A Reconnaissance Survey on Shear Wall Characteristics in Regions of Low- to-Moderate Seismicity

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ABSTRACT

Structural walls are the prevalent lateral-load-resistant systems in medium- to high-rise constructions and are commonly configured as “tubular elements” which are known as the building core. Isolated walls are more popular in shorter buildings. Whilst structural walls constructed in recent times have typically been designed to meet ductility requirements (that are stipulated by building codes of practices) a substantial number of existing buildings in regions of low-to-moderate seismicity have not been assessed for their potential seismic performance. A reliable estimate of the typical design parameters of slender shear walls would be required if a simplified displacement-based design procedure is to be developed. A field reconnaissance survey was conducted on eight buildings: four in Saudi Arabia, three in Australia, and one in Malaysia. The buildings were in the low- to high-rise ranges (ie. 3, 4, 6, 9, 21, 23, and 32 storeys). The typical parameter values identified from the field surveys, namely the axial load ratio, aspect ratio (height/length), geometry of wall cross-section, and the amount/distribution of longitudinal and transverse reinforcement will be reported in details in the paper. These parameters are important as they influence the force–displacement monotonic and hysteretic behaviour of the wall.

Keywords: slender shear walls, longitudinal reinforcement, axial load ratio, transverse reinforcement ratio.

1. INTRODUCTION

Shear walls are the preferred lateral load resisting system, because of their huge reserve in strength and stiffness characteristics which in turn safeguard non-structural elements from damage caused by excessive displacement demand (Elnashai, Pilakoutas & Ambraseys, 1990). As to current design philosophy, building codes stipulate stringent design checks and detailing requirements to maintain prolonged stable and ductile behavior in the inelastic range and to avoid any premature brittle failure. However, most of the existing buildings particularly old buildings in regions of low to moderate seismicity were designed to carry gravitational loads only and have not been checked for seismic compliance.

Developing a realistic and simplified displacement based assessment procedure (including the imposed demand and displacement capacity) for lightly reinforced walls in regions of low to moderate seismicity is one of the primary goals of the long term research strategy of the authors. The force-displacement backbone curve (and the hysteretic model used in nonlinear time history analyses) are essential elements on the assessment of the seismic demand and capacity behavior. This force-displacement relationship varies with the wall geometry along with other design parameters such as axial load ratio, aspect ratio, and longitudinal and transverse reinforcement ratios. A field reconnaissance survey was conducted on eight buildings in an effort to support the author’s investigation with representative design parameters for structural walls in regions of low to moderate seismicity.

2. OVERVIEW OF THE FIELD SURVEY BUILDINGS

Eight buildings were analysed: four in Saudi Arabia, one in Malaysia and three in Australia (details of those buildings are listed in Table 1). They are common in that they are all located in regions of low to moderate seismicity. Those buildings were analysed to determine the typical values adopted in practice with respect to the wall axial load ratio, aspect ratio, longitudinal and horizontal reinforcement ratios, as well as wall geometry. A detailed discussion on the mentioned parameters will be presented in the subsequent sections. The following assumptions were made in the analysis process:

- Given that walls’ properties (e.g., reinforcement quantity and axial load) vary with height, the most critical section of the wall (the ground floor segment) was considered.
- Not all walls in the buildings have been included in the analysis, e.g., when different wall shapes existed, a representative sample from each wall shape was selected (one or more).
- Walls that contained a large number of openings were excluded to avoid the associated complexity of reinforcement calculations.
- Core or L-shape walls were conservatively simplified into isolated rectangles which resulted in more indicative design parameters (e.g., reinforcement ratios).

- The axial load was calculated based on data obtained from the structural drawings. However, in cases of missing data (e.g., the dead and live loads), appropriate assumptions have been made.

Table 1: Details of the Field Survey Buildings.

Building No.	Location	No. of Floors	Type of Occupancy	Type of the Main Lateral Resistance System
Building 1	Al-Taif, Saudi Arabia	3	Hospital/community center	One core
Building 2	Al-Taif, Saudi Arabia	4	Residential	One core Five rectangular Two L-shape
Building 3	Jeddah, Saudi Arabia	6	Hospital	Three cores one L-shape
Building 4	Riyadh, Saudi Arabia	9	Offices	Two cores Eight rectangular
Building 5	Melbourne, Australia	23	Residential	One core
Building 6	Melbourne, Australia	23	Residential	Two cores
Building 7	Melbourne, Australia	32	Residential	One core
Building 8	Kuala Lumpur, Malaysia	21	Residential	One core

3. DESIGN PARAMETERS DISCUSSION

3.1. AXIAL LOAD RATIO

The axial load ratio is calculated as the ratio of the axial load applied on a structural member to the member axial compression capacity, which is known by the term (n) as shown in equation 1.

$$n = \frac{P}{f_c^{'} A_g} \tag{1}$$

where P is the axial force imposed on a structural member, $f_c^{'}$ is the concrete cylinder compressive strength, and A_g is the concrete cross sectional area.

