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EFFECTIVENESS OF LSB CONNECTORS IN CONTROLLING SEISMIC DAMAGE IN PRECAST PANEL STRUCTURES

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ABSTRACT

This paper examines the use of limited slip bolted (LSB) connectors placed along the vertical joints of precast concrete panel structures in order to control the level of expected seismic damage. Tuning the slip load of these connectors allows overall response to be optimized through efficient energy dissipation by friction. Primary attention is focussed on the level and significance of deformation induced in the horizontal joints of a 10-story prototype shear wall. It is shown that, for the tuned structure with uniformly distributed vertical reinforcement, response in the horizontal joints can be expected to remain essentially damage free for most earthquakes. For particularly severe ground motion, however, some localized damage at the base of the structure in the form of edge crushing is nevertheless to be anticipated, although the magnitude of even this localized damage is reduced considerably by the action of the vertical joint LSB connectors.

KEYWORDS: Earthquakes, Precast Panels, Energy Dissipation

INTRODUCTION

Failure of precast panel wall systems during severe earthquake excitation can be expected to occur as a result of damage to the interpanel joints, where locations of weakness exist due to reduced stiffness and strength in comparison to the panels. As the development of overall ductility in precast systems is difficult, acceptable seismic response therefore depends on inelastic action in the joints.

Damage to the vertical joints during seismic activity, where shear deformation dominates, can be controlled by employing deliberately "weak but ductile" mechanical connectors. Mueller and Becker (1980) studied the performance of walls coupled by elasto-plastic connectors and showed the existence of an optimum connector yield strength for which seismic response was minimized. In this study both the walls and the horizontal joints were assumed to behave elastically. In a similar study for elastic walls but without horizontal joints, Pall et al. (1980) proposed the use of limited slip bolted (LSB) mechanical connectors to eliminate all damage along the vertical joint. These connectors are designed to slip at a predetermined slip load, thereby imposing a bound on the force attracted and at the same time allowing the connector anchorages to remain elastic. The resulting improvement in seismic response was shown to be considerable due to the inherent efficiency of these connectors in dissipating seismic energy input through friction. The additional advantage of the proposed connectors lies in the ease with which optimal response can be achieved, namely by simply adjusting or "tuning" the slip load of the connectors.

While use of the above LSB connectors allows the vertical joints to remain free of damage, controlling corresponding damage otherwise incurred in the horizontal joints remains to be investigated. The horizontal joints commonly used in North America are of the platform type, which 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 (Becker et al. 1980; Shricker and Powell 1980; Harris and Caccese 1984; Oliva and Shahrooz 1984; Kianoush and Scanlon 1988a, b). Thus, a potential exists for serious damage in the horizontal joints of precast panel structures, which may undermine overall stability during earthquake response.

The primary purpose of this paper is to assess the effectiveness of employing the aforementioned vertical joint LSB connectors in controlling damage in the horizontal joints. This is accomplished by subjecting a 10-story prototype structure to a parametric study in which both the degree and significance of response induced in vertically reinforced platform-type horizontal joints is examined. The results demonstrate that a panel structure with a "tuned" slip load of the LSB connectors can remain almost damage free for the earthquakes considered.

PROTOTYPE STRUCTURE AND ANALYTICAL MODEL

1. Description of 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. It is similar to the precast wall of Pall et al. (1980) and consists of two panel stacks coupled along the vertical joint by the aforementioned limited slip bolted (LSB) connectors placed two per story as shown in Figure 1. The details of these connectors are adopted also from Pall et al. (1980) and depicted in Figure 2(a). The steel connecting plates have slotted holes which allow slippage once the design slip load F_{sb} is reached; the latter is governed by the prestress in the bolts and friction pads which are placed between the connecting plates and the steel inserts anchored into the adjoining panels. More specific description of the experimental behaviour and proposed construction details are available in Pall et al. (1980).

