SEISMIC DESIGN OF PRECAST WALL PANEL SYSTEMS

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ABSTRACT

Precast wall panel systems have been used extensively in construction in the last century. The use of these panels has several advantages including short construction time and concrete high quality. There are many advantages of using coupling beams in the precast wall systems such as providing a better structural seismic response compared to isolated walls. In the current study a general design procedure proposed after modifying Clough's methodology is applied to a coupled shear wall system. Using this method, inelastic deformations are calculated based on the kinematics of the deformed shape of the structural system under the application of the International Building Code, IBC 2012 based seismic loads. Two types of walls are investigated in this paper: (1) precast walls with deep coupling beams, and (2) precast walls with slender coupling beams. The results of the analyses were validated by comparing the predicted wall movements with the results of the analyses performed using Finite Element Method (FEM) for the same coupled shear wall systems. The FEM was used under inelastic static loading conditions. This study showed that the wall inelastic deformations predicted using the general design method is in general agreement with the FEM results.

Keywords: Precast, Panels, Seismic, wall systems.

INTRODUCTION

Precast wall panel construction has been used extensively in Europe over the past century. The use of precast panel systems has several advantages including high quality of the product and a short construction time. This makes precast concrete buildings both economically and aesthetically competitive with other types of construction. The excellent performance of the precast panel systems was observed in the 1977 Romanian earthquake and the 1988 Armenian earthquake as reported by Fintel[1,2]. A report by Ghosh[3] on the 1995 earthquake in Kobe indicates that structures employing precast concrete shear walls performed very well. These structures, mostly mid-rise apartment buildings, suffered no damage except some minor cracking and spalling off of concrete near the foundation. Despite this good performance, the North American building codes limit the use of these types of systems in high seismic zones.

LITERATURE REVIEW

The behavior of precast wall panels has been studied analytically by Becker and Llorente[4], Pall and Marsh[5], Schricker and Powell[6], and Pekau and Hum[7]. These studies have been limited to simple walls (i.e., without coupling beams) or coupled walls with only vertical joints. Kianoush and Scanlon[8,9] have studied the inelastic response of precast wall panels with coupling beams. There have been some experimental tests of precast panel wall systems in the past. Small scale models have been tested by Oliva and Shahrooz[10], and Oliva et al.[11]. The strength of wall panel joints has been experimentally studied by Mattock and Hawkins[12], Shiohara et al. [13], Rizkalla et al. [14], Foerster et al. [15], Hutchinson et al. [16], and Soudki et al. [17,18].

The precast panel systems can be used successfully in seismic areas provided that the connections behave similarly to those used in monolithic cast-in-place concrete construction. This implies that the connections must be strong enough to form plastic hinges at the base of the wall. Because the strength and stiffness of the horizontal connections are considerably lower than the wall panels, precast walls require considerable detailing in order to meet the above requirement. This can be very difficult from an economic and construction perspective. An alternative approach is to apply the provisions for cast-in-place concrete structures to precast panel systems, provided that those provisions are modified to meet the seismic strength requirements consistent with the available ductility of precast structures.
The advantage of using coupling beams in precast wall systems has been discussed by Kianoush and Scanlon[9]. The study showed that coupled walls provide better structural response compared to isolated walls. An optimum design approach can be a combination of energy dissipation in coupling beams with some controlled amount of inelastic action in the horizontal connections.

CLOUGH'S DESIGN APPROACH

Clough[19] has proposed a practical design approach that specifically considers both strength and inelastic deformation of members. Based on Clough's design method, and using the predicted inelastic displacement at the top of the structure, hinge rotations and vertical and horizontal displacements can be obtained by applying simple trigonometric relationships. This methodology assumes that the wall rotates about its corner. The gap opening is the only mode of deformation for the horizontal joints while sliding has been neglected.

Major components of Clough’s methodology are described below. As the initial step, the fundamental period of the structure should be evaluated. The code-specified base shear using static analysis must be established. This is achieved using the two load conditions shown in Figure 1 and described as follows:

(1) The usual load condition describing the structure's required ultimate capacity (F_y). The strength criterion is used to define the ultimate capacity. Assuming that the behavior of the structure is elasto-plastic, the ultimate capacity is the same as the yield capacity.
(2) An auxiliary load condition describing the maximum seismic force that the structure would experience if it had infinite strength, referred to as the "Elastic Strength Demand" (ESD). Loads defining the ESD are derived from the base shear formulas represented at Applied Technology Council report, ATC-322[20] using an R value of 1.0.

