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Factors Affecting the Response of Large Panel Wall Systems

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ABSTRACT

The seismic resistant of large panel coupled wall systems is reviewed and the problems associated with the behaviour of these types of systems are highlighted. Based on the results of inelastic finite element analysis, the major factors affecting the response of a 10-storey large panel precast wall system are described. This includes the effect of joint reinforcement and coupling beam reinforcement. It is concluded that large panel systems can be designed in areas of high seismicity provided that the amount of deformation in the horizontal joints are controlled using proper details. A set of suggestions for improved performance of large panel systems is given.

INTRODUCTION

The term Large Panel (LP) construction is used to describe a structural system composed of precast wall panels with floors and roofs of precast panels or planks. The wall panels are usually solid and of one storey height. The use of LP systems has attractive features such as good quality control of the product and speedier construction. LP systems can be used effectively for the construction of multistorey buildings of commercial and residential types.

LP precast walls behave quite differently from monolithic cast-in-place walls due to the presence of the horizontal joints which create planes of discontinuity in the system. In LP systems, the horizontal joints have considerably lower strength and stiffness as compared to wall panels. Therefore, most of deformations during seismic shaking are expected to occur in this region.

Due to the lack of understanding and problems associated with LP systems, current North American building codes are virtually silent on earthquake resistant design criteria. However, precasters are showing a growing interest to expand their market into the more active seismic regions of North America. In addition, seismic risk assessments for regions traditionally viewed as earthquake free are being revised upward. Therefore, a clear understanding of the behaviour of LP systems under seismic excitations is necessary.

In the present study, an analytical investigation was made to determine the effect of various parameters on the response of LP systems. Based on the results of this study and other studies, the major factors affecting the response of LP systems are highlighted.

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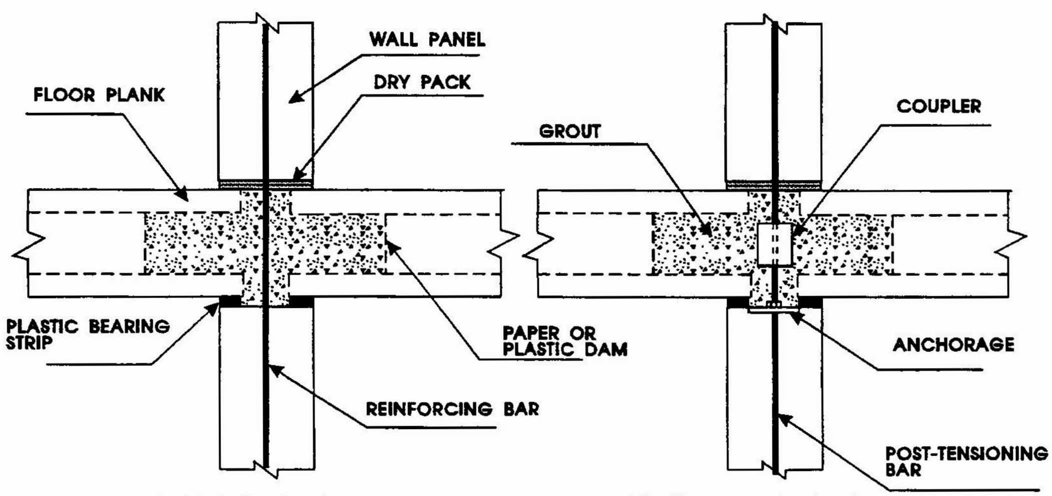
BEHAVIOUR OF HORIZONTAL JOINTS

In LP systems, the two principle mechanisms at the horizontal joints are rocking and shear slip when resisting strong seismic motion. Rocking is a term which describes the overturning response of the structure. Previous studies by Kianoush and Scanlon (1988a, b), Schricker and Powell (1980) , Becker and Llorente (1979) and Oliva et al (1989) have indicated that rocking mechanism dissipates little energy. Rocking also creates severe stress concentration in the compression region of the wall. This could lead to a crushing failure of the joint or severe damage to the corners of the panel. However, rocking exhibits an isolation behaviour which limits the force that can be transferred into the wall.