The axial load ratio was calculated based on service conditions (Dead load + live load) for 35 walls as presented in Fig. 1. The calculated axial load percentage was low in general; 75% of the walls had an axial load ratio of 5% or less. The highest percentage did not exceed 10% for walls of different heights (3 floors to 32 floors). A field survey conducted on 17 buildings in Hong Kong and China showed that the upper bound of the axial load percentage is about 20% under service load conditions (Su & Wong, 2007; cited in Su, Lam & Tsang, 2008). Such a minor variation might be attributed to the higher reliance on the building core which was built alongside a gravity load bearing system as featured in many high rise buildings located in Hong Kong and China.

The observations from the two field surveys are also compatible with experimental tests reported in the literature. Experimental investigation on slender walls tested in Hong

Kong and China adopted very high axial load ratios of well over 20%, as featured in tests conducted by Zhang and Wang (2000), Wong (2005), Liang et al. (2010), Li & Li (2010) and Cao et al. (2010). On the other hand, tests conducted in other regions featured low axial load percentage that ranged from 0 to 10% (e.g. Thomson & Wallace, 2004).

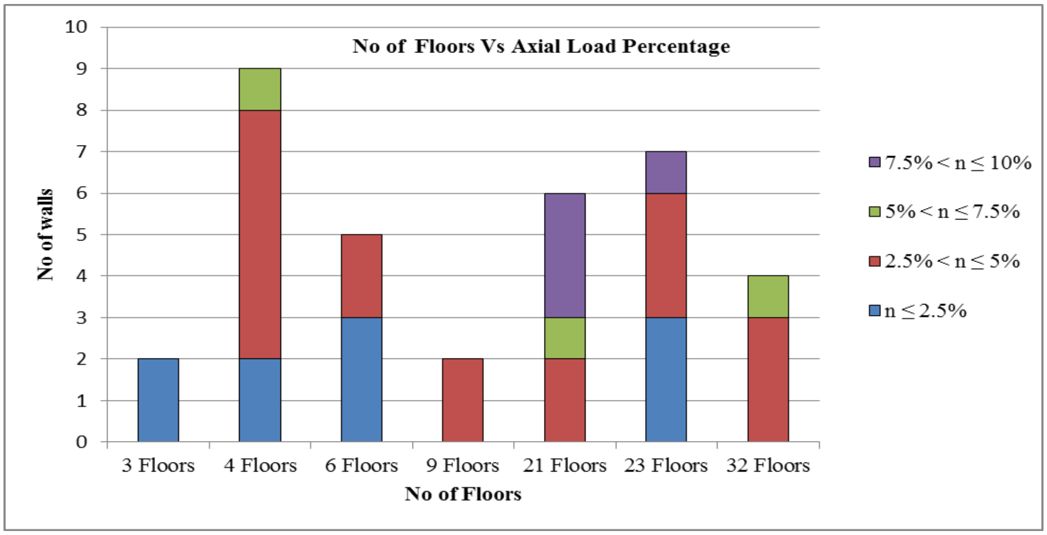

Fig. 1: Number of Floors vs Axial Load Percentage.

3.2. WALL ASPECT RATIO

The wall aspect ratio is commonly adopted to quantify the slenderness of a structural wall, and is defined as the ratio of the wall height to the wall length at the base (H/L). This quantity is often confused with the shear span ratio which is expressed as the shear span length (distance from the critical section to the point of contra-flexure) relative to the wall length. However, the shear span ratio becomes identical to the aspect ratio only in the case of a cantilever loaded at its tip by a single lateral load.