Figure 1 shows a comparison between the force-displacement relationships for elastic and elasto-plastic Single Degree of Freedom (SDOF) systems. For either the elastic or elasto-plastic systems, the area under the force-displacement curve is the strain energy absorbed by the system. The elastic system is under the force equal to the ESD. The elasto-plastic system is displaced by an amount D_{ep}, the maximum inelastic displacement the structure would experience under the design earthquake, assuming its strength is less than the ESD. By the "equal energy" concept of Newmark and Hall[21], D_{ep} is the value that makes a trapezoidal area equal to the triangular area of the elastic system under the displacement D_e. As shown in Fig. 1, D_{ep} consists of two components. One is the elastic displacement, D_y, which is the displacement the structure experiences before yield. This value is obtained by scaling upward or downward the results of the unit load static analysis according to the code-specified base shear. The other component is the plastic displacement, D_p, which can be easily calculated because the shaded areas are equal.

Using the predicted inelastic displacement at the top of the building, a kinematic analysis can now be performed to determine the corresponding deformations at individual joints. In the kinematic analysis, inelastic displacements are significantly larger than the structure's elastic deformations. Thus, motions of vertical elements (such as walls, or similar stiff elements) can be approximated as rigid body rotations about their respective foundations, with concentrated hinge lines or hinge points where they intersect the horizontal elements (such as floor and roof systems).

MODIFICATIONS TO CLOUGH'S DESIGN METHOD

In this study the structure's required ultimate capacity is calculated using the seismic base shear of International Building Code, IBC 2012[22] with appropriate R factor. Importance, site, and seismic acceleration values are selected based on the building’s use and site conditions. The ESD is also calculated using the IBC 2012[22] Code for seismic base shears with R=1.0. This base shear is equivalent to maximum seismic force that the structure would experience if it had infinite strength.

In this study wall deformations are based on the findings of the finite element analysis results of Kianoush et el. [23]. In their study they noticed that under seismic loading the precast wall rotates as rigid bodies at a distance of one-third of the length of the wall panel from its corner as shown in Figure 2. In this figure, the displacement pattern of a one-story coupled wall structure with a deep coupling beam is shown. Under inelastic deformations the coupling beam is expected to undergo severe cracking and the diagonal bars connecting the walls would undergo elongation in the tension bar and buckling in the compression bar. As shown in this figure, the gap opening at the base of the wall, h, the wall base rotation, ϕ, and the tension bar elongation can be calculated using the plastic displacement at the top of the wall, D_p, using the geometric properties of the rigid body motion of the wall as shown in the figure by applying simple trigonometric relationships. This approximation is justified by the fact that the elastic deformations are insignificant when compared with the inelastic deformations. Both the wall panels on the left and the right are treated as a rigid body and they experience the same amount of displacement and rotation. This method will be referred to as the modified Clough's method.

Figure 3 shows the displacement pattern of a one-story coupled wall structure with slender beam. In this figure, the inelastic wall movement is associated with creation of the plastic hinge at the beam wall connection. From the shown rigid body motion, geometric properties can be utilized in calculating the gap opening at the base of the wall, the wall base rotation, and the beam rotation ϕ_2 using the plastic displacement at the top of the wall.

APPLICATIONS TO MULTI STORY COUPLED WALLS

The deformed geometry of the one-story shear wall system with a deep coupling beam is used to construct the deformed shape of a ten-story coupled shear wall building with deep coupling beams as shown in Figure 4. The total gap opening is assumed to be concentrated at the lower levels with the ratios of 40, 30, 20, and 10 percent at the base, first, second, and third floors, respectively (Clough[19]). Applying the simple trigonometric relationships based on rigid body motions the wall rotations and tension bars elongation are calculated. The ductility of the coupling beams is defined here as the ratio of the maximum extension of the diagonal tension reinforcement to the extension at the yield level.

Figure 5 shows the deformed shape of a ten-story shear wall system with slender coupling beams. The geometry of the deformed shape is developed using the single story deformations described above. Gap openings are also assumed to follow the same distribution ratios used for the shear wall system with deep coupling beams. Applying the simple trigonometric relationships based on rigid body motions, the wall and beam rotations are calculated. The ductility of the coupling beams is defined here as the ratio of the maximum beam rotation to the beam rotation at the yield level.

FINITE ELEMENT ANALYSIS (FEA) AND COMPARISON

In this study a non-linear finite element analysis model is developed to validate the design method results. In this model the wall panels are modeled using plane stress elements. Concrete in the horizontal joints are modeled using gap elements that take compression loading only. Steel reinforcement is modeled using non linear truss elements in the joints. Slender coupling beams are modeled using non-linear beam elements and deep coupling beams are modeled using diagonal truss elements.