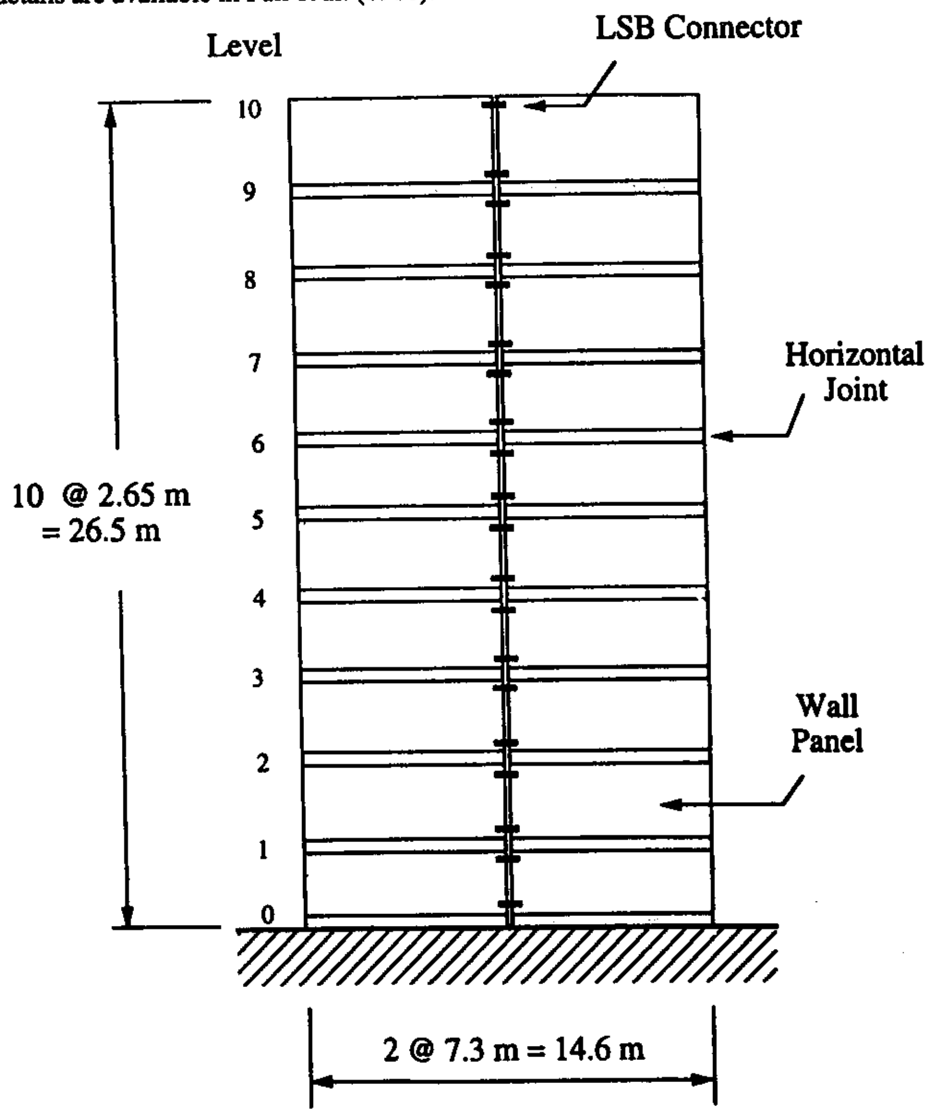


Fig. 1 Prototype precast panel end wall equipped with LSB conectors

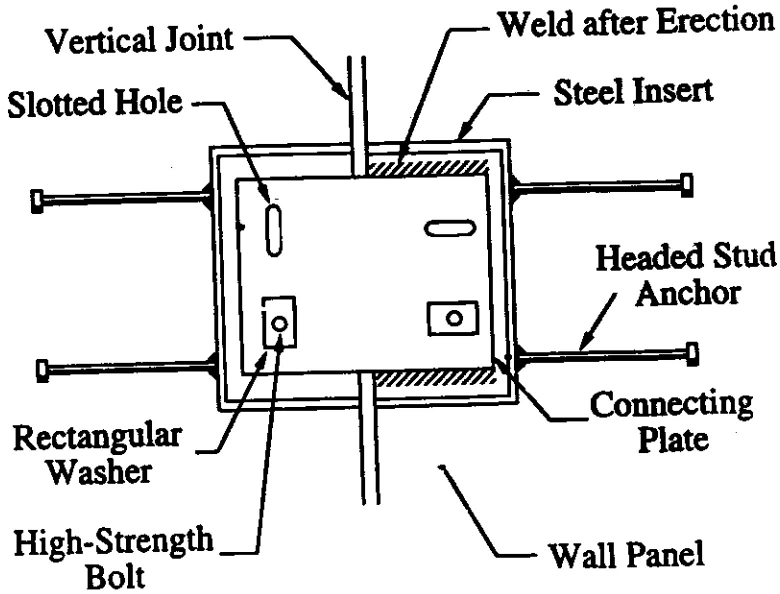
The horizontal joints are of the wet platform type shown in Fig. 2(b). Steel reinforcement equal to 0.5 % of the gross cross-sectional area provides vertical continuity across these joints. Panel properties, loading and parameters related to horizontal and vertical joint behaviour (discussed below) are given in Table 1.