According to the walls investigated in the survey, the wall aspect ratio ranged from three to about thirty (Fig. 2). Furthermore, the aspect ratio of more than 90 percent of the walls was higher than 6. The appearance of a high aspect ratio was not limited to medium and high rise buildings; relatively short buildings also showed a high aspect ratio (e.g., 10 for four story buildings). In fact, the wall aspect ratio as obtained from this survey was very high in comparison with slender walls tested in previous studies. Based on the literature reviewed by the authors, the highest aspect ratio adopted experimentally was about 7.2, by Adebar, Ibrahim and Bryson (2007), while the majority of the slender walls were between 2 and 3. Such a variation between the tested walls and the real ones (field survey) was sourced from the researcher's interest in simplifying the dynamic earthquake loading into a single lateral load acting at a distance of (M/V) from the base of the wall as opposed to testing the entire wall (where M and V are the ultimate moment and shear force at the critical cross section respectively). It should be noted that the value of M/V varies significantly based on the method of calculating the earthquake demand (static or dynamic). As an example, Ali and Wight (1990) conducted an experimental work on a prototype wall with an aspect ratio of 6 which was reduced to a much lower value of 2.9 when considering the critical length of the wall only.

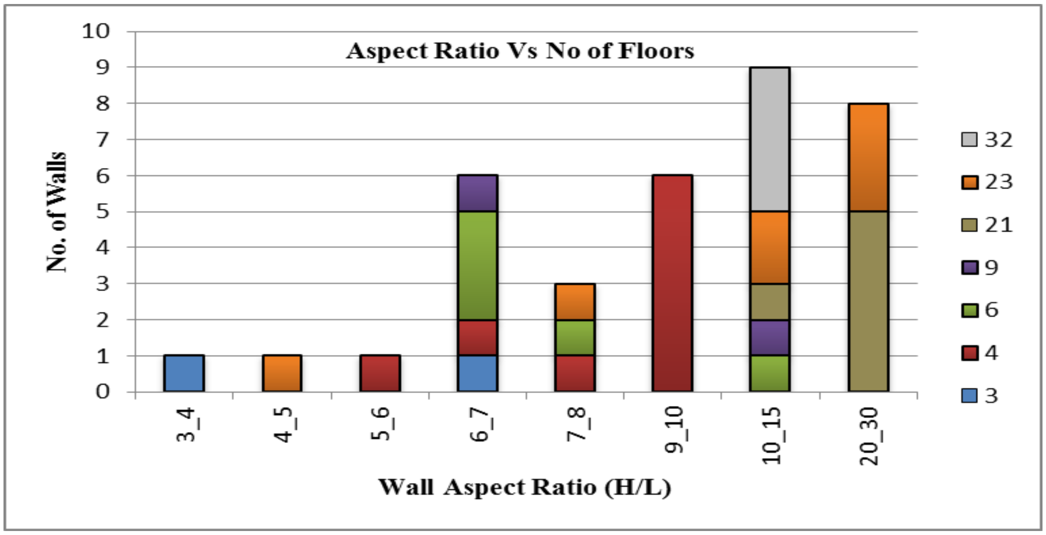

Fig. 2: Aspect Ratio Distribution vs No of Floors.

3.3. LONGITUDINAL RIENFORCEMENT RATIO

The gross longitudinal reinforcement content is expressed as the ratio of the steel reinforcement area to the concrete cross-sectional area. This definition delivers a good indication only if the reinforcement is uniformly distributed over the wall cross-section. In real practice, engineers tend to increase the section efficiency by concentrating most of the reinforcement at the wall boundaries and providing minimum steel at the wall web. As a result, the web reinforcement ratio can be calculated separately as the web steel area to the web concrete area.

According to the data obtained from the field survey analysis, longitudinal steels were typically congregated around the wall edges and less steel proportion was distributed over the wall web. The gross longitudinal steel percentage ranged from less than 0.5% up to 4.5%, as shown in Fig. 3. About 50% of the walls had a percentage of less than 1.5. It should be noted that this field survey incorporated relatively new developments which explains the appearance of high gross longitudinal reinforcement ratios. In other words, old existing buildings are expected to incorporate lower longitudinal reinforcement ratios as they might have been designed to resist vertical loads only.

On the other hand, the longitudinal web reinforcement was very low compared to the gross reinforcement ratio (Fig. 4). Three quarters of the walls covered by the investigation had a steel percentage of less than 1% in the web while higher ratios were found in sections with uniformly distributed steel.