The second mechanism, shear slip, is a term which describes the transfer of shear forces in the horizontal joints through normal compressive forces and vertical continuity steel and post-tensioning. Shear slip is capable of dissipating a significant portion of the energy in the structure. It also acts as a force isolating mechanism by reducing the forces at the base of the structure. Despite these beneficial effects, shear slip is undesirable because once sliding starts, it will lead to accumulated displacement in one direction. The accumulated slip could result in an eccentricity sufficient to threaten the overall stability and integrity of the structure.

Both of the above mechanisms prevent the spread of inelasticity into the wall and create softening of the structural system. Of the two mechanisms, shear slip is the most undesirable and should be avoided.

The rocking and slip mechanism in precast walls is strongly affected by the method of providing vertical continuity. Vertical continuity can be provided with either post-tensioning or reinforcing bars. The North American "Platform" connection details are shown in Figure 1.



a) Reinforcing bar b) Post-tensioning bar

Figure 1. Platform connection details

Previous studies by Kianoush and Scanlon (1988b) showed that the amount of slip was considerably lower for reinforced walls than for post-tensioned walls. When mild reinforcing bars are provided across the joints, shear forces are mainly carried by aggregate interlock, interface shear transfer and the dowel action of the reinforcement. Due to this interface shear friction mechanism, reinforced walls tend to resist slip and the walls have a tendency to fail due to rocking mechanism. However, when post-tensioning bars are provided as vertical continuity, precast walls are expected to fail first in slip.

Slip can be controlled in precast walls by providing a sufficient amount of vertical reinforcement with adequate shear keys confined in the joint region. Horizontal joint details are also currently being developed at the Portland Cement Association in Skokie, Illinois (Schultz, 1994) to restrain this movement. Such details are similar to the vertical joint details as described by Schultz et al (1994).

SEISMIC ANALYSIS

Finite Element Modelling

A 10-storey coupled wall with deep coupling beams was analyzed to investigate the major parameters affecting the response of LP systems. The study was based on inelastic static analysis. The finite element discretization of part of the structure is shown in Figure 2. It was assumed that all the stories are of the same height. The total height of the building was 32.5 m.

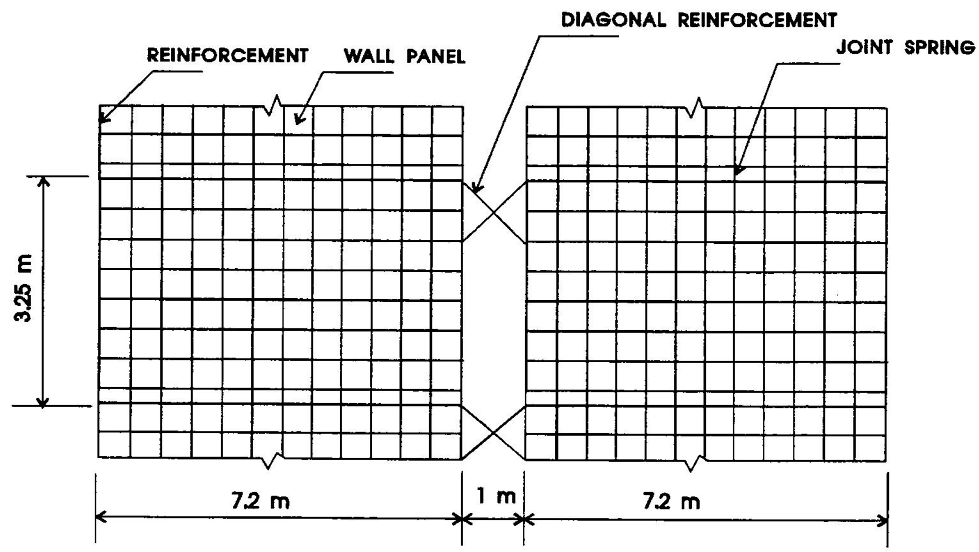


Figure 2. Finite element discretization of the 10-storey structure

For finite element modelling, the only mode of deformation in the horizontal joint was assumed to be due to rocking and the effect of shear slip was neglected for reasons described previously. All of the inelastic action was assumed to take place in the horizontal joints while wall panels were assumed to remain linear elastic. Wall panels were modelled using a 4-node rectangular plane stress elements. The vertical continuity steel was assumed to behave elasto-plastic in tension and compression. Inelastic springs were placed normal to the joint surfaces to model the rocking behaviour. The spring elements behave elasto-plastic having finite strength and stiffness in compression and zero strength and stiffness in tension. This is based on the assumption that the horizontal joints are precracked and are incapable of developing any tensile force except in the vertical continuity steel. The joint's compressive strength was assumed to be 50% of the panel's strength. Deep coupling beams were represented by two diagonal inelastic truss elements yielding in tension and buckling in compression. This representation is based on the fact that at the development of yield strength, the behaviour of deep beams is governed by the diagonal bars (Paulay, 1977).