Table 1: Properties of Prototype Wall

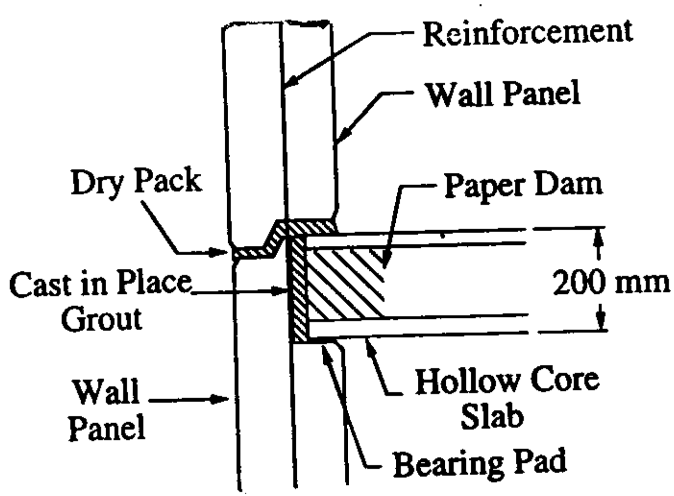
Description		Value
(a) Panels and Loading		
Panel thickness (mm)		200
Modulus of elasticity (MPa)		29.2×10^3
Poisson's ratio		0.15
Compressive strength (MPa)		34
Gravity load per story (kN)		490
Tributary story mass (kg)		128×10^3
(b) Horizontal joints		
Thickness (mm)		200
Modulus of elasticity (MPa)		13.8×10^3
Compressive strength (MPa)		14.5
Axial parameters:	k_1 (kN/mm/mm)	13.15
	k_2 (kN/mm/mm)	2.39
	k_3 (kN/mm/mm)	0.001
	k_4 (kN/mm/mm)	0.25
	u_1 (kN/mm/mm)	0.176
	u_2 (mm)	0.420
Shear parameters:	k_s (kN/mm/mm)	5.75
	k_r (kN/mm/mm)	0.575
	r	0.15
	μ_f	0.40
(c) Vertical joint LSB connectors		
Axial stiffness:	k_c (kN/mm)	1950
	k_t (kN/mm)	490
Shear stiffness:	k_s (kN/mm)	640

2. Idealized Behaviour of Joints

Nonlinear behaviour in the horizontal joints arises from gap opening due to rocking and shear slip once the frictional capacity of the joints is reached. This coupled behaviour in the horizontal joints is modelled by the force-deformation relationships shown in Figure 3. Axial behaviour normal to the joint is depicted in Figure 3(a) where compression follows a tri-linear model approximating available concrete stress-strain curves. Once the ultimate concrete compressive strength f'_c is reached at joint deformation u_2 crushing is assumed to commence, whereas the onset of yielding is considered to occur at deformation u_1 corresponding to stress of 0.8 f'_c. Unloading and reloading take place elastically in both compression and tension, with the latter governed by the elastic stiffness of the vertical reinforcement. The effect of the vertical steel on the shear-friction behaviour under varying normal force is shown in Figure 3(b). Here, first slip when instantaneous normal force is F_{c1} is followed by stiffness in shear k_r due to dowel action of the vertical steel, which in turn is followed by restoration of elastic stiffness k_s and subsequent slip under new normal force F_{c2}. This shear-friction model, as well as the magnitudes of the related parameters (k_r and r of Table 1), was first proposed by Kianoush and Scanlon (1988a,b).



