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Coupled axial tension-shear behavior of reinforced concrete walls

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ABSTRACT

Reinforced concrete (RC) shear walls in high-rise buildings may experience coupled axial tension-shear loading when subjected to strong ground motions. To understand how the tensile force influences shear strength and stiffness of RC walls, a series of quasi-static tests are conducted on six wall specimens with low aspect ratios. The failure modes of the specimens vary with different degrees of axial tension forces, which include diagonal tension failure (without tensile force), shear-sliding failure (under low to moderate tensile force) and sliding failure (under high tensile force). Increase of axial tensile force leads to linear decrease of the shear strength capacity of RC walls, with a factor of approximately 0.35. Sliding shear strength of specimens subjected to high axial tension is only 24%–33% of the shear strength capacity of the specimen not subjected to axial tension. High axial tensile force also results in a significant decrease in lateral stiffness of the walls. In addition, the axial tensile behavior of RC wall specimens is also presented to validate various tension-stiffening models of cracked concrete. Finally, design formulae of shear stiffness and strength of RC walls under axial tension are estimated, using the data from this experimental program and past tests. The strut-and-tie model provides a reasonable estimate of effective lateral stiffness of low-aspect-ratio RC walls under low to moderate tensile forces. The design formulae specified in ACI 318–14 (U.S.) code provide a conservative estimate of the shear strength capacity of the RC walls subjected to tensile forces. The average experimental-to-calculated ratio is 1.68. However, the JGJ 3–2010 formulae (China) tend to overestimate the shear strength capacity of RC walls under moderate axial tensile forces, with an average experimental-to-calculated ratio of 0.93.

1. Introduction

Shear walls are widely used as the major lateral load-carrying structural components in high-rise buildings. Under strong ground motions, some reinforced concrete (RC) shear walls may be subjected to combined axial tensile forces and shear forces. In such a critical loading condition, RC walls are susceptible to significant structural damage and failure, as observed in the 2010 Chile earthquake [1].

Quasi-static tests [2–4] and shaking table tests [5] of tall building models have shown that RC walls may be subjected to coupled axial tension-shear forces. One such example (Fig. 1a) shows that, if the coupled wall has a high coupling ratio, the tensile force induced by shear forces of coupling beams in the single-sided wall pier may exceed the applied gravity load. The wall pier will sustain axial tensile forces, combined with shear forces induced by lateral loading. Another example of core walls under bi-directional ground motion (Fig. 1b) shows that the peripheral wall is subjected to tensile forces caused by a large overturning moment from lateral loading in the x-direction and shear forces induced by lateral loading in the y-direction. Past research indicates that axial tension leads to decreased stiffness and strength of RC walls, and consequently results in lateral force redistribution among walls [2,3]. Therefore, in seismic design of high-rise buildings, special attention shall be given to RC walls if they are subjected to coupled axial tension-shear loading.

In practical design, the solution to the possible adverse influence of axial tensile force is to limit the level of tensile force applied on RC walls. For example, in accordance with the Chinese Technical Guideline of Peer Review for Seismic Design of Super-Tall Buildings [6], the nominal tensile stress of RC walls ($\sigma_n = T/A$) shall be less than the tensile strength of concrete (f_t) under design basis earthquakes (DBEs). T denotes the axial tensile force applied at the wall section and A denotes the gross cross-sectional area of the wall. Otherwise, the use of steel reinforced concrete (SRC) walls or steel-plate composite walls is suggested in which the steel profiles or plates are added in the walls [7–9], for enhancement of the wall's resistance to combined axial tension and shear loading. Nevertheless, this design provision is majorly

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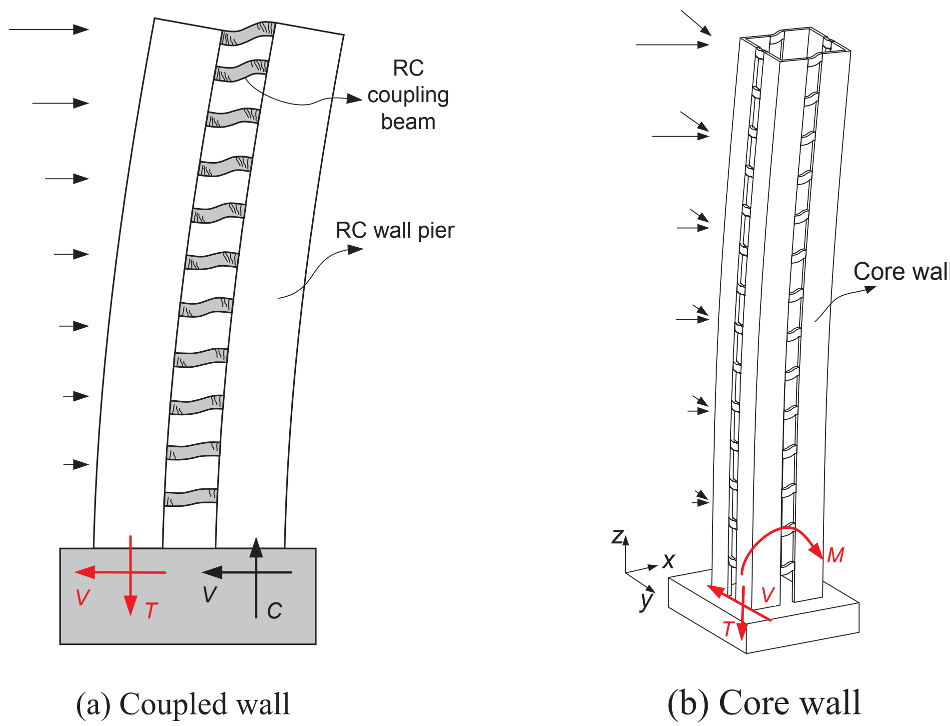

