A Review on Seismic Behaviour of Coupled Wall Structures

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ABSTRACT

Increase in population density and shortage of land are the two major problems in all developing countries including India. To mitigate these problems, the designers resort to high rise building. One of the most important criteria for designing a structural system is its resistance to lateral loads. Coupled walls structures is considered to be one of the potential option for resisting lateral loads in high-rise structure and have widely been used around the world in multi-story buildings. Coupled walls, mainly consist of pier walls which are connected by coupling beams at each floor level. These systems are typically located in the service core and sometimes on the perimeter of the buildings. The main benefit of coupled wall over cantilever walls are, a part of the total overturning moment is resisted by coupling action and there is energy dissipation along the height of the structure through the formation of plastic hinges at both ends of the coupling beams. The present work reviews different factors influencing the seismic performance of coupled wall structural system, importance of coupling ratio, different modeling techniques, a comparative study on different coupled wall systems and a brief overview of design methodologies. Considering structural performance, energy absorption capacity and higher shear stiffness to limit lateral deformation, coupled wall structures were considered to be efficient and economical structural system in high-rise building.

Keywords: coupled wall structures, seismic performance, coupling ratio, coupling beam

1 Introduction

The growth of population density and shortage of land areas are the major problems faced by all developing countries including India. In order to mitigate these two problems, the designers resort to high rise buildings. Since earthquake is a devastating event that happening around the world and the recent change in the seismic zones of India, it is very important to design the building according to the earthquake resistant provisions. The earthquake events that happened in India points to the considerable damages to RCC high-rise buildings and tremendous loss of life. The basic reason for the damages were most of the buildings having soft and weak ground storey that provided open space for parking, poor quality of materials and poor detailing of the structural components. So these remarks calls for the designing of the building providing sufficient earthquake resistant provisions with regards to planning, design and detailing in high-rise building to improve its efficacy as a lateral load resisting system.

However the Indian code of practice do not provide sufficient guidelines with regards to earthquake resistant design of coupled wall structure. So more design provisions must be included in the seismic code to improve its applicability in practical purpose for that more investigation should be done. Practical arrangement of coupled wall incorporates a single band or multiple band of opening arranged in elevation, either symmetrically asymmetrically or in a staggered arrangement (Elijadei, 2012).

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1.1 Coupled Wall

Reinforced concrete coupled walls are efficient structural systems for resisting lateral loads in high-rise buildings. A coupled wall is formed by connecting cantilever walls at each floor level by deep and short coupling beams. The two-fold benefits of coupled walls over cantilever walls are: (1) increased lateral load resistance and (2) increased equivalent viscous damping through the formation of plastic hinges at the ends of the coupling beams along the height of the structures. Architectural requirements in multi-story buildings (openings required for elevators, stairs, doors and windows) sometimes warrant the use of coupled wall systems. These systems are typically located in the service core and sometimes on the perimeter of the building.

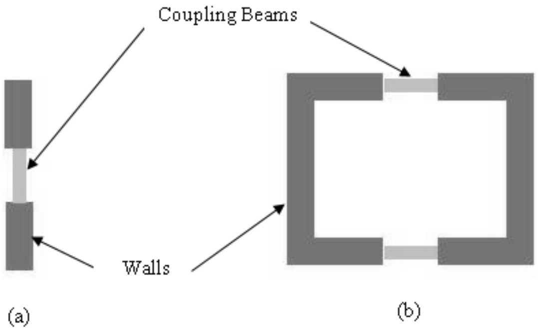

Figure1. Typical coupled wall configurations: (a) Planer wall and (b) Core wall (Adhikari, 2015)

1.1.1 Advantages of Coupled Walls

- They provide an architecturally practical structural system
- Coupling effect provide large lateral stiffness and strength
- Since a part of the base overturning moment is resisted by axial force, foundation restraint is more easily provided for coupled wall than for comparable cantilever wall
- Coupling beam provide an ideal energy dissipation mechanism which distributed along the height of the structure without significantly affecting the stability of the walls
- A tolerable level of damage can be specified in the coupling beams

2 Literature Review

2.1 Behaviour of Coupled Wall Structures

Fig. 2 shows a coupled wall system deformed due to overturning moment (OTM) under the influence of lateral loads. Due to the applied loading moment will be developed on coupling beam and corresponding shears which act on the individual walls. Shear force developed in the coupling beam “push down” on one wall and “pull up” on the other. The coupled system resists OTM through the development of an axial force couple V_{beamj}, over the lever arm (L), resulting from the accumulation of the effect of beam shears, as well as flexural reactions in the individual wall piers $M1$ and $M2$. Shear reaction developed at the base of the wall pier resist base shear. In this idealized case, the coupling beams are assumed to maintain their plastic shear capacity as the wall piers yield (Fortney and Shahrooz 2009).