The above models were incorporated into the computer program, PC-ANSR (Maison, 1992) for analysis. Full details on modelling technique are given by Elmorsi (1994).

Specification of Seismic Loads

Static loads were applied to the model described above at each floor level according to NBCC (1990). The force modification factor, R = 2.0 was used. This value was determined according to a design approach for jointed precast structures proposed by Clough (1986), commonly known as the PCI design method. This method is based on a simple concept involving the equal energy concept for estimating the maximum inelastic displacement of a structure during an earthquake. Global displacements are transformed into deformations of individual joints and connectors using the kinematic principles. Further details on the application of this technique to precast coupled walls are given by Yu (1993) and Elmorsi (1994).

RESULTS OF INVESTIGATIONS

Effect of Joint Reinforcement

In precast walls, uniformly distributed mild steel reinforcement is provided over the entire cross-section of the wall to resist shear forces developed across the joint. Concentrated reinforcement is also necessary at the corners of the walls to resist forces due to overturning.

To study the effect of joint reinforcement on the response of LP systems, it was assumed that concentrated reinforcement is distributed over a length of 1.8 m on each end of the walls. Three different values of joint reinforcement were used in this investigation: 2.86%, 1.43% and 0.72%. The amount of uniformly distributed reinforcement was kept to a constant value of 0.62% for all cases. The 10-storey structure described above was assumed to be located in a high seismic zone with the zonal velocity ratio of 0.4 (Za/Zv = 1.0, T = 0.38 seconds).

Figure 3 shows that the response of the 10 storey structure is significantly affected due to the variation of wall reinforcement. As wall reinforcement is increased, the amount of gap opening