(a) Limited slip bolted (LSB) connector



(b) Platform type horizontal joint

Fig. 2 Details of vertical and horizontal joints

The corresponding behaviour assumed for the vertical joint LSB connectors is shown in Figure 4. Unlike the preceding coupled behaviour of the horizontal joints, in the vertical joint resistance to shear along the joint is assumed to act independently of resistance to normal force across the joint. Thus, tension and compression follow the respective linear elastic force-deformation idealizations of Figure 4(a), whereas behaviour in vertical shear exhibits the stable elasto-plastic hysteresis of Figure 4(b). The experimental results for LSB connectors, reported by Pall et al. (1980) employing brake lining pads between the connector plates, showed remarkably stable elasto-plastic characteristics and thus justify the present model for the vertical joint connectors. It needs to be noted that the slot length in the connecting plates has been assumed sufficient to prevent bearing of the bolts following slip. Based on computed maximum slip distances (to follow), the latter is easily accomplished in the detailing of the connecting plates.

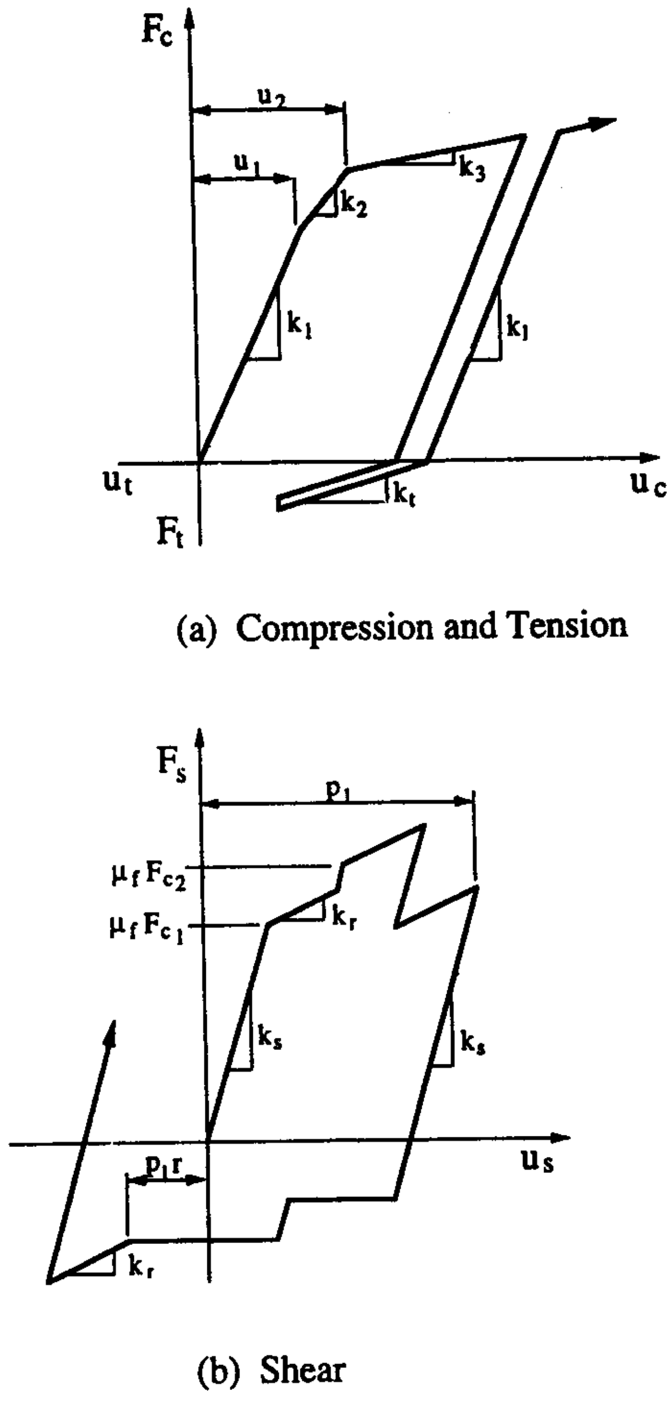
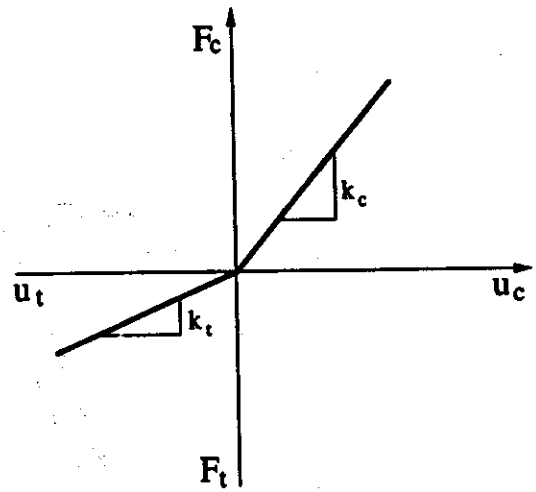


