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Flange effects on seismic performance of reinforced concrete squat walls with irregular or regular openings

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ABSTRACT

A series of six one-third scaled reinforced concrete (RC) structural walls with irregular or regular openings were tested to investigate the effects of size, arrangement, and irregularities of the openings on the seismic behaviour of RC walls. The crack pattern development, failure mechanism, and hysteretic responses of tested specimens are presented. The stiffness deterioration and equivalent hysteretic damping (energy absorption capacity) of tested specimens are compared and discussed. Another series of six rectangular walls with openings, which are tested by Yanez et al., are also introduced for quantification of the flange effects on seismic behaviour of RC walls with openings. It is found that flanges could significantly increase ultimate strength but reduce deformation capacities. Moreover, flanges may change the failure mode of rectangular walls from ductile flexural failure to brittle sliding shear failure. Flanges may aggravate the concrete crushing, spalling as well as buckling and fracture of vertical reinforcements. However, concrete crushing and rebar fracture is mainly concentrated in the flanges.

1. Introduction and background

Structural walls make up a crucial part of most tall buildings, providing structures with sufficient stiffness while minimizing deformations and damage to non-structural elements. These walls are also capable of providing sufficient strength, deformation, and energy dissipation capacities when subjected to severe seismic excitations to prevent collapse and casualties. During its design phase, walls often require openings to accommodate windows, doors or utility ducts. The effects of these openings are often ignored as their sizes are relatively small when compared to the wall dimensions. However, in the case where these openings are relatively large or located within a critical region, they may influence the seismic behaviour of RC walls significantly. The large openings could change the force transfer mechanism within RC wall, reducing its strength, stiffness, as well as its deformation capacity.

Majority of previous studies on structural walls are focused on the solid walls without openings or coupled wall systems. Su and Wong [1] experimentally studied the effects of axial load ratio and confinement on the seismic behaviour of RC rectangular walls. It was found that the effectiveness of confinement is highly dependent on the arrangement of the transverse reinforcement. The axial load ratio has significant influence on the deformability and failure mode of the specimens. The maximum rotation ductility decreased with increases in the axial load ratio. Paulay et al. [2] discussed the failure modes of rectangular shear walls. The efficiency of diagonal crossing rebar for preventing the sliding shear failure was also addressed. Alarcon et al. [3] experimentally examined the effects of axial loads on the seismic behaviour of RC rectangular walls with unconfined boundaries. It was found that high axial load has a significant effect on the seismic performance and failure mode of RC walls. Indeed, the high axial load will trigger a dangerous brittle concrete crushing failure which occurs immediately after spalling of the concrete cover. Subedi [4] proposed an analytical method to predict the failure mode and the ultimate strength of coupled shear wall structures. It was found that the behaviour of RC coupled shear wall structures is greatly influenced by the stiffness of the coupling beams. Additional research was conducted afterward [5,6]. The proposed method could predict the failure modes of test specimen well. Hube et al. [7] conducted six tests to study the seismic behaviour of RC rectangular slender walls with different wall thickness, wall aspect ratio, and different amount of stirrups in boundaries. It was found that closed stirrups and cross-ties could increase the displacement capacity and ductility effectively. In addition, closed stirrups were able to prevent out-of-plane buckling of the wall after compression failure effective. Li and Xiang

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Nomenclature

A_h	area enclosed by a hysteretic loop
A_o	opening area
A_w	gross area of the wall
α	angle between the diagonal and the side of rectangle
F_m	peak loading of the loop of each loop
h	depth of the coupling beam
h_w	vertical distance from the lateral loading point to the wall base
L	length of the diagonal
l_n	clear span of the coupling beam
P	theoretical ultimate strength of the test specimen
I_e	equivalent moments of inertia of the coupling beams
I_g	moment of inertia of the uncracked gross concrete section of the coupling beams
Δ	top drift imposed to the structure
Δ_1, Δ_2	deformations of the panel diagonals, which are positive when they are in extension
Δ_m	displacement of the loop of each loop
Δ_y	structural yield displacement

[8] proposed an analytical method to evaluate the effective stiffness of RC rectangular walls. Based on the parametric case studies, a simple equation was proposed for assessing the effective stiffness of RC structural walls. However, the walls usually have some openings according to the intention of the architectural design, and the opening ratio, locations and shapes may affect their seismic behaviour significantly. Thus, it is necessary to understand the seismic behaviour of RC walls with openings.