Details and dimensions of the structure selected for this study are shown in Figure 6. The structure is a large panel coupled shear wall with horizontal connections at each floor level. The coupling beams used are either deep beams of 1000 mm (39.4 in.) depth or slender beams of 700 mm (27.6 in.) depth. It is assumed that the coupling beams are precast with wall panels. The structure is assumed to rest on a rigid base and the floor slabs are considered infinitely rigid.

The structure is designed using the IBC code. The code specified seismic base shear and ESD are calculated as previously discussed. Elastic analysis is performed to calculate the elastic displacement at the top of the building under ESD loads which are applied at each floor level. The equal energy concept is applied to calculate the inelastic deformations in the walls as shown in Figures 4 and 5 based on the rigid body motion assumption.
Non-linear finite element analyses were performed to calculate the inelastic deformations of the walls and the beams to provide a basis for comparison with results of the design method. Figure 7 shows the gap opening distribution over the height of the building for the modified design and the finite element method. The finite element results are in general agreement with the modified deign method but it shows that the gap openings spill over to level Six. The modified design method is based on the assumption that gap opening is confined to the first four levels.

Figure 8 shows the gap opening distribution along the horizontal length of the wall for the modified design and the finite element method. The design method shows slightly higher gap opening values than the Finite element method.

Figure 9 shows the variation of the tensile forces in the diagonal bars of the coupling beams over the height of the structure for both methods. Good correlation is also noticed although the finite element results show lower level of forces.

CONCLUSIONS

Based on this study, it is concluded that the proposed modified design method offers reliable results. The inelastic deformations of the precast walls and the internal forces in the coupling beams predicted using this method are in general agreement with the results of the inelastic finite element analysis. Gap openings and beam forces calculated using the finite element analysis were generally lower than those predicted using the design method. This indicates that the design method offers conservative values as compared to the real values.

The Modified Clough Method presents a simpler approach for performing seismic design of precast walls as compared to using the non linear finite element analysis method. This study shows that the results of the Modified Clough Method are comparable to the FEM and thus offers a reliable alternative tool for the design of precast walls.

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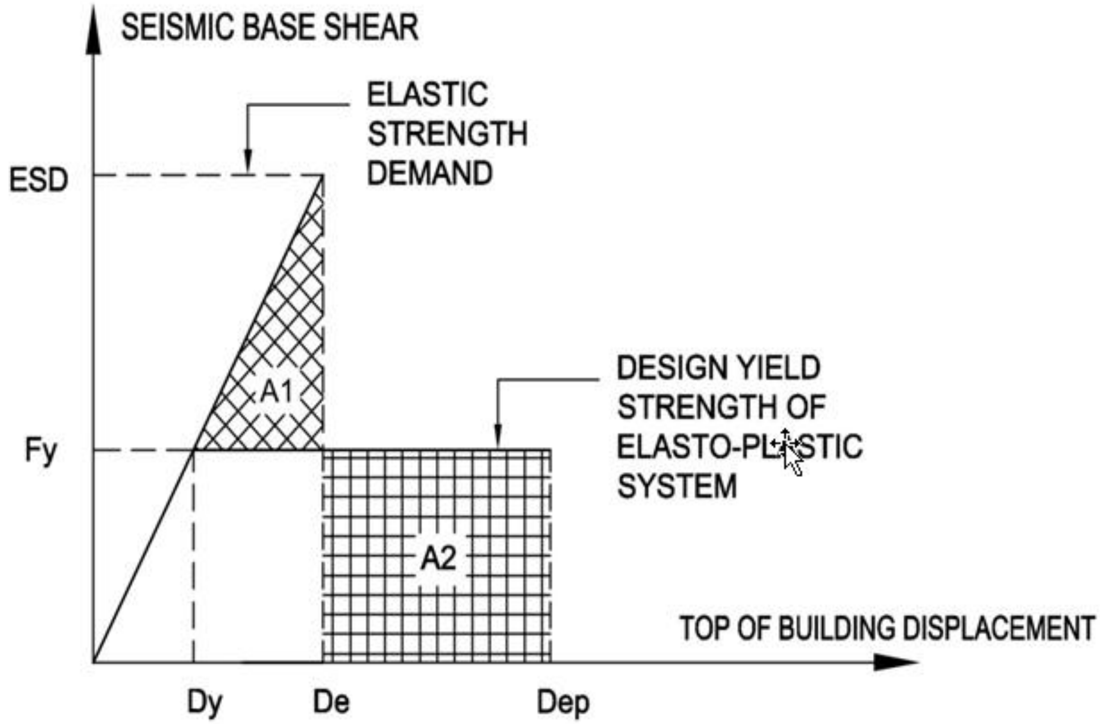