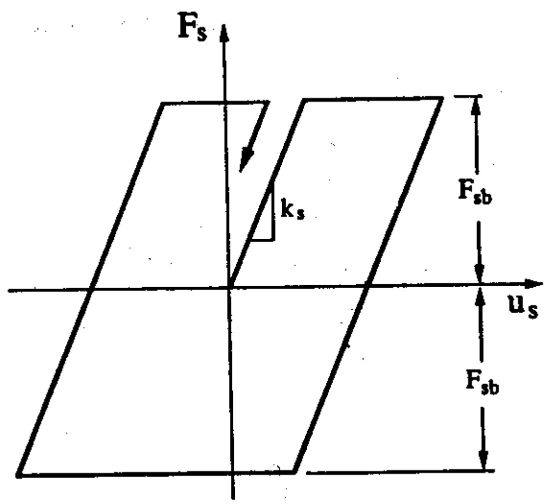
Fig. 3 Idealized behaviour of horizontal joints

SEISMIC ANALYSIS

The computer program ANSR-I (Mondkar and Powell 1975) was employed to obtain the dynamic response. The precast panels were modelled by linear elastic plane stress finite elements interconnected by two-node (four-degree-of-freedom) nonlinear spring elements to model both the horizontal and the vertical joints. Five spring elements were employed to discretize the horizontal joints across one panel width, whereas one such element represents each LSB connector.



(a) Compression and Tension



(b) Shear

Fig. 4 Idealized behaviour of vertical joint in LSB connectors

Five percent viscous damping in the two lowermost modes was assumed and the dynamic response was obtained by time step integration employing $\Delta t = 0.001\,\mathrm{sec}$.

Four different earthquake records were employed in this study. Only the first six seconds of these records were used, followed by one second of zero acceleration. The accelerograms were scaled to match the intensity of the 1940 El Centro NS record, with intensity defined as the area under the 5 % damped relative velocity response spectrum between periods of 0.1 and 3.0 sec. The records consist of the 1940 El Centro NS; 1952 Taft N69E; 1949 Olympia, N10W; and the Newmark-Blume-Kapur artificially generated earthquake. Since the El Centro record was demonstrated to yield the most severe structural response, it was used over the full range of slip load. The Taft record was employed similarly, although producing far less severe response. The Olympia and the artificial input excitations were used only for the case of the tuned LSB connectors.