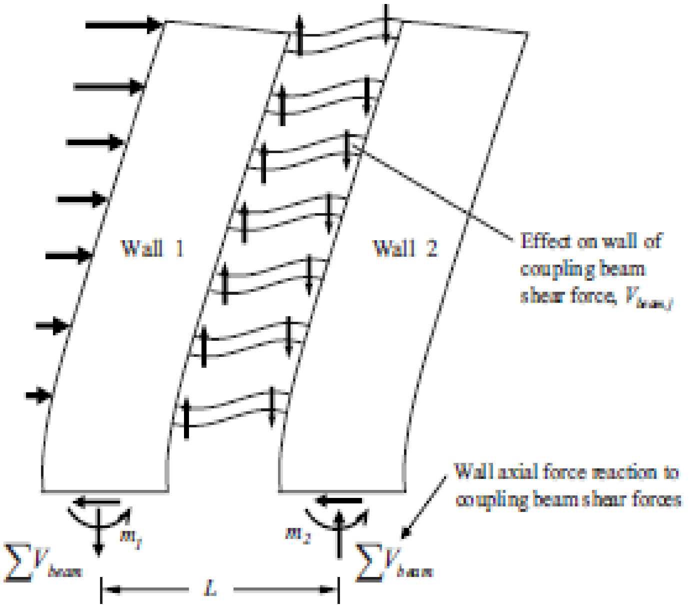

Figure 2. coupled wall system behavior (ASCE/SEI, 2007)

In a study conducted by Alarcon et al. (2015) on resisting plane of RC building suggest that the behavior of the structural walls are highly influenced by the interaction of the resisting plane with the rest of the structure. Furthermore, the experimental study conducted by Bertero et al. (1985) have shown that coupling of beams and slabs to the wall has an influence on building responses and Panagiotou et al. (2011) showed that the shear demand and overturning moment capacity of the wall increased by the three dimensional interaction between walls and slabs. Pennuccci at al. (2015) proposed the procedure for estimating the inelastic response of higher modes for coupled walls and for estimating seismic shear demand of wall buildings were developed by Pugh et al. (2017). A shake table test was conducted by Fischinger et al. (2017) on a five story coupled wall representing a building in central Europe, showed that coupled beam induces axial loads in the wall which contribute to the sudden shear failure. Studies conducted to identify the behavior of RC walls during seismic event identified that the high level of axial load as one of the principle cause of the observed wall damages on the building.

2.2 Coupling Beam

The behavior of the coupled wall is mainly governed by the coupling beam. For the effective dissipation of energy, the coupling beams are designed for ductile inelastic behavior. Different types of material used for coupling beams, which include reinforced concrete, steel or composite material. These coupling beam undergo large inelastic deformation and is the deformation controlled element in performance based design. The performance of the coupling beams are checked with non-linear analysis. For static non linear analysis pushover analysis can be performed. Non-linear dynamic analysis can be performed using non linear time history analysis. The base of the shear wall may be designed for ductile inelastic behavior. The amount of energy dissipation depends on the yield moment capacity and plastic rotation capacity of the coupling beams. If the yield moment capacity is too high, then the coupling beam undergoes only limited rotation.

Main benefit of coupling beam (by Pauley and Priestly, 1992):

- The main function of the coupling beam is to transfer the high shear from one wall pier to the joined wall pier. Most of the Coupling beams are designed as flexural members with shear confinement and are prone to diagonal tension failure. To overcome the diagonal tension failure, diagonal bars are provided with proper confinements which are either in compression or in tension over the full length.
- These coupling beams are the primary source of dissipating seismic energy
- The span to depth ratio of these coupling beams is relatively low hence their performance is influenced by high shear forces.

Coupling beam is an important research subject considering the importance of coupling beam in the coupled wall structure. Most of the works in the past were mostly concentrated on coupling beams and their coupling action. Pauley (1971) conducted a study on short and relatively deep coupling beams reinforced with conventional longitudinal bars and sufficient transverse reinforcement. Test results showed that conventionally reinforced coupling beams prevent diagonal tension failure, but are susceptible to sliding shear failure. As an alternative reinforcement to prevent diagonal tension failure and sliding shear failure Paulay and Binney (1974) proposed diagonally reinforced coupling beams. Since diagonal reinforcement creates construction difficulties, various studies were conducted to replace the existing reinforcement type. Harries et al. (1993) showed that steel coupling beams designed as steel link beams in an eccentrically-braced frame exhibited significant ductility and energy dissipation characteristics under cyclic loading. Shahrooz et al. (1993) investigated concrete-steel composite coupling beams in which a steel coupling beam was encased in reinforced concrete core. To simplify existing reinforcement in RC coupling beam, For difficulties and complexities in construction of beam-wall joints and high cost in post-damage repair of existing type of reinforcement, researchers have been focused on alternative coupling dampers and replicable fuse systems.