Fig. 1 Equal Energy Concept for Estimating Seismic Displacements

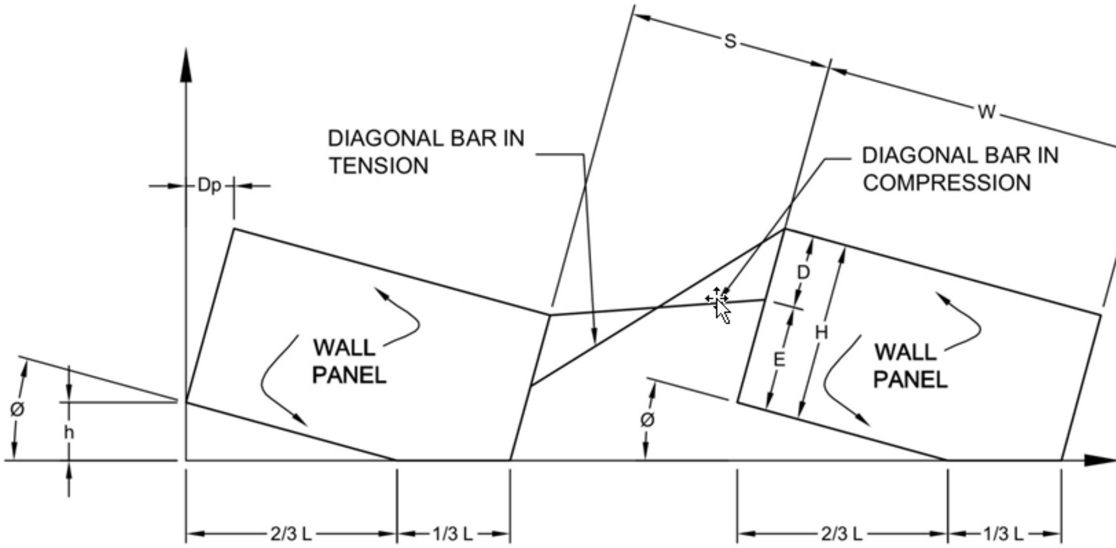

Fig. 2 Deformed Configuration of a Single Storey Building with Deep Beams

