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Controlling seismic damage in precast large panel structures

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ABSTRACT: The use of limited slip bolted (LSB) connectors placed along the vertical joints of precast panel structures in order to control the level of seismic damage is examined. Tuning the slip load of these connectors allows overall response to be optimized through efficient energy dissipation by friction. The level and significance of deformation induced in the horizontal joints of a 10-story prototype shear wall is studied. For the tuned structure with uniformly distributed vertical reinforcement, response in the horizontal joints remains essentially damage-free for most earthquakes. However, some localized damage at the base of the structure is nevertheless to be anticipated, although the magnitude of this damage is reduced considerably by the action of the LSB connectors. The addition of concentrated edge reinforcement eliminates yielding of the vertical reinforcement throughout the structure, whereas the provision of post-tensioned bars has limited effects at the critical lower levels of the structure.

1 INTRODUCTION

Seismic damage to the vertical joints of precast panel wall systems can be controlled by employing deliberately weak but ductile mechanical connectors. The use of limited slip bolted (LSB) connectors to eliminate all damage along the vertical joint and to provide energy dissipating ductility was proposed in an earlier study (Pall 1980). Horizontal joints at each floor level behave as continuous precracked planes. Shear slip and rocking along the crack interface introduce inelastic action and both analytical and experimental studies have predicted detrimental deformation in these joints during seismic response (Harris and Caccese 1984; Kianoush and Scanlon 1988).

This paper assesses the effectiveness of employing the aforementioned vertical joint LSB connectors in controlling damage in the horizontal joints and improving overall structural behaviour. A 10-story prototype structure is subjected to a parametric study and both the degree and significance of response induced in vertically reinforced platform-type horizontal joints is examined.

1.1 *Prototype structure*

The prototype structure selected for study consists of one of the end walls of a typical 10-story precast panel building of the crosswall type, consisting of two panel stacks coupled along the vertical joint by limited slip bolted (LSB) connectors placed two per story as shown in Fig. 1. Details of these connectors are depicted in Fig. 2 . The horizontal joints are of the wet platform type typical of North American construction. Steel reinforcement equal to 0.5 per cent of the gross cross-sectional area provides vertical continuity across these joints.

1.2 *Idealized behaviour of joints*

Nonlinear behaviour in the horizontal joints arises from gap opening due to rocking and from shear slip once the frictional capacity of the joints is reached. This coupled

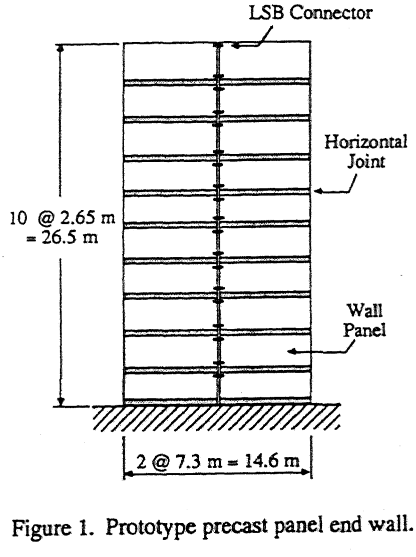

Figure 1. Prototype precast panel end wall.

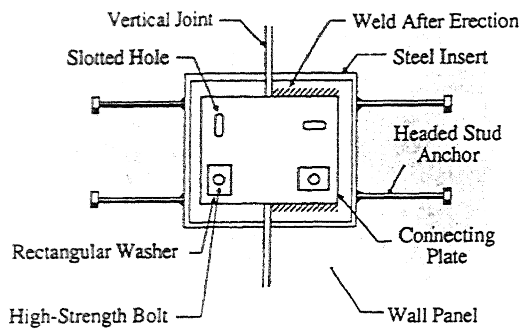

Figure 2. Limited slip bolted (LSB) connector.

behaviour in the horizontal joints, as well as the effect of vertical steel reinforcement on the shear-friction behaviour, is modeled; elastic behaviour is restored by dowel action of the vertical steel following the initiation of shear slip (Kianoush and Scanlon 1988).