Fig. 1. RC walls undergoing coupled axial tension-shear forces.

based on engineering judgement.

More recently, effort has been devoted to the study of tension-shear behavior of RC walls and composite walls. Wang et al. [10] conducted experimental tests of five RC wall specimens with a shear-to-span ratio of 1.45, where the specimens were subjected to the axial tensile forces and cyclic shear loading. Dense boundary longitudinal rebar, corresponding to a 10.9% reinforcement ratio of the boundary elements, were intentionally used to ensure that flexural strength of the wall specimens exceeded their shear strength. These wall specimens failed in diagonal tensile failure. The wall's shear strength and stiffness was found to significantly decrease with an increase of axial tensile forces. Fang et al. [11] conducted experimental tests on nine steel tube-reinforced concrete wall (ST-RC) specimens, where the steel tubes were embedded in the RC walls for enhancing their seismic performance. The test variables included the axial tensile force, concrete compressive strength, reinforcement ratio, and shear-to-span ratio (ranging from 0.5 to 1.0). Shear failure was observed for all specimens. While the presence of axial tensile force had unfavorable effect on the lateral strength and stiffness of ST-RC walls, the addition of embedded steel tubes could provide increased tensile-shear strength and deformation capacities relative to RC walls.

The objective of this study is to determine how axial tensile forces influence failure mode and the strength and stiffness of RC walls with low shear-to-span ratio under cyclic shear reversal. An experimental program is presented that involves six wall specimens subjected to tensile forces and cyclic shear loading. The test results are detailed in terms of failure mode, hysteretic response, and shear strength and deformation capacities. Various tension-stiffening models of cracked concrete are validated using axial tension test data. Finally, estimates of relevant design formulae of the shear stiffness and strength of RC walls under tensile forces are presented in comparison with test data.

2. Experimental program

2.1. Test specimens

Test specimens were designed to represent shear walls in the lower story of a high-rise building and were fabricated at approximately one-third-scale to accommodate the capacity of loading facility. The shear-to-span ratio of the walls varies in different situation and loading cases, which is influenced by the structural layout, high mode effect, and ground motions, etc. This paper presents the experimental tests of RC walls with a relatively low shear-to-span ratio of 1.1. The experimental tests for RC walls with moderate and high shear-to-span ratios will be reported in future papers. A total of six shear wall specimens (SW1 to SW6) were designed and fabricated, each with identical dimensions and reinforcement details. As shown in Fig. 2, the clear height of wall specimens above the foundation was 1.35 m, with a sectional depth and thickness of 1.5 m and 0.18 m, respectively. The foundation and top beams were intentionally designed with large dimensions and heavy reinforcement to ensure they remained damage-free during testing. The foundation beams were fabricated first, followed by construction of the wall and top beams. The surface of the hardened concrete of the foundation beam was carefully roughened before casting of the wall concrete to mitigate the adverse influence of construction joints.

Eight D22 (diameter of 22 mm) steel reinforcing bars (hereinafter referred to as rebar) were used as boundary longitudinal reinforcement for all specimens, corresponding to a 5.6% reinforcement ratio (the ratio of gross cross-sectional area of longitudinal rebar to that of the boundary element). The high reinforcement ratio was intended to ensure that flexural strength of the wall specimens exceeded their shear strength capacity.

D10 steel rebar was used as vertically distributed reinforcement in the web of the specimens at a spacing of 150 mm, which corresponds to a 0.58% reinforcement ratio. D8 steel rebar was used as horizontally distributed reinforcement at a spacing of 150 mm, corresponding to a 0.37% reinforcement ratio. The boundary transverse reinforcement consisted of D8 steel rebar fabricated as rectangular hoops with a vertical spacing of 100 mm (1.5% volumetric transverse reinforcement ratio). The distributed reinforcement ratio and the boundary transverse reinforcement satisfied the requirement of ductile walls specified in the Chinese Technical Specification for Concrete Structures for Tall Buildings (JGJ 3-2010) [12].

The strength grade of concrete used in the wall specimens was C55