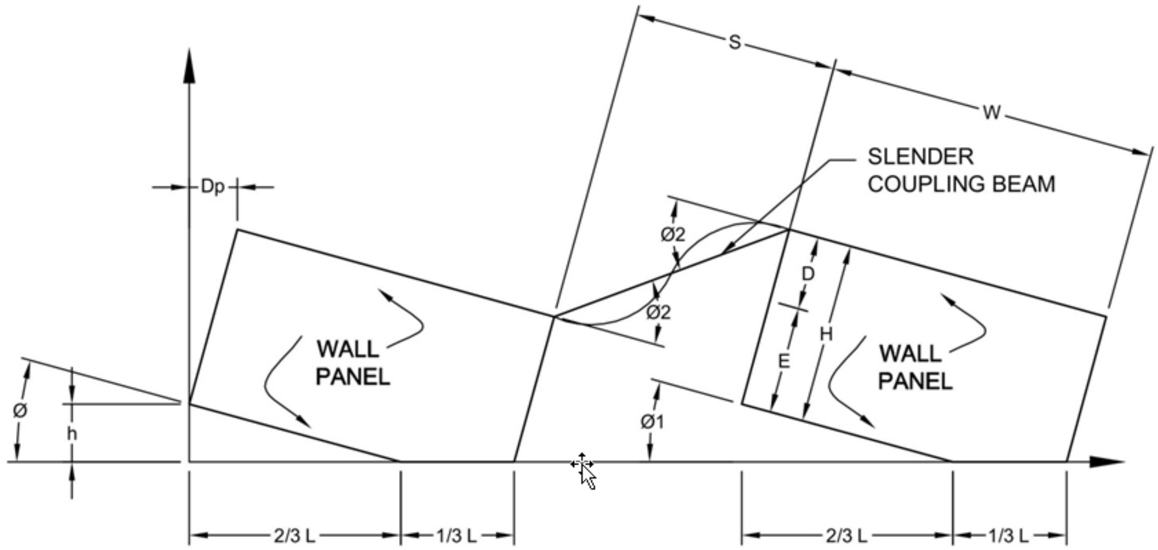

Fig. 3 Deformed Configuration of a Single Storey Building with Slender Beams

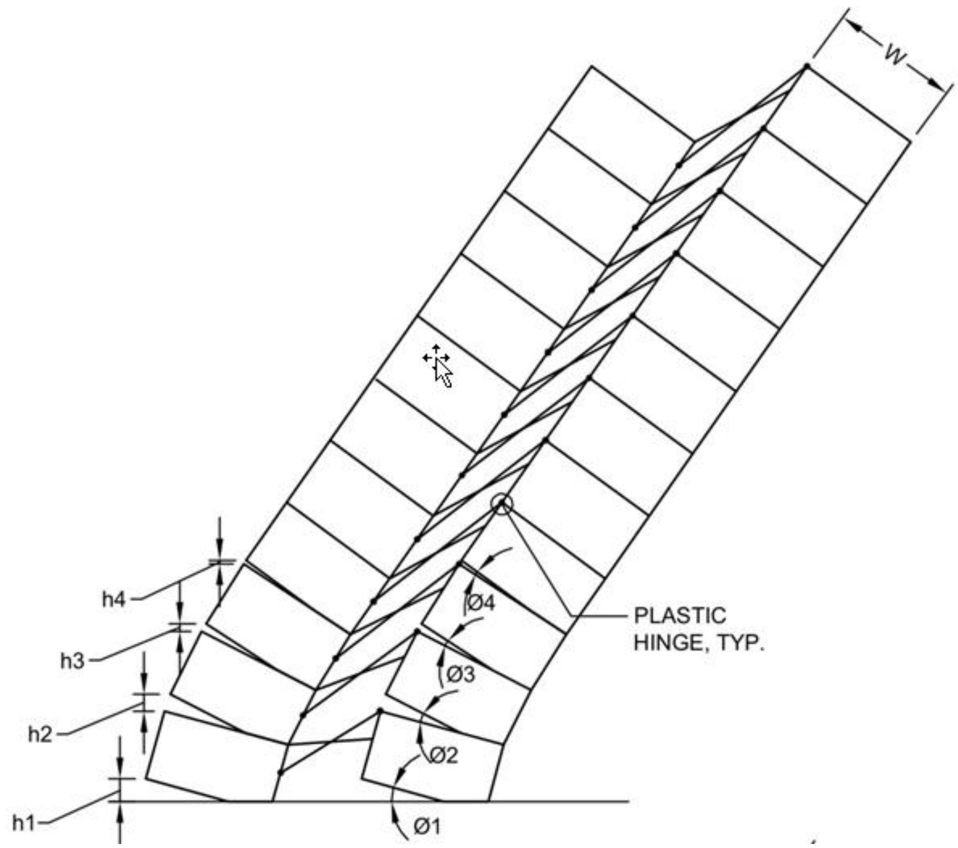

Fig. 4 Kinematic Analysis with Four Joint