In the vertical joints, resistance to shear along the joint is assumed to act independently of resistance to normal force across the joint. Normal tensile and compressive stiffnesses follow a linear elastic force-deformation curve, whereas behaviour in vertical shear exhibits a stable elasto-plastic hysteretic loop with yield point F_{sb}.

1.3 Seismic analysis

The computer program ANSR-I (Mondkar and Powell 1975) was employed to obtain the dynamic response. The precast panels were modeled by linear elastic plane stress finite elements interconnected by discrete two-noded nonlinear spring elements to model both the horizontal and the vertical joints. Five per cent viscous damping in the two lowermost modes was assumed and the dynamic response was obtained by time step integration employing $\Delta t = 0.001$ sec.

Four different earthquake records were employed in this study, scaled to match the intensity of the 1940 El Centro NS record. The records consist of the 1940 El Centro NS, 1952 Taft N69E, 1949 Olympia N10W and the Newmark-Blume-Kapur artificially generated earthquake.

2 RESULTS

2.1 Optimum slip load

For structures equipped with LSB connectors, the slip load F_{sb} can be adjusted to achieve maximum energy dissipation. Fig.3 plots maximum panel stress, base shear and top displacement as functions of connector slip load F_{sb} for the El Centro and Taft excitations. For both earthquake records, an optimum slip load (load producing minimum response) in the range of 40-160 kN is observed. It should be noted that slip must be

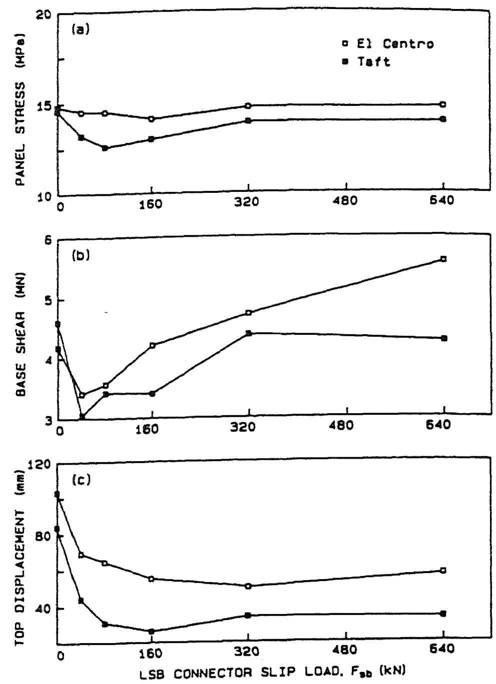

Figure 3. Effect of connector slip load on overall response parameters.

accommodated in the slot length of the connecting plates as, otherwise, it has been found that bearing of the bolts results in increased response.

The magnitude of the optimum slip load can be more precisely determined by considering the energy dissipated by the LSB connectors. Energy dissipated by the LSB connector having the maximum value out of all the connectors (i.e. the critical connector) is shown in Fig.4a as a function of the connector slip load. Energy dissipation peaks at F_{sb} = 80 kN, confirming the optimum range for the response parameters of Fig.3. Figs. 4b and 4c show envelopes of energy dissipation at selected slip loads for El Centro and Taft, respectively, and reveal that the relationship between slip load and critical connector energy dissipation as disclosed in Fig. 4a also holds true at all floor levels; hence, the total energy dissipated in all the connectors is also maximum at F_{sb} = 80 kN. Although the topmost connector absorbs the most energy, at this slip load practically all the connectors contribute equally toward energy dissipation.