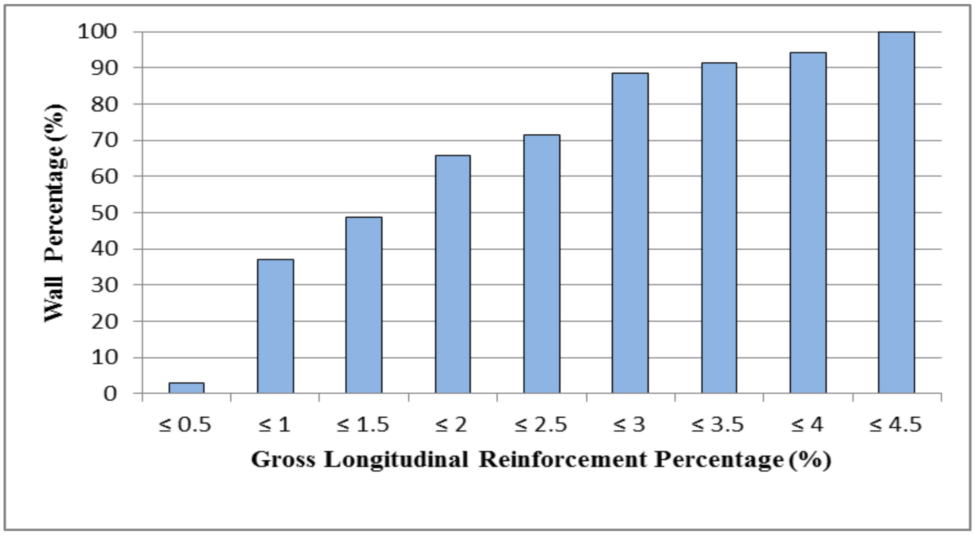

Fig. 3: Gross Longitudinal Reinforcement Percentage.

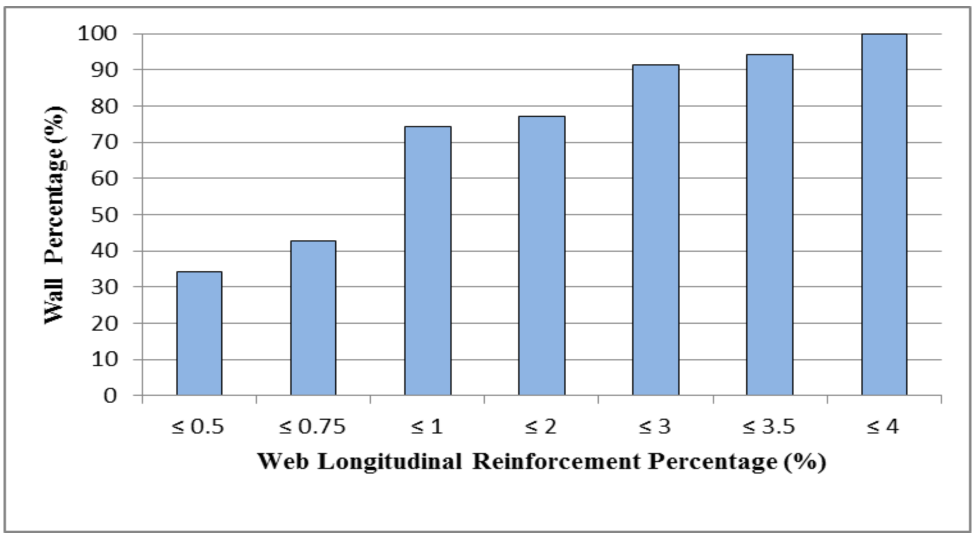

Fig. 4: Web Longitudinal Reinforcement Percentage.

3.4. TRANSVERSE RIENFORCEMENT RATIO

Transverse reinforcement is commonly incorporated in the wall web in the form of a mesh. The amount of the horizontal web reinforcement is estimated based on the expected mode of failure (e.g., diagonal tension or shear failure). Additional reinforcement in the form of hoops at wall boundaries might be added especially if the wall response is dominated by flexure.

The horizontal reinforcement amount can be defined based on the relative steel to the concrete area, the relative volume, or the state of confinement (e.g. the confinement effectiveness factor). However, the first definition is adopted in this survey for both the web and boundary steel.

According to the walls investigated in the field survey, the horizontal web reinforcement content did not exceed 1%, and about two thirds of the walls had an even lower content of less than 0.5% (Fig. 5). This observation is within expectation given that the risk of web shear failure in shear walls (slender walls dominated by flexure) is generally considered to be low. Building codes typically recommend a minimum steel content of 0.25% (e.g., ACI code).

Boundary horizontal reinforcement content ranged between about 0.25% and less than 2% as presented in Fig. 6. It is clear from the graph that about 80% of the walls covered by the survey featured a horizontal reinforcement content of less than 1%; those walls have not been specifically detailed for countering seismic actions and have rather large spacings between the hoops.