The failure mechanism of coupling beam is greatly influenced by the resistance provided by the coupled wall system against lateral load. Well designed coupled beam can enhance ductility, strength and stiffness of coupled wall compared to individual wall. Various design code proposes deep coupling beam with small span to depth ratio that will be designed for shear to ensure the ductility of coupled wall. Also some previous study suggests that hybrid steel truss is an alternative for coupling beam. (Bhunia et al. 2003) conducted a large study on behaviour of coupled shear walls under non-linear static analysis and discussed completely about the type of reinforcement used in coupling beams and its ductile deformation analytically and found behaviour of coupling beams should be governed by shear. While following the standards from FEMA 356 and ATC 40 and concluded that base of coupled shear wall can be a pinned restraint because it shows better non-linear behaviour rather than fixed base conditions. The depth of coupling beams is always being a frequently discussed parameter in previous researches as depth of coupling beam decides the angle of inclination (α) of diagonal reinforced bars (Pauley & Priestly, 1992). If the angle of inclination is low the diagonal reinforcement can't be able to transfer large axial forces into wall piers adequately and remains in flexure which is not the relevant behaviour of coupling beams. In conventional RC Coupling beams, the top and bottom rebar undergoes tension or compression simultaneously and leads to the diagonal cracks. According to IS13920:2016; if τve> 0.1 (Ls/D) then diagonal reinforcement is recommended to resist earthquake produced shear in coupling beams. However guidelines provided by Indian Codes are very limited for the practical behaviour of coupling beams and there is no any description provided for the performance based designs (PBD). An updated context is needed in Indian standards regarding performance based designs.

As per FEMA 356, ATC 40 coupling beams are dominated by shear rather than flexure if $\phi \leq 2$ *or* $Lb/Db \leq 4$. The plastic moment capacity and yield moment capacity of the coupling beams must be kept low such that the rotations in coupling beams are greater than the plastic moment capacity so that coupling beam can dissipate seismic energy.

2.3 Coupling Ratio

The proportion of OTM resisted by the couple is defined as the coupling ratio (CR). Mainly, CR is calculated at the base of the wall.

$$\text{CR} = \frac{TL}{(M1+M2)+TL}$$

where T = ΣV_{beam} = C is the axial force exerted at the base of the walls due to the shear developed in the coupling beams, L is the centroidal distance between the walls and , M1 and M2 are the moment of resistance of individual walls (Figure 2). If coupling strength between the walls is too low, coupling beams can neither provide much lateral load resistance nor an effective energy dissipation since it fail early during earthquakes. On the other hand, in case of very high coupling strength, large axial force will be exerted in the walls, thereby reducing the ductility and flexural capacity of walls, leading them to yield before coupling beams thereby resulting in an inefficient design (Shiu *et al.*, 1984; Munshi and Ghosh, 2000). Many researchers have attempted to limit the value of degree of coupling for efficient seismic behavior of coupled wall systems. Harries (2001) recommended an upper limit of degree of coupling of 0.55 for coupled walls with diagonally reinforced coupling beams. However, Paulay (2002) has advocated for higher values (as high as 0.75) of degree of coupling. Again, Harries *et al.* (2004), through a parametric study, concluded that attaining a degree of coupling of more than 0.7 is inefficient. In study conducted by Lequesne (2011) recommended a degree of coupling range of 0.2 to 0.55 for efficient structural behavior of coupled wall systems.

For the better understanding of this ratio, 3 cases were considered: (i) CR=0 implies that no end moment developed on coupling beams and therefore there will be no coupling action ;(ii) CR=50% implies that the half of the imposed OTM resisted by coupling action while the individual wall pier moment provide remaining half of the resistance to the OTM (*m*1 and *m*2 in Fig. 2); and (iii) CR =100% is the theoretical case where the two-wall piers effectively behave as a single pier.

Due to shear force in the coupling beam, RC wall pier will subject to axial forces. So there is a chance for the net compressive axial force acting on a wall pier to increase substantially, that leads to reduce the ductility of the wall due to crushing failure (El-Tawil and Kuenzli 2002; Aktan and Bertero 1984). Similarly, if the wall pier subjected to axial tension which adversely affect the shear capacity of the wall and impacts the design of the foundation system. Finally, these stress reversals, cause considerable degradation of wall pier behavior.