2.2 Structural integrity of the horizontal joints

In the horizontal joints of precast panel structures, both the axial deformations due to rocking and the magnitude of the shear slip represent potential sources of damage. However, horizontal joint slip of the present study has been found to be localized in nature, occurring over a

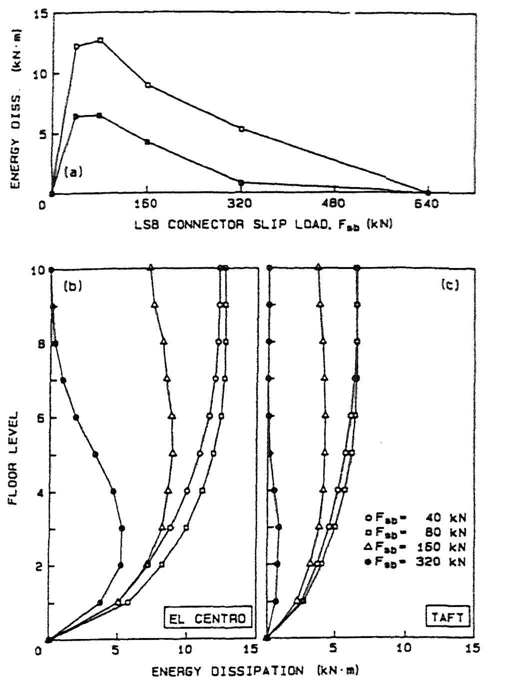

Figure 4. Energy dissipation in LSB connectors: (a) critical connector; (b) envelopes over height.

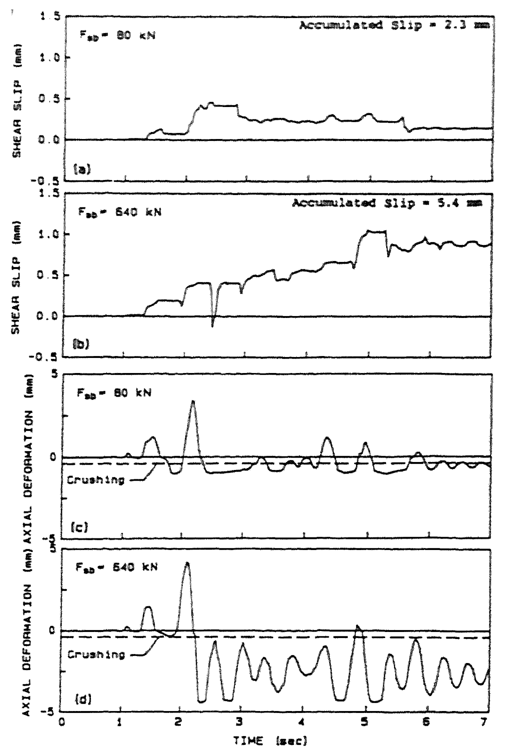

Figure 5. Time histories of base horizontal joint slip and axial deformation - El Centro.

relatively small region as a result of rocking. Global slip across the entire joint is more serious in terms of joint degradation, since all points along the joint are in contact and reach the ultimate strength.

A time-history of such localized slip at the left edge of the base joint is presented in Figs.5a and 5b for F_{sb} = 80 and 640 kN. The data demonstrates an essentially monotonic increase in slip with time and, combined with the reduction shown in accumulated slip for optimum F_{sb}, the danger of shear degradation for the present LSB equipped structure is minimized. Similar time-histories of axial deformation, shown in Figs. 5c and 5d, show significant reduction in cyclic joint crushing over the full duration of the excitation. For F_{sb} = 0 kN (not shown), response is also higher than for optimum slip load. It should be noted that crushing of the horizontal joints is found to be confined to the lower levels and at the edges.

The deformed shapes of the wall at 0.75 sec after termination of the El Centro excitation is presented in Fig. 6. For both F_{sb} = 80 and 640 kN, the wall returns nearly to its initial undeformed shape. For uncoupled behaviour (F_{sb} = 0 kN), Fig. 6a does not suggest that the structure develops severe permanent deformation but implies continued oscillation. In the cases of both coupled and fully coupled behaviour, however, severe compressive deformations are observed at the base horizontal joint edges. Some permanent edge damage at the base even for the optimum slip load can be noticed. Thus, although integrity of the structure as a whole is observed to be generally excellent for optimum LSB connector slip load, the residual compressive deformation in the base horizontal joint warrants concern.