Openings for Walls with Deep Beams

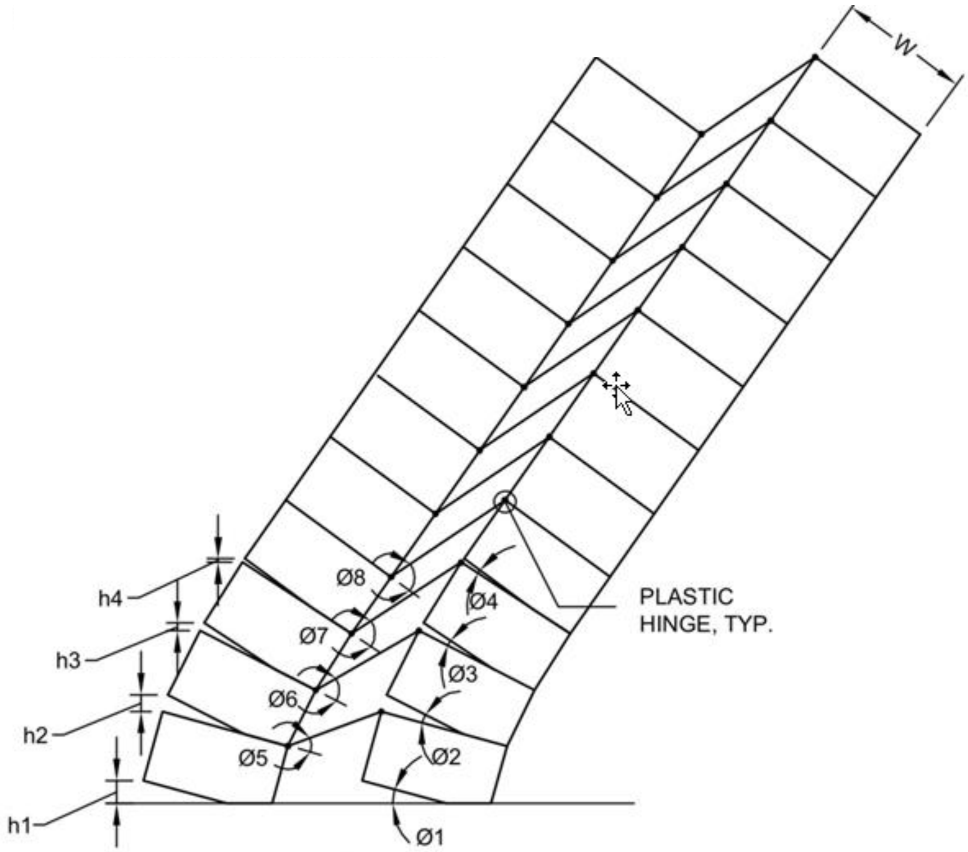

Fig. 5 Kinematic Analysis with Four Joint Openings for Walls with Slender Beams

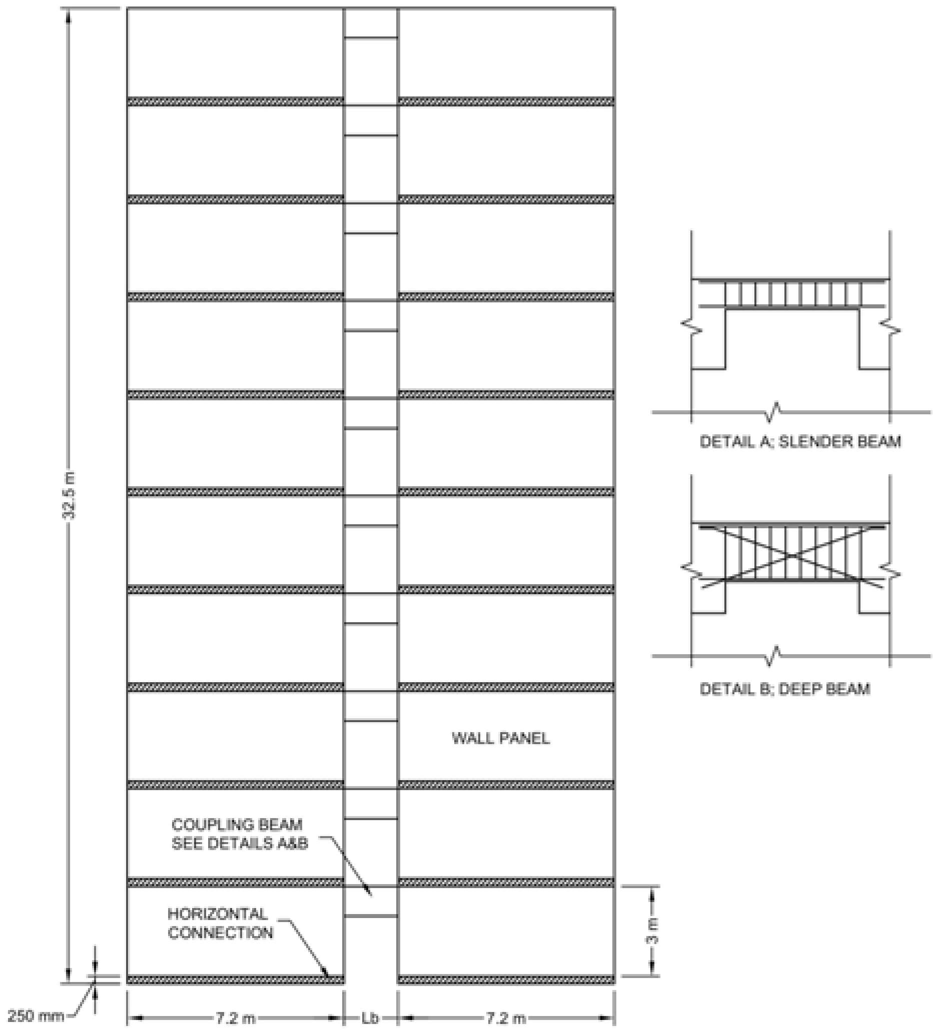

