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Strut-and-tie model for a reinforced concrete wall strengthened with carbon fibre-reinforced polymers

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ABSTRACT

This study describes a nonlinear truss modelling approach for a reinforced concrete (RC) wall strengthened with carbon fibre-reinforced polymers (CFRP) subjected to a lateral displacement load test. Nonlinear vertical and diagonal truss elements are used to represent the reinforcement and the concrete. The model is developed based on a truss analysis of the RC strut and tie model. The capability of the model is demonstrated by comparing the measured and computed load response behaviours of non-strengthened RC walls and RC walls strengthened externally with CFRP.

1. Introduction

In recent years, reinforced concrete walls have been considered an integral part of building structures. Post-earthquake surveys have highlighted the significance of these walls in confining earthquake-induced damage. Although reinforced concrete walls are used in buildings to dissipate seismic-induced energy, they are also vulnerable to seismic damage. The main causes of damage to concrete walls are the occurrence of unpredictable high seismic activity, improper design and construction flaws [1–3]. The reinforced concrete (RC) wall load response behaviour strongly depends on its height to length ratio. An RC wall that has an H/L ratio of less than 2 is considered to be a short wall, and a wall that has an H/L ratio greater than 2 is considered to be a slender/long wall [4]. Short walls endure higher shear stress than slender walls. The failure modes of short walls include the separation of the wall from its supporting foundation, the development of diagonal shear cracks within the wall and concrete crushing at the wall toe [5].

In recent years, numerous strengthening techniques have been developed and implemented to strengthen RC walls. These techniques are steel-plate bonding, pre-stressing, reinforced concrete jacketing and fibre-reinforced polymer (FRP) reinforcement. Among these techniques, the FRP strengthening technique is the most popular because of its light weight, easy implementation and high resistance to corrosion. The FRP strengthening technique involves the external bonding of the FRP material in the form of strips or laminate to the tensioned surface of the RC structural element with the help of an adhesive (epoxy).

It is well-known that the behaviour of shear walls cannot be accurately described using conventional beam theory because of the interaction of flexure and shear. As a result, the analysis of shear walls has been a contentious issue for both researchers and structural engineers for decades. The modelling approaches used may be divided into five main categories: (1) lumped plasticity models [6]; (2) the truss or strut-and-tie model [7]; (3) the stringer and panel model [8]; (4) fibre element models [9,10]; and (5) FE models [11,12]. The truss model has been used to evaluate the linear and nonlinear behaviour of RC structural elements subjected to monotonic and cyclic loading. The idea of using a truss model was first proposed by Ritter [13] and Mörsch [14] in the early 1900s for the shear design of flexural concrete members. The publications of Collins and Mitchell [15] and Schlaich et al. [16] played a key role in the wide-spread acceptance of the truss model. Design codes such as ACI 318–08 [17] and CEB-FIP Model Code 1990 [18] have also adopted strut-and-tie models for the assessment and design of RC members. The truss or STM model consists of concrete struts stressed under compression, steel ties stressed under tension and nodes where the struts and ties join together. The only requirements for a truss model to be admissible are as follows: (1) to satisfy static equilibrium under the applied external loads; (2) to have sufficient strength in each element to resist the corresponding internal forces; and, desirably, (3) to be isostatic to simplify the computation of the forces on each element of the truss. Oesterle et al. [19] used a truss model to analyse an RC wall. This model consisted of two vertical boundary elements to carry wall

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moments; diagonal compression members called struts, which represent concrete; and horizontal tie members representing shear steel reinforcement. The model appropriately predicts the shear capacity of a wall. Hwang et al. [20] proposed a strut-and-tie model to evaluate the shear strength of a squat wall for diagonal compression failure. The model satisfies the equilibrium, compatibility and constitutive law of cracked reinforced concrete, and it is based on the assembly of diagonal, horizontal and vertical shear resisting mechanisms for walls. The model adequately predicts the shear strength of the wall. Greifenhagen [21] used the strut-and-tie model to calculate the nonlinear response of a specimen (labelled as S4: $\rho_v = \rho_h = 1.03\%$) tested by Maier and Thürlimann [22]. The model he used consisted of an assembly of trusses. Each truss consisted of a tie and a strut. The locations of the ties were based on the location of the vertical steel rebar in the test specimen. The proposed model well approximated the wall capacity but could not predict the wall response behaviour. The simplified truss model proposed in this article well depicts the model props.

This study investigates the influence of an external CFRP reinforcement on the load response behaviour of a short RC wall and the capability of the proposed truss model by comparing the measured and computed load response behaviour of non-strengthened RC walls and RC walls strengthened externally with CFRP.