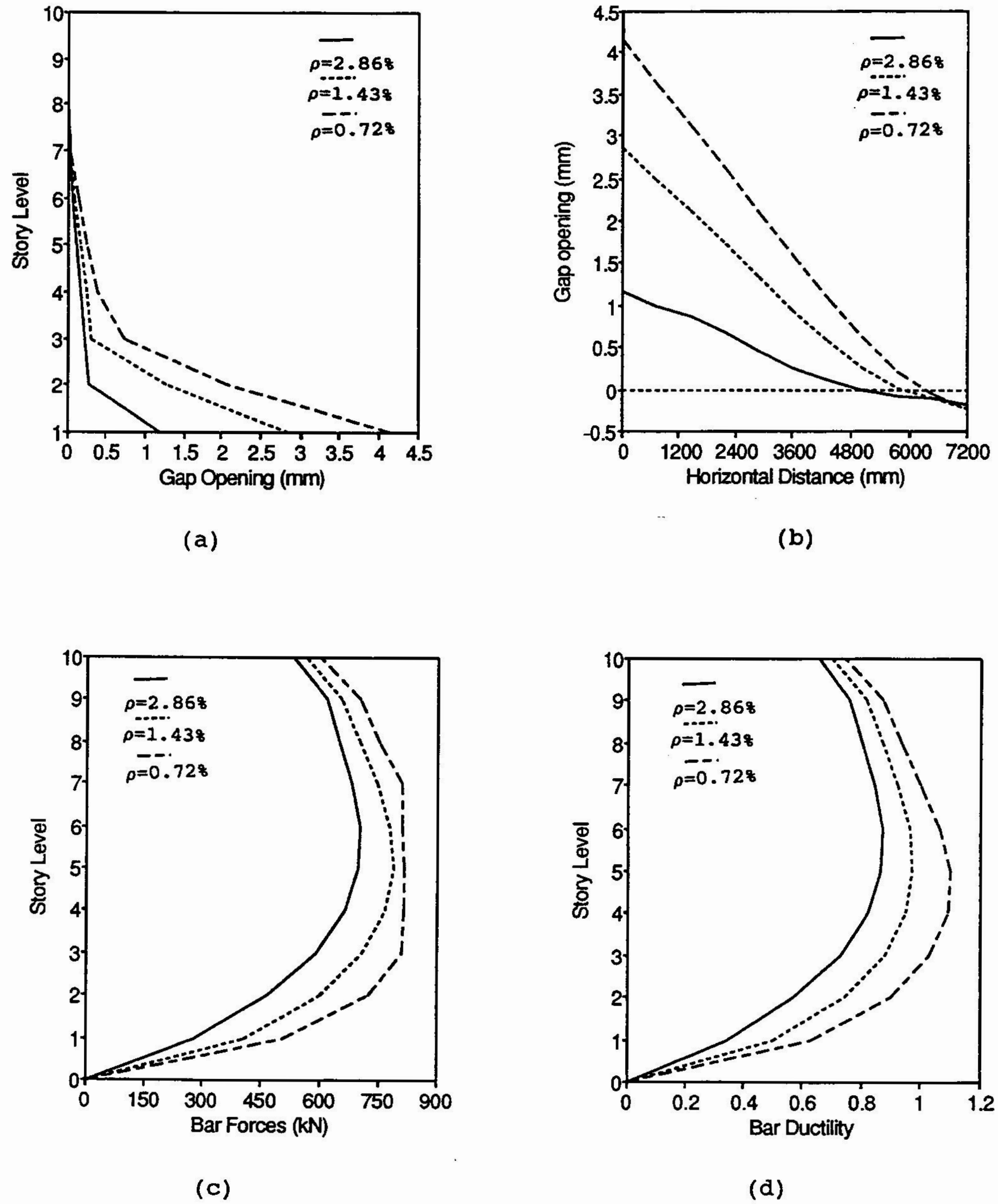


Figure 3 Effect of variation of joint reinforcement ratio on the response of the 10-story structure.

is decreased significantly. The beam forces and the beam ductilities are also reduced, due to this effect. The amount of gap opening has a direct effect on beam forces and ductilities. As gap opening reduces, the coupling beams undergo lower deformations and consequently lower forces and ductilities are developed in the coupling beams. The beam ductility is defined here as the ratio of the maximum bar extension divided by extension at yield level.

Effect of Coupling Beam Reinforcement

To study the effect of the amount of coupling beams reinforcement ratio on the response of precast wall systems, the amount of the diagonal reinforcement ratio was varied from the minimum required reinforcement ratio as specified by CAN3-A23.3-M84 (1984) up to 1.5%. There is no maximum limit on the amount of the reinforcement that can be used in the coupling beams because the amount of tension and compression reinforcement is the same and there is no possibility of brittle failure. Isolated walls are represented as having zero beam reinforcement. Results of the analysis showed that isolated walls fail to sustain the high lateral loads for seismic zone $v = 0.4$. Large gap openings occurred at the base of the structure. These were accompanied by high compressive stresses at the corner of the wall which affected the stability of the structure. In order to make a complete comparison, the structure was reanalysed using $v = 0.3$.

The effect of variation of the coupling beams reinforcement ratio is shown in Figure 4. The increase in the beams' reinforcement ratio reduces the gap opening. This is mainly because the increase in the amount of the beams' reinforcement increases the beams' stiffness and consequently increases the coupling effect. Therefore less moments are developed in the walls which consequently reduces the amount of gap opening across the horizontal joints. The effect of the increase in the beams' reinforcement ratio was to increase the beams' forces and decrease the beams' ductilities as expected. Coupling beams with minimum reinforcement are the only case in which the amount of extensions exceed the yield level. This is mainly due to the larger gap openings and the larger walls' rotations as a result of less stiff coupling beams.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, large panel structures can be designed to withstand the effects of major earthquakes provided that the amount of deformations in the horizontal joints can be controlled. The amount of deformations in the horizontal joints is sensitive to the strength and stiffness of the connecting elements. Of the two joint mechanisms, shear slip is the most undesirable which needs to be controlled. To achieve this, the current North American joint details need to be modified. The use of high strength joint material and sufficient amount of vertical mild reinforcement and the provision of some form of shear keys in the joint region can improve the response of precast walls considerably. The use of vertical continuity elements such as coupling beams is also important. Providing coupling beams can significantly improve behaviour by suppressing the rocking mechanism and thereby reducing the likelihood of strain and stress concentration in the horizontal joints. The use of coupling beams as energy dissipating elements will complement the lack of ductility in the rest of the structure.