Fig. 6 Details for Coupled Wall Selected for Study

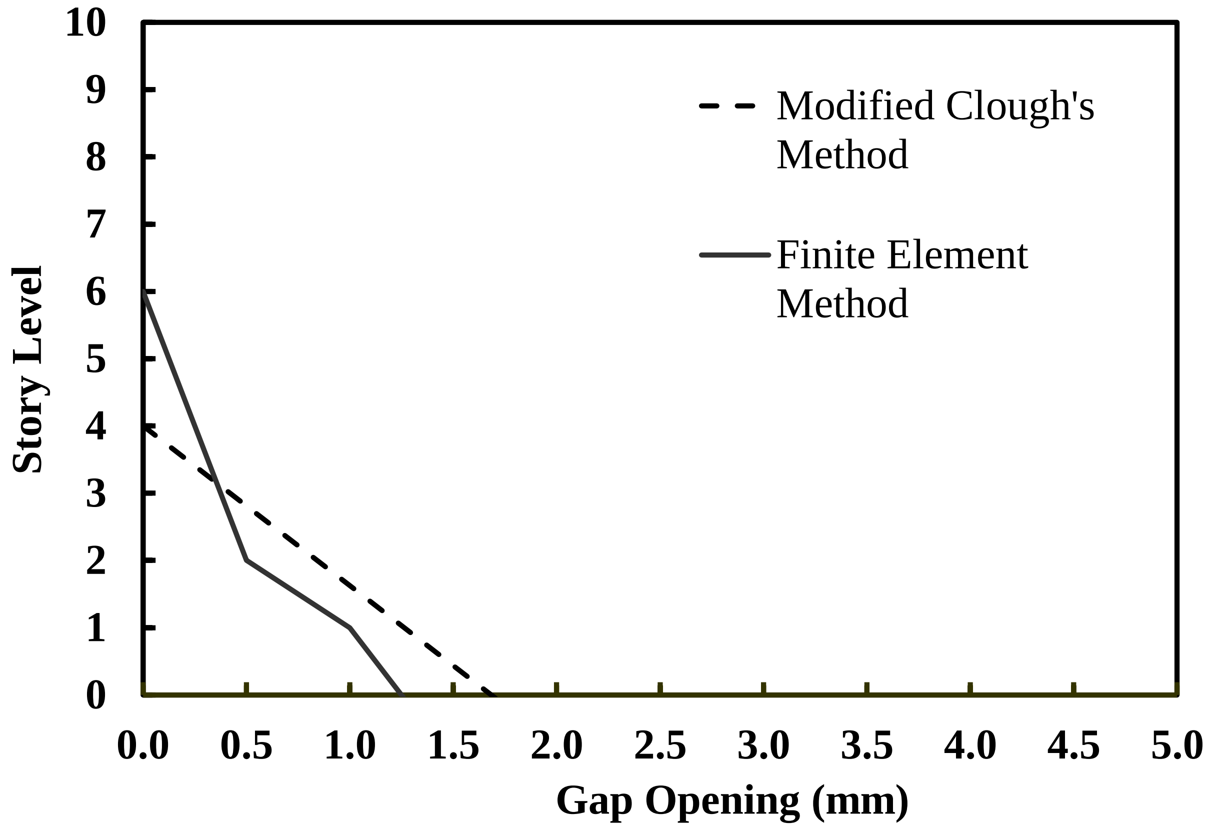

Fig. 7 Distribution of gap openings over the height of the structure