Comparing to solid walls, the studies on RC walls with openings are relatively less. Ali and Wight [9] conducted a series of tests to study the effects of staggered door openings on the seismic behaviour of RC walls. It was found that the door openings located to close to the edge of the boundary column zone will remove the in-plane confinement and can trigger an early shear-compression failure. Moreover, the walls with staggered openings could decrease the energy dissipation capacity up by 29%. Yanez [10,11] tested a series of rectangular RC walls with irregularly distributed openings. It was found that the size and arrangement of the openings did not have a significant effect on the behaviour of the walls under cyclic lateral loading. The strut-and-tie models predicted the ultimate strength of the walls with irregular openings conservatively. Although existing studies had improved the understanding and design tools of the seismic behaviour of RC walls with openings significantly [12,13], more studies still should be carried out for the walls incorporating flanges as the flanges may change the seismic behaviour of RC walls with openings significantly [14,15]. In this study, the effects of flanges on the seismic behaviour of RC walls with openings were quantified by comparison of two series of tests: S and S-F where S and S-F represent rectangular walls without flanges and barbell walls with flanges. As the results of S series specimens had been introduced in [10] in detail. Therefore, the presentation of the results of S-F series specimens and discussion of the flange effects are the main focus of this paper.

2. Experimental program

A series of six RC flanged walls with openings (S-F series) were designed and tested under quasit-static cyclic lateral loading. In addition, for easier evaluation of the flange effects, the tests of another series of specimens (S series), which were tested by a previous study Yanez et al. [10], were also introduced briefly.

2.1. Test specimens

Fig. 1 illustrates the dimensions and reinforcement details of tested specimens. As shown in Fig. 1, S-F series specimens have three subassemblies which are as follows: (a) the top beam, (b) the web, and (c) the foundation beam. It is 2000 mm wide, 2300 mm high and 120 mm thick, with aspect ratio about $h_w/l_w = 1.27$, where $h_w = 2540$ mm is the vertical distance from the lateral loading point to the wall base (refer to Fig. 1) while $l_w = 2000$ mm is the length of the wall. S-F1, which served as a control specimen, is a solid wall without openings. S-F2, S-F3, and S-F4 have irregularly distributed openings while S-F5 and S-F6 have regularly distributed openings. Specimens S-F2, S-F3, and S-F5 have 600 mm x 600 mm openings and have opening ratio of 23.5%, defined as (A_o/A_w), where A_o and A_w are the opening and wall area, respectively. However, Specimens S-F4 and S-F6 have 400 mm × 400 mm openings and an opening ratio of 10.3%. The concrete clear cover to the horizontal bars, which are placed outside the vertical bars, is 14 mm and 18 mm to the wall faces and sides, respectively. Fig. 2 gives the dimensions and reinforcement layout of S-series specimens while Fig. 3 gives the horizontal sections of the walls. As shown in Figs. 1–3, S-F and S series specimens have similar dimensions and reinforcement details varying only in terms of the presence of flanges at their boundaries.

Following the provisions of NZS 3101 [16], the solid walls S-F1 and S1 are designed based on conventional flexural design by assuming the walls are cantilever. The horizontal design force applied on top of the specimen along the axis of top beam is 353.3 kN based on the measured properties of reinforcing bars and concrete. The web horizontal and vertical reinforcement ratio of S-F1 is determined as 0.5%. For the typical hooks in the horizontal reinforcements, please refer to Fig. 3. However, 135-degree bends were utilized for the hooks in the boundaries of the wall or the flanges,

Specimens S-F2, S-F3, and S-F4 with irregular openings are designed by strut-and-tie models, similar to the models proposed by Yanez et al. [10], due to the complexity of the stress distribution and invalidity of plane assumption. Figs. 4–6 present the models corresponding to the positive and negative directions of loads. The web reinforcements of these walls with irregular openings are located following the tensile load paths (ties) of the models. However, the numbers of vertical and horizontal reinforcement of these specimens keep similar to that of S-F1. Therefore, the vertical main bars of the flanged walls with irregular openings are distributed in the column zones between the openings and the bottom panels. The horizontal main bars are distributed in the beam zones. In the other zones, secondary reinforcements, which are assigned to limit the crack opening, are applied. Moreover, the magnitude of theoretical ultimate strength (P) of these S-F2, S-F3, and S-F4 are determined using the strut-and-tie models based on the measured properties of reinforcing bars and concrete. It should be noted that the ultimate strength of these three specimens in negative loading direction may different to their positive ultimate strength due to their irregularly distributed openings, which lead to different load paths in negative and positive loading directions. For S-F2, the negative ultimate strength is determined as −214.2 kN and it is controlled by the capacity of tie AG, where 6T10 bars are lumped. Controlled by the yielding of horizontal tie LK, the positive ultimate strength is predicted as 220.0 kN.