2.3 Effect of additional vertical reinforcement

Thus far, vertical continuity for the structure has been provided by steel reinforcing bars equal to 0.5 per cent

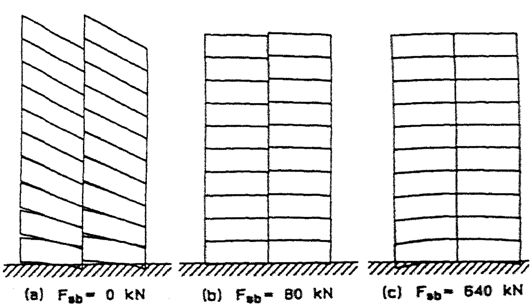

Figure 6. Deformed wall configurations after earthquake for different slip loads - El Centro.

of the gross cross-sectional area distributed evenly across the joint. Fig. 7 shows the effect that additions to this form of continuity have on base joint response.

Fig. 7a shows that the added edge reinforcement significantly reduces the maximum gap opening across the base horizontal joint, displaying a peak magnitude of 1.7 mm compared to 4.3 mm for distributed steel; post-tensioning, on the other hand, is noted to have only marginal effect. Results not shown, however, reveal reductions in gap opening at level 4 and above (with zero gap opening at the topmost levels) using post-tensioning, thus indicating that such vertical continuity is most effective at the upper floor levels. Compressive base deformation, shown in Fig. 7b, shows little change either with the addition of concentrated reinforcement or post-tensioning. Edge deformation remains above the axial deformation at ultimate joint strength and, thus, the problem of base corner crushing is not alleviated through the above additional vertical reinforcement.

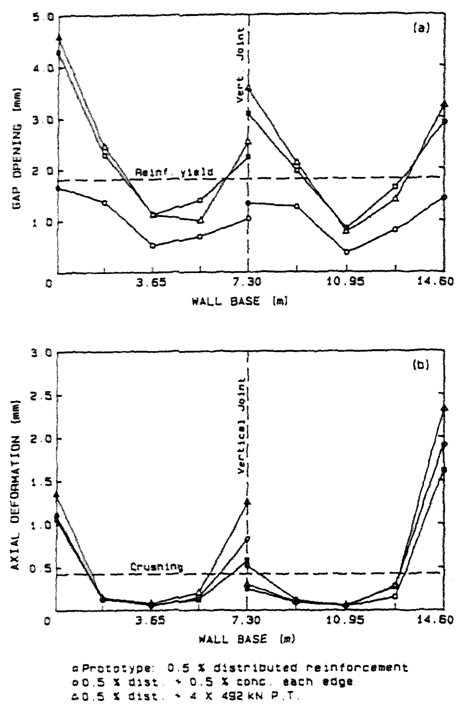

Figure 7. Effect of vertical continuity on maximum joint response at optimum slip load F_{sb} = 80 kN - El Centro.

3 CONCLUSIONS

The seismic performance of a prototype 10-story precast shear wall with nonlinear behaving horizontal joints and equipped with LSB vertical connectors has been studied, with particular emphasis on controlling damage in the horizontal joints. Based on the results obtained, the following observations are noted:

1. A slip load of 80 kN per connector was found to minimize seismic response for both the El Centro and Taft earthquakes. Energy dissipation in the LSB connectors is maximized over the height of the wall at this optimum slip load.
2. For the LSB optimized structure shear slip is relatively low in magnitude which, combined with its essentially monotonic variation over time, ensures reduced likelihood of damage in the horizontal joints due to this mode of response.
3. Although problems of crushing in the horizontal joints due to panel rocking and slip is to be expected, this is confined to the lower level joint edges and deformations are significantly reduced at optimum F_{sb}.
4. The addition of concentrated edge reinforcement limits gap opening to a level which is sufficient to ensure elastic behaviour of the vertical steel throughout the structure. Post-tensioning bars, on the other hand, are effective only at the upper levels of the structure.

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