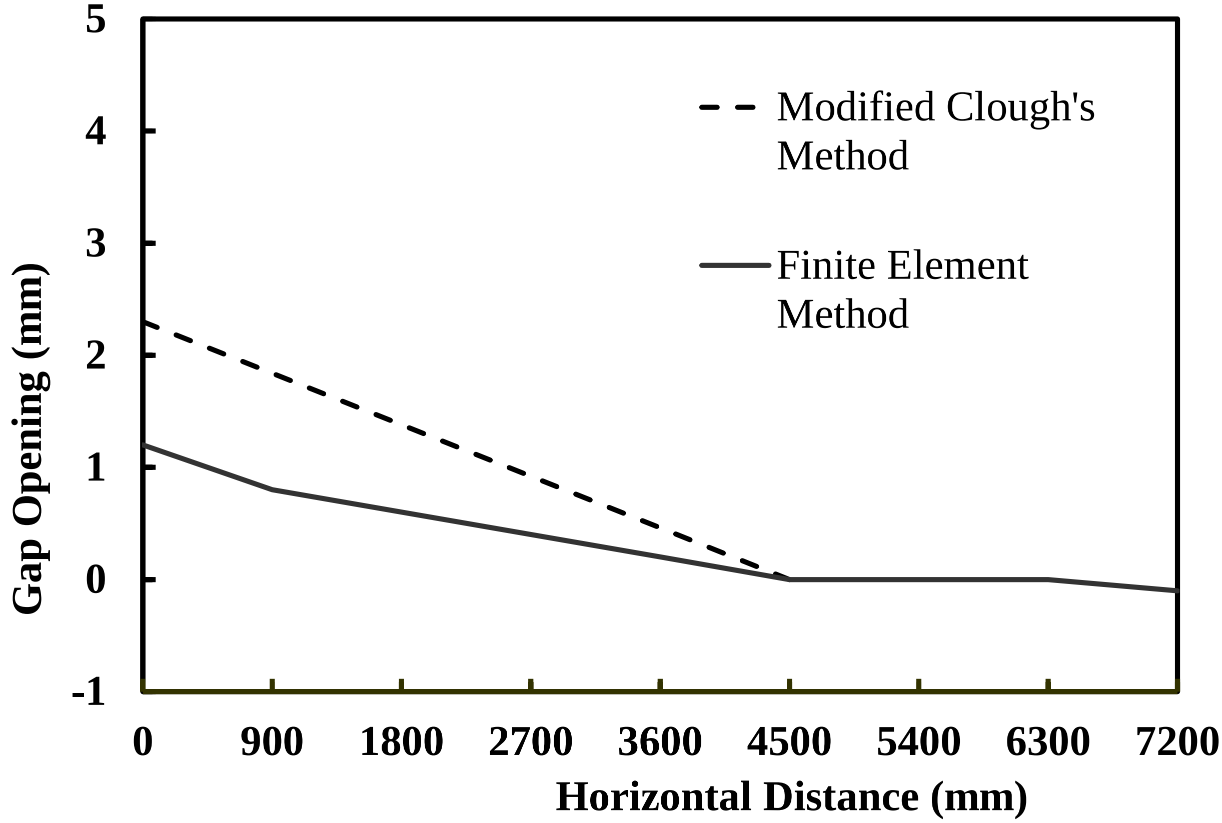

Fig. 8 Distribution of gap openings across the horizontal connection

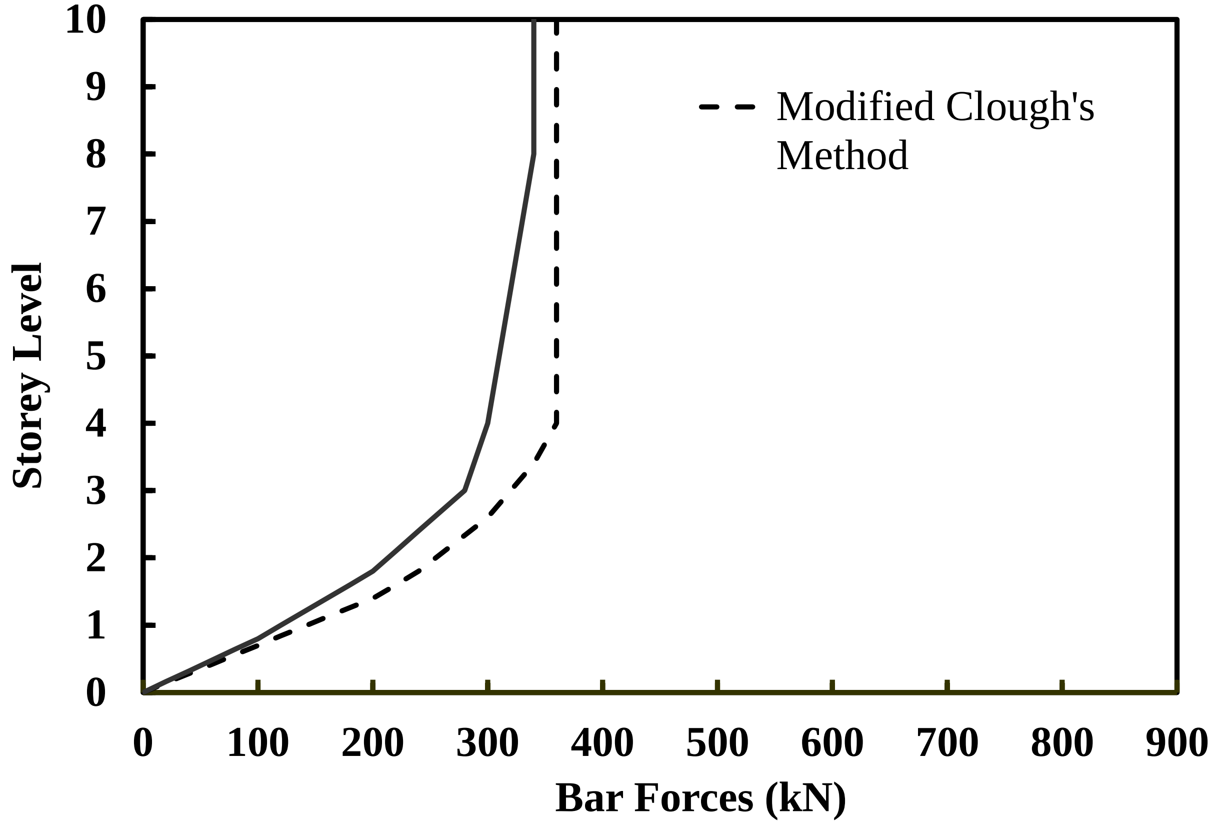

Fig. 9 Internal beam forces over the height of the structure