materials. In total six medium-scaled shear wall specimens were manufactured. In the first phase of the study three pristine specimens: steel shear wall (SSW-P), hybrid steel /CFRP shear wall (HSCSW-P) and hybrid steel/GFRP shear wall (HSGSW-P) were tested. In the second phase of the project, the specimens tested in phase one were retrofitted and retested; these specimens were identified as SSW-R, HSCSW-R and HSGSW-R. The structural repair and strengthening of specimens in the second phase was achieved by replacing the damaged infill plates with new infill plates of the same type, strengthening of the vertical steel frame elements with CFRP laminates and GFRP fabric. All shear wall specimens were tested under quasi-static cyclic loading following the ATC-24 protocol. The behaviour and failure modes of the pristine and retrofitted specimens were compared. The results show that the retrofitted specimens with the procedure developed have higher stiffness, higher ultimate loading capacity and similar energy dissipation capability relative to pristine specimens. For hybrid retrofitted specimens the ultimate load capacity increased more than 11% in comparison with pristine hybrid specimens.

1. Introduction

Steel shear walls (SSW), consisting of steel boundary elements and steel infill plate, have good lateral resisting properties and hence they can be used in regions with high levels of seismic

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activity. Their benefits such as lightweight, high load bearing capacity and high energy dissipation make them an attractive alternative in the construction of high-rise buildings particularly in areas of seismic activity. However, one of the main problems limiting their practical application is difficulty in repairing them after an earthquake event. Since the 1970s, SSWs have been popular in the USA and Japan for construction of high-rise buildings; they provide significant reduction in wall thickness as well as weight of the building and as a result reduction of foundation and inertia loads [1]. Hybrid shear walls (HSW) consisting of steel boundary elements and steel infill plates laminated with fibre reinforced polymers (FRP) on both sides of the plate are in process of the development. The established definition for steel shear walls is a combination of the steel frame with steel infill plate (e.g. see [1–3] to name a few). In this research the existing definition of steel shear walls was further developed as hybrid shear walls for elements consisting of steel frames and hybrid steel/FRP infill plates in aspect of infill plate modifications.

When buildings are subjected to seismic loading, severe damage to shear walls can occur. It is important to use effective techniques to recover initial strength and stiffness of the shear walls in order to avoid demolition of the building or requirement for introduction of new additional elements. This paper will address the use of the fibre reinforced polymer composites for enhancing the performance of SSW and also for a permanent retrofitting and strengthening of steel and hybrid (steel/FRP) shear walls after earthquake damage. These strengthening methods could also be applied to undamaged structures when changes in the structural loads on an existing building require design of higher capacity SSWs or HSWs.

2. Background

FRP materials have been used in civil engineering over several decades for strengthening of reinforced concrete and steel structures, improving capacity of buildings, bridges, dams and other structures. The most common FRP materials used for strengthening purposes are glass FRP (GFRP) and carbon FRP (CFRP). The high tensile strength of FRP and ease of application provides a clear benefit for their use in strengthening of structures. Advantages of FRP over steel as a strengthening material include higher strength-to-weight and stiffness-to-weight ratios, corrosion resistance, ease and speed of transportation and installation, electromagnetic neutrality and ability to follow irregular shapes of structures via wet lay-up-processes.

2.1. FRP strengthening of steel structures

Strengthening of steel structures with FRP in comparison with strengthening steel members by welding additional steel plates can be particularly beneficial in applications where it is important to avoid new residual stresses caused by the welding process and to avoid local strength reductions in heat affected zones [4].

Review of the current applications of steel structures strengthened with FRP by Teng et al. [5] and Zhao and Zhang [6] highlighted that the behaviour of the steel/FRP structural elements depends on the selection of the adhesive with appropriate mechanical properties not only in short-term performance, but also in long-term durability. It is important for bond-critical applications to use appropriate preparation techniques of the steel surfaces before adhesive application.

The main area of applications of using FRP for strengthening of steel structures can be summarised in the following categories:

- Strengthening of steel elements against local buckling [7,8].
- Flexural strengthening of the steel beams [9].
- Fatigue strengthening for steel beams, steel plates and connections [10,11].
- Strengthening of steel hollow sections and concrete filled steel tubes [12,13].

Harries et al. [7] conducted experiments on retrofitting columns made of WT steel sections with ultra-high modulus of elasticity GFRP strips, which were tested under concentric cyclic compressive loading to failure. Application of the FRP material prior to the test resulted in delay of the plastic buckling and formation of the plastic “kink” which positively affects energy dissipation and ultimate cyclic ductility properties. Similar conclusions were made by El-Tawil et al. [8]. They investigated the behaviour of three double channel built-up members wrapped with CFRP in the regions of plastic hinges tested under cyclic loading. It was concluded that structural behaviour of CFRP reinforced specimens was considerably better than unreinforced ones. CFRP wrapping in the regions of plastic hinges increased the size of the plastic hinge region and slowed down the occurrence of the local buckling. It also delayed the onset of lateral torsional buckling and resulted in a higher energy dissipation capacity in the plastic hinge regions.

2.2. FRP and steel applications for improving seismic resistance

An important aspect for the use of the FRP is to improve seismic resistance of the existing lateral load resisting system of buildings, particularly for shear walls. Several experimental and numerical studies have been conducted to investigate the behaviour of undamaged steel shear walls [14–16].

An innovative lateral resisting system in the form of hybrid shear walls (HSW), consisting of steel frames and steel infill plates laminated with FRP, have been investigated by several researchers in the past five years [3,17–20]. Experimental studies on the use of hybrid steel/GFRP shear walls showed that they provide higher stiffness, larger energy dissipation capacity and more uniform tension field during loading than steel shear walls with the same thickness of the steel infill plate [17]. Nateghi et al. [18] tested steel shear walls with infill plates laminated with GFRP, reaching a similar conclusion to Maleki et al. [17] that it significantly increases ultimate strength and initial stiffness. Cumulative energy dissipation of the hybrid steel/GFRP shear walls was larger than steel shear walls. Both studies concluded that the fibre orientation plays a significant role in the behaviour of the specimens, and laminates with fibres in the direction of the tension field exhibit better performance.

Use of CFRP in laminating steel plates was initially investigated by Hatami and Rahai [19]. They concluded that HSW with CFRP/steel infill plates in comparison with steel shear walls have higher energy dissipation and enhanced elastic stiffness and shear capacity [19]. Petkune et al. [20] compared the behaviour of both GFRP/steel and CFRP/steel infill plates in HSW design within steel boundary elements. Further, more detailed investigation of the role of boundary conditions [21] in the usage of CFRP or GFRP as an element in hybrid infill plates was presented.

Initial steps in the application of infrared thermography (IRT) for detecting delamination between GFRP and steel in hybrid infill plates are reported in [17]. Petkune et al. [22,23] have extended this work for detection of delamination in hybrid steel/FRP infill plates using IRT.

2.3. Structural repair of SSW and HSW

Limited studies are available on the structural repair and strengthening of the damaged SSWs to recover their initial capacity after earthquakes. Petkune et al. [24] conducted experimental