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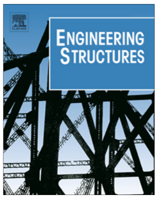

Numerical modelling of reinforced concrete walls with minimum vertical reinforcement

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A B S T R A C T

Recent experimental results have shown that current minimum vertical reinforcement limits in many concrete design standards are insufficient to ensure that large ductility can be achieved during earthquakes. A detailed finite element model was developed in VecTor2 to provide a tool for further investigating the seismic behaviour of lightly reinforced concrete (RC) walls. The model was verified using experimental data from recent RC wall tests with minimum vertical reinforcement, and was shown to accurately capture both the overall response and local response parameters with good accuracy such as the cyclic hysteresis response, crack pattern, and vertical reinforcement strains. The model could also be used to estimate the drifts at which reinforcement buckling initiated and when reinforcement fractured occurred. The results from additional analyses showed that a potential size effect exists when considering the failure of lightly reinforced concrete walls. When keeping the reinforcement ratio and shear span ratio constant, the lateral drift capacity decreased significantly as the wall length increased. Using reinforcement with higher strength and lower ductility did not significantly impact the crack pattern, but did decrease the lateral drift capacity of the walls. Furthermore, reducing the strain hardening ratio of the reinforcement, or increasing the concrete strength, both resulted in a reduction in secondary cracking in the plastic hinge region and a reduced lateral drift capacity. It is recommended that wall length and average material properties should be accounted for when assessing the seismic behaviour of lightly reinforced concrete walls or when developing design standard requirements.

1. Introduction

In regions of low or moderate seismicity, reinforced concrete (RC) walls with minimum vertical reinforcement are common when the dimensions of the wall are larger than that required for strength, or when axial loads provide sufficient flexural capacity. Recent research suggested that the minimum vertical reinforcement limits in the current version of the New Zealand Concrete Structures Standard, NZS 3101:2006 [1], may be insufficient to ensure that a large number of distributed cracks form in the plastic hinge region of RC walls [2]. A series of tests were recently conducted on six RC walls designed in accordance with the current minimum vertical reinforcement requirements in NZS 3101:2006 [3]. The test results confirmed that RC walls designed with minimum allowable distributed vertical reinforcement are unlikely to form a large number of secondary cracks in plastic hinge region, with the behaviour of the test walls controlled by 1–3 large primary flexural cracks at the wall base. The observed performance of these six test walls was better than that observed in several lightly reinforced concrete walls that were damaged during the 2010/1011 Canterbury Earthquakes, where a single crack occurred at the wall base [4]. However, behaviour dominated by a limited number of wide flexural cracks can still lead to premature fracture of vertical reinforcement and low lateral drift capacities.

The tests conducted by Lu et al. [3] included six RC walls with identical dimensions that were approximately 40–50% of full-scale. Three parameters were varied during the tests, including shear span ratio, axial load, and anti-buckling ties. Other important variables such as wall dimension and scale, reinforcing steel properties, and concrete strength were not investigated during these tests. The effect of these parameters have been studied by numerous researcher for RC beams, however, there is limited existing research that highlights how these parameters influence the behaviour of RC walls with minimum vertical reinforcement. To investigate a wider range of parameters for lightly reinforced concrete walls, a numerical model capable of accurately capturing both the overall and local response was required. Despite extensive modelling techniques existing for RC walls, few numerical models have been developed or verified for flexure-dominant lightly

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reinforced concrete walls. Wibowo et al. [5] proposed a lumped plasticity model for lightly reinforced concrete walls for use as a simple design tool, but this technique does not model the local behaviour and so cannot accurately capture the crack distribution or lateral drift capacity when considering different failure modes.

The aim of this study was to develop a reliable model of lightly reinforced concrete walls that can accurately capture the overall lateral load response in addition to local response parameters such as crack pattern and reinforcement strains. A detailed finite element model was developed using plane stress membrane elements in VecTor2 and was verified against experimental results from recent tests on RC walls with minimum vertical reinforcement. Additional analyses were conducted using the developed model to investigate the effect of key parameters that were considered important for lightly reinforced concrete walls, but had not previously been investigated experimentally. Recommendations are provided regarding how these parameters should be accounted for when designing or assessing the seismic behaviour of lightly reinforced concrete walls.

