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Effects of axial load on seismic performance of reinforced concrete walls with short shear span

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ABSTRACT

Reinforced concrete (RC) shear walls in tall buildings are found to have a short shear span, particularly in high-degree coupled walls supported on transfer structures in low-to-moderate seismic regions. These non-seismically detailed walls in existing buildings are exposed to a high risk of failing in shear or compression before plastic hinges are formed at their base. Whilst previous research have focused on squat walls used in low-rise structures tested with zero or low axial loads, the structural response of these walls with a short shear span and limited ductility under high axial load is rarely discussed. Therefore, an experimental study that investigates the influence of the axial load ratio (ALR) on RC walls with a short shear span is presented in this paper. The specimens are designed with a low shear span-to-length ratio (SLR) and detailed with a characteristic 2% vertical and longitudinal reinforcement to represent a wall sub-structure above the transfer structure of tall buildings. Four walls are tested under reverse cyclic loading and subjected to target ALRs that range from 0.1 to 0.4 to investigate the seismic performance until gravity collapse. The ALR is found to have significant effects on crack patterns, failure modes and deformability. Two modified empirical prediction models are proposed to estimate the shear strength capacity and ultimate drift ratio of rectangular RC shear walls with a short shear span under the effects of the ALR. A unique model of the drift limit of collapse under axial load as a function of the reinforcement ratio is put forward for performance based design and assessment.

1. Introduction

1.1. Effects of short shear span on shear walls

Conventionally, shear walls were classified in accordance with their physical aspect ratio by using the height-to-length ratio (H/L), which led to the classification of walls as slender cantilever walls in many tall buildings. On the contrary, shear span, which is defined as the storey moment over storey shear ratio ($a = M/V$) as a result of internal stress response to lateral loads, is an alternate definition rather than simply referring to the physical height. The shear span of walls is greatly dependent on the height of the wall, pattern of the loading (a concentrated load or uniformly distributed load) and degree of coupling. A controlled cantilever wall that only allows flexural bending and only shows bending deformation is rare. Reinforced concrete (RC) buildings are either structurally framed with coupled shear walls or designed through the interaction between the wall and frame (dual structures), thus resulting in a certain degree of reverse bending. In regions of low-to-moderately seismicity, highly over-strength coupling beams without strength hierarchy consideration are often used to optimise lateral elastic deflection of coupled shear walls under wind load. The low storey moment and high value of shear resulted in the formation of walls with a short shear span. Such effects are more critical for walls above transfer structures, which are concurrently under gravity and concentration of shear stress from lateral load due to the out-of-plane deformation of the transfer structures [1,2]. Hence, this special class of RC shear wall which has the distinctive features of short shear span and non-strength hierarchy design, is essentially a sub-structure at the base of a shear wall. These non-seismically detailed walls that have limited deformability in existing buildings have a high risk of failing in shear or compression before forming plastic hinges at their base in the event of an earthquake.

Fig. 1 shows a histogram of the shear span-to-length ratio (SLR) of the walls in a 45-storey tall RC building with transfer plates that support 41 storeys. The model was analysed by using ETABS, an

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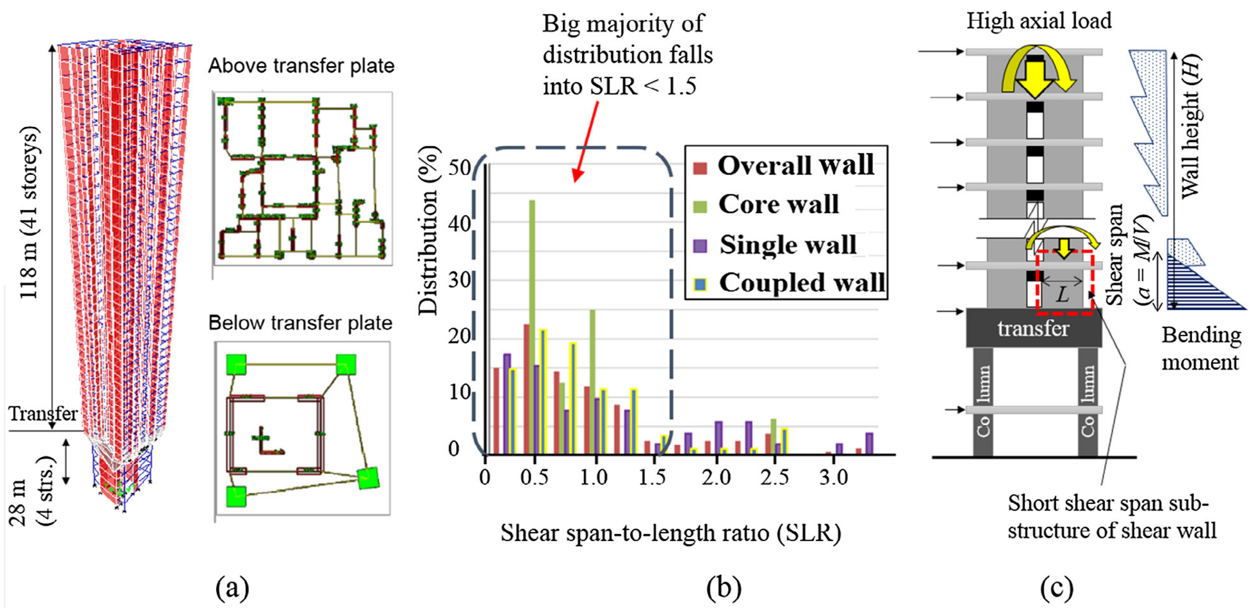