While designing a CWS, the choice of a suitable CR depends on the experience and judgment of the designer. Providing a low CR will have little structural benefit, since the reduction in lateral drift and wall moments will be relatively small. On the other hand, providing high CR result in large ductility demands on RC coupling beams (Harries 2001). A high CR allows smaller wall section (since reduced moment demands on the wall piers). However, the high CR also results in a greater axial couple, resulting in a greater likelihood that the walls will experience net tension and uplift. Similarly, the high axial compression forces that result may substantially reduce the ductility of the wall piers. These combined effects indicate that a high CR may also result in an impractical design scenario.

A practical limit of 66% for CR was proposed by Harries (2001). Harries and McNeice (2006) designed two 30-story RC structures by using performance-based design approach, and CR values ranges from 67 to78%. Here they have considered five coupling beam with different details and wall capacities were considered to be reduced three times over the wall height. A 15 story reinforced concrete structure was designed by Xuan et al. (2008), designed using three groups of coupling beams having the largest capacity CB were used in the lower one-half of the structure. The CR obtained were around 80%.

2.4 Analytical Models

To promote research on the structural system and its seismic performance an efficient and accurate analytical model is required. That model should be efficient enough to conduct the dynamic time history analysis and thereby it widen the horizon of performance based design method. Different modeling approaches include:
Kolozvari et al (2018) used multiple vertical line element model. Both coupling beam and wall pier are simulated by beam element to get higher calculation efficiency. It is quiet difficult to capture the complex sliding-shear-sip behavior of coupling beam by using this approach. On the other hand, this model captures the complicated compression-bending-shear or tension- bending-shear behavior of wall piers, but the parameters of the model are difficult to obtain. Also the damage state of the wall piers cannot easily recognizable by the researchers and designers.

While considering the accuracy of the analytical model, Lu et al. (2015) used 3D shell element or membrane element to model coupled wall structure. This approach requires too much calculation time due to suitable for large-scale structural time-history dynamic analysis. It cannot capture the complex shear, sliding and slip behavior of coupling beams.

Alvaraz et al (2020) focuses on the Beam-Truss Model (BTM) methodology. The BTM naturally considers the flexure-shear interaction and warping associated with multi-axial stress states in nonplanar elements, which allows to model not only walls but slabs and core walls. Furthermore, the BTM has been used to compute the seismic response of complete buildings with nonlinear time-history analysis.

2.5 Comparative Study

As a lateral load resisting system, the use of coupled shear wall is one of the potential option in comparison with the moment resisting frames and shear wall frame combination system in RCC high rise building. MRF system and shear wall frame combination system are controlled by flexure and shear behavior; whereas the behavior of coupled wall structure is governed by flexure behavior. However, the behavior of beams in MRF and shear wall frame combination are governed by flexure capacity, while in coupled wall system the behavior of coupling beam is governed by shear capacity. During a seismic event, the earthquake energy dissipates through inelastic yielding in both beams and columns for MRF and shear wall combination system; where as in coupled wall, energy dissipation through inelastic yielding in coupling beam and at the base of shear wall. Hence, the amount of dissipation of earthquake energy and ductility obtained from both MRF and shear wall combination are less than those of the coupled shear wall system in high rise building (Bhumia et al., 2013).

3 Conclusion

From the past studies, it is evident that coupled wall structures are excellent lateral load resisting system and can be used to design structures in regions of moderate to high seismic risk. The behavior of the coupled wall is mainly governed by the coupling beam. Coupling beam provide an ideal energy dissipation mechanism, distributed along the height of the structure without significantly affecting the stability of the walls. Among different type of coupled wall structures, code advocate for the diagonally reinforced coupled wall for better seismic performance. Since difficulty in construction of diagonally reinforced coupling beam, different materials were used in coupling beam to comply with the properties of former. Alternative materials used for coupling beams to improve the performance of the coupled structural system are critically analyzed. Among that hybrid coupled wall structure performs better.

Coupling ratio is an important factor that should be taken into consideration while designing coupled wall structure. Many researchers have attempted to limit the value of degree of coupling for efficient seismic behavior of coupled wall systems. Optimum range of coupling ratio for the reinforced concrete coupled wall structure is 0.2 to 0.55. If coupling strength between the walls is too low, coupling beams can neither provide much lateral load resistance nor an effective energy dissipation as they fail early during earthquakes. On the other hand, in case of very high strength of coupling, large axial force is exerted in the walls, thereby reducing the ductility and flexural capacity of walls, leading them to yield before coupling beams thereby resulting in an inefficient design. Various analysis model commonly used for CW structures were analysed. Among the listed analysis model beam truss model performs better since it considers flexure-shear interaction and captures the non linear behaviour of coupled wall structures in a better way.

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