2. Review of RC wall modelling

A large number of modelling approaches have been proposed for RC walls. These modelling approaches can generally be divided into four main categories: lumped plasticity models, macro models, distributed plasticity fibre element models, and continuum finite element models. Each modelling technique has advantages and disadvantages and may be suitable for different applications. To model the seismic behaviour and drift capacity of lightly reinforced concrete walls, it is important to capture both the overall lateral load response and local response parameters such as crack formation and reinforcement and concrete strains. Lumped plasticity models are simple and efficient but require extensive calibration with experimental data and can only predict the overall response rather than cracking and reinforcement strains at the wall base [5,6]. Distributed plasticity fibre based elements and macro models, such as truss models and multi-spring models, are shown to balance the efficiency of a simplified model and the refinements of a microscopic model. These models can accurately capture the lateral load response, energy dissipation, and stiffness degradation, and also local response parameters in ductile flexure dominant RC walls [7–10]. However, fibre element or macro models cannot accurately predict the behaviour of lightly reinforced concrete walls that exhibit limited flexural cracking and localisation of strains prior to and during failure. Continuum finite element models that use membrane, shell, or solid elements can provide the most detailed global and local response parameters in RC walls, but require increased computational effort and accurate multi-axial, nonlinear cyclic constitutive material models. When correctly implemented, finite element models can provide accurate estimation of RC crack development and local material strains [11–14].

VecTor2 [15] is a two-dimensional nonlinear finite element program specifically designed for modelling RC members. It implements both Modified Compression Field Theory [16] and the Disturbed Stress Field Model [17] to predict the response of elements subject to in-plane normal and shear stresses. Additionally, VecTor2 uses state-of-the-art material models that can account for compression softening, tension stiffening, tension softening, and tension splitting. In order to accurately capture both the overall response and local crack development, VecTor2 was selected for modelling lightly reinforced concrete walls.

VecTor2 has been used by numerous researchers to model the lateral load behaviour of RC walls. For example, Palermo and Vecchio [18] built VecTor2 models for both shear-dominant walls and flexure-dominant walls. The comparison of modelling and test results showed that VecTor2 could capture overall response for both shear-dominant and flexure-dominant walls with reasonable accuracy. In addition, Model reports by Sritharan et al. [4] and Ghorbani-Renani et al. [12] showed that VecTor2 can accurately simulate the lateral-load response of flexure-dominant RC walls, including initial stiffness, shear deformations, energy dissipation, failure mechanisms, and cracking behaviour. Despite the suitability of VecTor2 for modelling lightly reinforced concrete walls, most previous studies have used it to model ductile RC walls with heavily reinforced end regions that generate well distributed secondary cracks. Luu et al. [13] used VecTor2 to model a slender 8-story lightly reinforced concrete wall with debonded reinforcement that was tested on a shake table and more recently Almeida et al. [19] built a VecTor2 model for a T-shaped lightly reinforced concrete wall with a total vertical reinforcement ratio of 0.51%. However, the walls considered by both of the studies were not representative of the lightly reinforced flexure-dominant concrete walls that exhibit discrete cracking behaviour. Validation of a numerical model capable of capturing the discrete flexural cracks and localisation of inelastic reinforcement strains was required to investigate a wider range of parameters for lightly reinforced concrete walls.

3. Finite element model

As discussed previously, VecTor2 [15] was selected for analysing lightly reinforced concrete walls that controlled by discrete cracking behaviour. Cracked concrete in VecTor2 is modelled as an orthotropic material using a smeared rotating crack approach where the cracks can re-orientate to align with the changing direction of the principal concrete compressive stress field [16]. The post-cracking rotation of the principal stress field is related to the post-cracking rotation of the principal strain field by a rotation lag [17]. Cracking strength is calculated depending on different stress states using Mohr-Coulomb Stress model [15]. In addition, crack shear-slip deformations are accounted for by relating shear slip along cracks to local shear stresses at cracks [20].

3.1. Model description

Diagrams of the lightly reinforced concrete walls tested by Lu et al. [3] and the corresponding models developed in VecTor2 are shown in Fig. 1. The test walls all had the same height, but were subjected to loading that represented three different shear span ratios equal to 2, 4 and 6. Test walls with a shear span ratio of 2 were subjected to horizontal force and axial load at the top of the wall, as shown in Fig. 1-a, while test walls with a shear span ratio of 4 or 6 were subjected a combination of horizontal force, axial load, and moment at the top of the wall, as shown in Fig. 1-c. The models were built for the test wall region with identical dimensions, material properties and vertical reinforcement details. For the walls with a shear span ratio of 2, a rigid beam element was used to model the steel loading beam and the loading height was the same as that of the test, as shown in Fig. 1-b. For the walls with shear span ratio larger than 2, a rigid region was also modelled to simulate the increased height of the prototype wall and to generate the same moment and shear actions at the top of the test wall, as shown in Fig. 1-d. For the model, the lateral displacement was applied on the top of the rigid region of the wall, but the lateral drift was monitored at the same height as the test walls to achieve a comparable lateral displacement loading protocol. For all the wall models, the axial load and lateral drift targets applied during the model analyses were identical to those applied to the test walls. Axial compression was applied at the top of the test wall region uniformly and held constant during the model analyses.