Fig. 1. (a) 45-storey tall RC building with transfer plate (b) Histogram of shear span-to-length ratio of 45-storey building (c) Definition of short shear span RC walls.

engineering software [3]. It was found that the combination of high gravity load (average building density of 5.5 kN/m^3 in Hong Kong) and high wind load results in walls with an SLR that is less than 1.5. The definition of short shear span walls is illustrated in Fig. 1(c).

1.2. Effects of high axial load on shear walls

Post-earthquake investigations conducted after the 2010 M_w 8.8 Chile earthquake [4,5] showed that many shear wall buildings were seriously damaged. High axial load ratios (ALR = $P/f_{c,m}'A_g$, where P is the working axial load, $f_{c,m}'$ is the strength of the concrete cylinder and A_g is the gross cross section of the wall) were found to be the primary factor responsible for triggering the brittle failure of shear walls [4]. However, contrary to much of the research work on squat walls used in low-rise structures tested with zero or low axial load [6–8], and high axial load on slender walls [9–11], the structural response of these walls with a short shear span and limited deformability under high axial load with gravity is rarely discussed.

Walls with such a low SLR are commonly treated as force-controlled components in capacity designs to ensure that the structure remains essentially elastic under maximum considered earthquake (MCE) ground motions that are typical in regions of moderate seismicity. However, in the rare event where the actual level of ground shaking exceeds the MCE level, allowing damage to the walls subject to a larger seismic displacement but ensuring that they do not lose their vertical load carrying capacity is challenging as noted in the current literature on shear walls. More importantly, the ALR was found to increase on average 50% when earthquake loads are added to the gravity load [11]. Therefore, this paper presents an experimental study that examines the influence of the ALR on rectangular shear walls with a short shear span, which are largely found in current building stocks in regions of low-to-moderate seismicity where vertical irregularities (such as transfer structures) are allowed in construction practices.

1.3. ALR limit of shear walls in design codes

A quick survey of the ALR limit in design codes around the world compared to the local design guide in Hong Kong shows that there is no consensus among the codes. The previous Structural Use of Concrete Code [12] in Hong Kong which followed the British Standards neither imposed limits on the ALR nor provided any seismic details. Thus, the ALRs of shear walls in many existing tall buildings are relatively high. In the 1997 Uniform Building Code [13], wall axial loads were limited to 0.35 P_0, where P_0 is the nominal axial load strength at zero eccentricity. Unfortunately, this limit is not correlated with the concrete strength, but merely based on an assumed corresponding balance point from a force-moment interaction diagram for wall piers. The American Concrete Institute (ACI) 318-14 [14] suggests that confinement is required where the maximum extreme fibre compressive stress exceeds a critical value of 0.2 f_c'. The axial load corresponds to load combinations that include earthquakes. There is no limit in Standards New Zealand (NZS) 3101 [15] and its earthquake code NZS 1170.5 [16]; however, a wall with an ALR of 0.2 is considered to have a high axial load as stated in Cl. 11.3.7. Yuen and Kuang [17] provided the ALR limits in Eurocode 8 [18], the most recent Structural Use of Concrete code of practice in Hong Kong [19] and the Chinese code GB50011 [20]. Their results seem to echo NZS 3101 [15], which recognises that a shear wall with an ALR greater than 0.2 is under a high axial load (and less than 0.2 is moderate). Hence, the experimental investigation will be conducted based on target ALRs of 0.1, 0.2, 0.3 and 0.4.

In the opinion of the authors, it is more convenient to standardise the vertical working load under gravity without bending due to lateral force (assumed as ultimate P_{ult} = 1.45 × working P) and the concrete is taken as the mean cylinder strength $f_{c,m}'$ (assumed as cylinder strength f_c' = 0.8 cube strength f_{cu}; and mean $f_{c,m}'$ = 1.5 characteristic $f_{c,k}'$). The following discussion will use this definition unless otherwise stated.

2. Experimental programme

This experiment is based on a prototype of a typical tall RC building on a transfer structure located in Hong Kong (Fig. 1). The building is not seismically designed but subject to rather high wind load due to typhoons and hence the walls are strongly coupled with coupling beams to control roof drift. An SLR histogram showed that the majority of the walls above the transfer structure