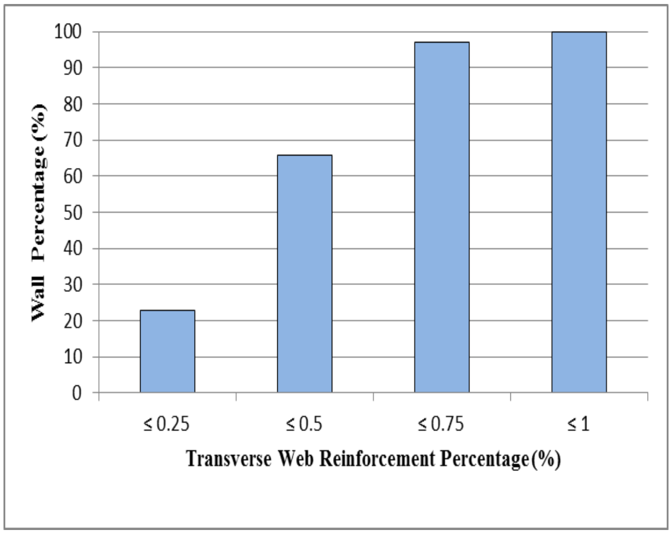

Fig. 5: Horizontal Web Reinforcement Percentage.

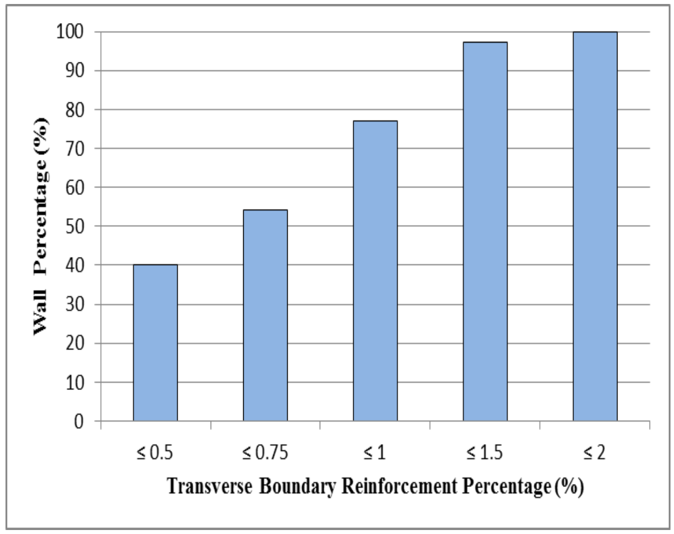

Fig. 6: Horizontal Boundary Reinforcement Percentage.

3.5. WALL SHAPE

It was found from the field survey that structural walls in support of a building featured many different shapes: rectangular, L-shaped or in a configuration of intersecting walls around the lifts and stair-cases (in what is known as the building “core”). In general, isolated (mostly rectangular) walls are likely to be found in shorter buildings while L-shaped and core walls are more common in medium to high rise buildings. Core walls are preferred due to their enhanced flexural capacity (because of the effective flanges of the perpendicular walls).

Although walls with C-channel or flanged shapes could better mimic the behavior of the core walls, the majority of the conducted experimental work used rectangular wall specimens. The common approach in experimental investigations in ignoring contributions from the flanges (by working with rectangular sections) is believed to be motivated by simplicity in terms of maintaining uniform axial loads during the test.

4. CONCLUSION

- This paper reported the findings from a field survey on eight buildings which were located in three different countries to make observations on the typical range of design parameter values on structural walls in regions of low to moderate seismicity.

- The axial load ratio was low in general; the majority of the walls had a ratio of 5% or less with an upper bound of 10%.

- The aspect ratio (wall height/ wall length) was very high; about 90% of the walls had aspect ratios exceeding 6.

- Longitudinal reinforcement mostly congregated around the wall boundaries whereas a minimum amount of steel was allocated to the wall web. The gross longitudinal reinforcement percentage ranged from less than 0.5% and up to 1.5% for 50% of the walls investigated. Given that this survey incorporated relatively new developments, old buildings are expected to incorporate even less longitudinal reinforcement ratios.

- The transverse web reinforcement content was very low in walls with high slenderness ratio (which runs a very low risk of developing shear web failure). Similarly, wall boundaries were not specially detailed as the hoops were widely spaced.

- In medium to high rise buildings, walls are commonly designed in the form of cores or L-shapes. However, isolated rectangular walls are more often found in short buildings.

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