Further analytical and experimental investigations especially three dimensional studies are needed to establish the stability and the integrity of the entire assemblage of LP systems.

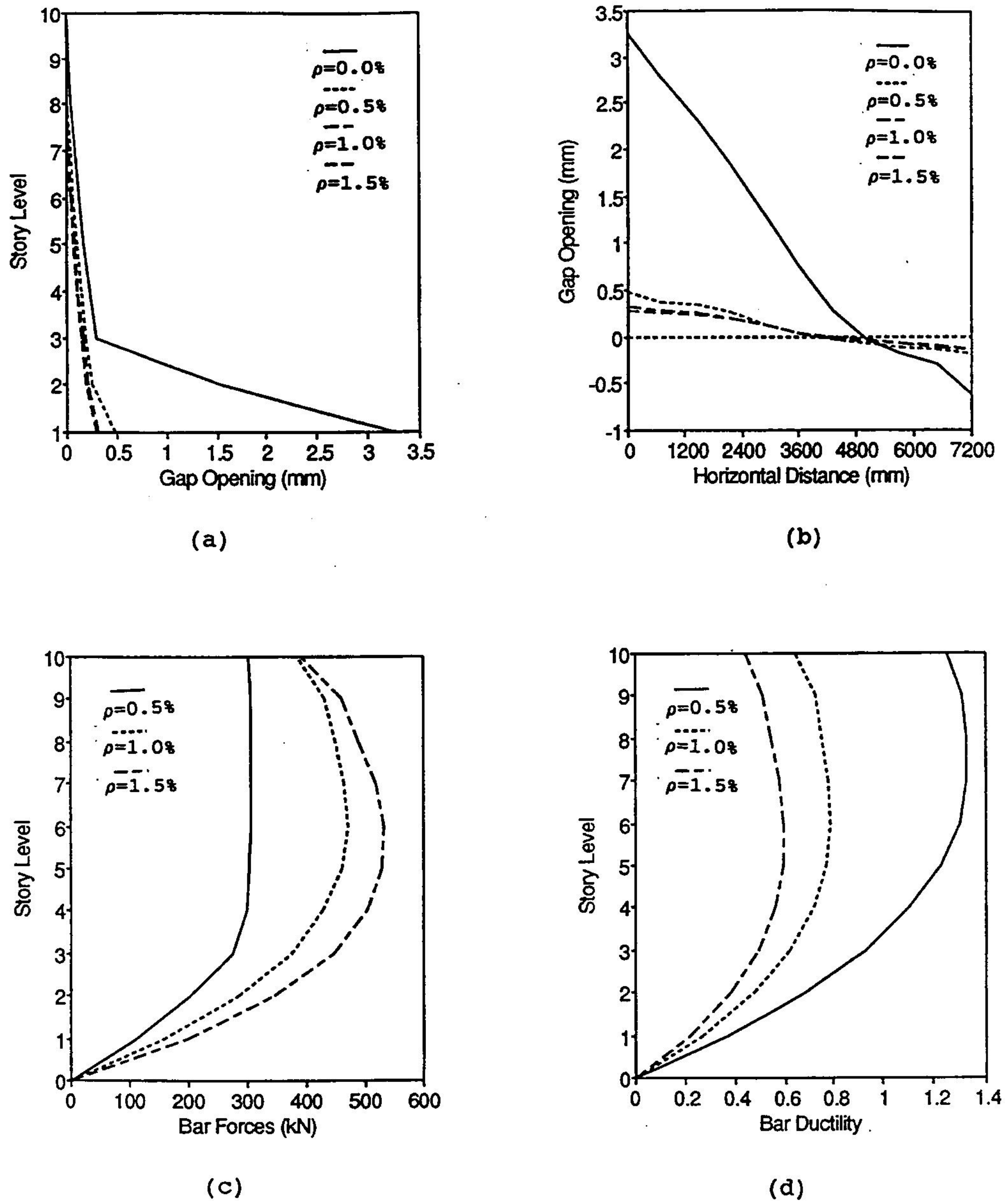


Figure 4 Effect of variation of coupling beams reinforcement ratio on the response of the 10-story structure.

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