2. Test setup

The basic idea of the short RC wall geometry was derived from Greifenhagen's [21] research. RC walls are considered to be short if the ratio between the height and the width is less than 2. In this study, the specimen represents the lower part of an existing building at a scale of 1:3. The effective height of the walls was 610 mm, the width was 900 mm and the thickness was 80 mm. The compressive strength of concrete was 35 MPa ± 5 MPa. In the wall, two metallic panels made of 4.5 mm-diameter rebar spaced every 200 mm in each direction are placed with a covering equal to 20 mm. Two rebars with diameters of 6 mm were also implemented on each end of the wall. Two concrete footings, which are considered rigid, are placed in the upper and lower parts of the wall to model the floors of the building. The casting of the specimens was performed in two steps. The footings were completed first, and after correctly placing the two flanges, the RC wall was built. This procedure took into account the construction joints between the components (Fig. 1). The adopted external CFRP reinforcement pattern (Fig. 2) was based on the crack pattern observed in the RC wall load test. The composite reinforcement was made from carbon fabric strips that were 50 mm wide and 0.48 mm thick. The Young's modulus was 105 GPa, and the ultimate strength was 1400 MPa. The bonding areas from the layout plan of the composite strips were mechanically sanded to achieve a good quality bond between the concrete and the reinforcement composite. In addition, all of the vertical bands were connected to the lower foundation through anchor strand composites. This extra reinforcement provided better use of the mechanical properties of the carbon strips.

The RC walls test setup is depicted in Fig. 3. The test specimens were subjected to displacement control lateral loading with the walls acting as cantilevers. The axial load ratio of the applied axial load to the axial load capacity at the concrete section had a significant influence on the shear wall's performance, deformability and failure modes [22,23]. The axial load ratios used in earlier studies for wall tests based on specimen models and material properties ranged from 0.03 to 0.85 [24–26].

Four of the five specimens were retrofitted using the CFRP material. The reinforcement configuration used for each short wall is briefly discussed in the following section.

The first specimen, "Wall S1", was subjected to a monotonic load test and was not retrofitted. This specimen was tested as a control specimen and used to observe the RC wall failure mode (Fig. 2(a)).

The second short wall specimen, labelled SR2, was retrofitted by bonding eight CFRP strips onto each wall face to improve its shear strength and to control cracking within the wall panel (Fig. 2(b)). On each face, four strips were bonded along the vertical axis of the wall, and four were bonded in the transverse direction. The

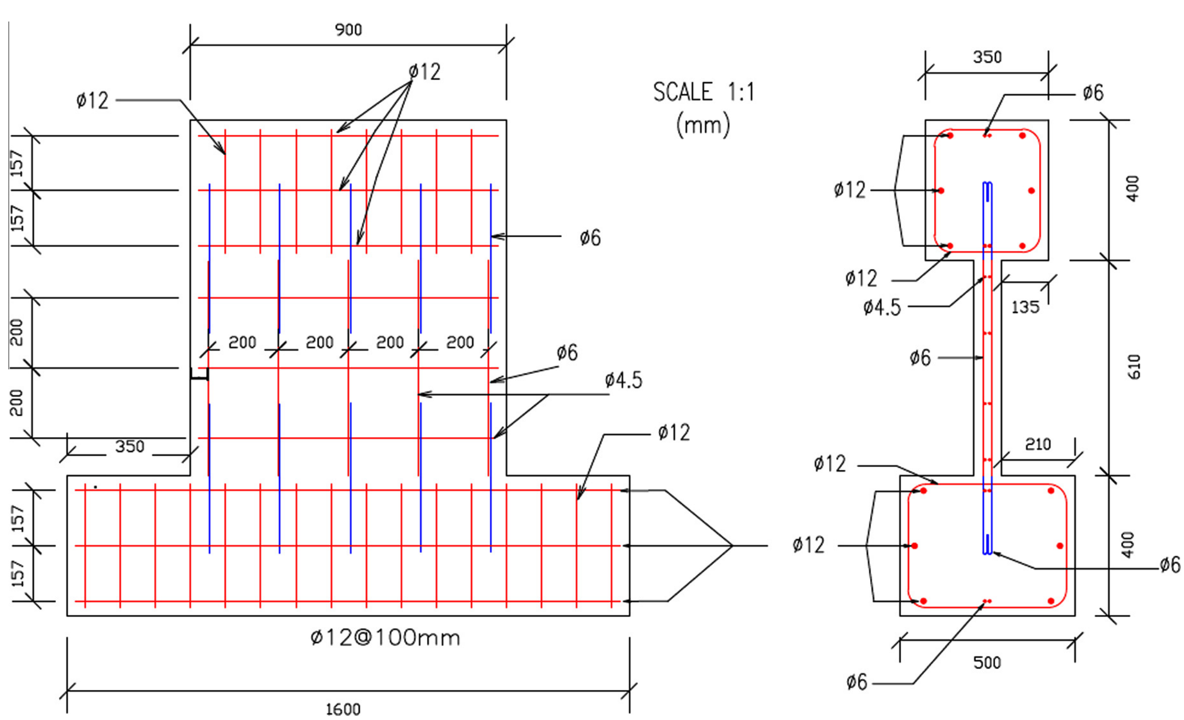

Fig. 1. RC short wall geometric and reinforcement details.