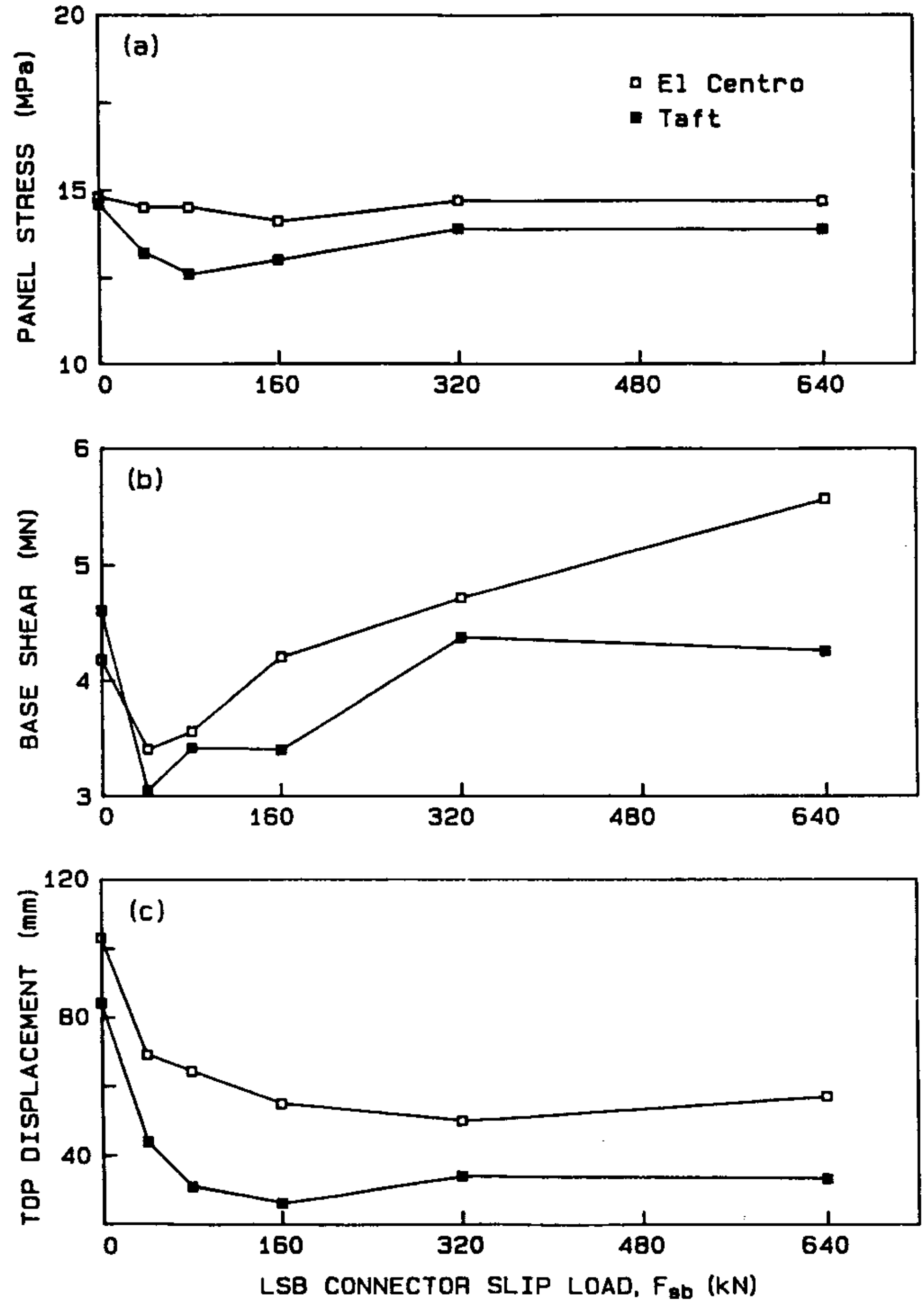


Fig. 5 Optimum connector slip load for overall response parameters

LSB OPTIMIZATION OF OVERALL RESPONSE

1. Optimum Slip Load

Optimization of earthquake response entails minimizing the difference between the seismic energy fed into and that dissipated by the structure. For a given earthquake, input energy depends primarily upon the building's mass and natural frequency, while energy dissipation is largely controlled by the level of ductility or inelastic action. For structures equipped with LSB connectors, the slip load F_{sb} can be adjusted to achieve maximum energy dissipation. At a slip load of 640 kN, the present structure acts as two elastically coupled panel stacks, since the connector capacity is sufficient to prevent slip from occurring along the vertical joint.

Figure 5 depicts 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 excitations, an optimum slip load of approximately 80 kN is observed. This common slip load for both earthquakes indicates that the design value of F_{sb} can be based only on the characteristics of the structure and remains relatively independent of the ground motion itself. It should be noted that both the existence and the magnitude of optimum F_{sb} are in agreement with the results reported by Mueller and Becker (1980) and Pall et al. (1980) for coupled walls but wherein the influence of nonlinear behaving horizontal joints was not considered. It should also be noted that the relative insensitivity of maximum panel stress to F_{sb} and hence the apparent lack of an "optimum" as noted in Figure 5(a), is readily explained by the fact that the observed maximum panel stress corresponds to the crushing strength of the horizontal joints (14.5 MPa). This problem, ignored in the aforementioned studies, will be discussed in substantial detail later in this paper.

Figure 6 plots the corresponding peak response in the LSB connectors versus slip load F_{sb}. Figure 6(a) shows that LSB slip at optimum (F_{sb} = 80 kN) is 8 mm and 20 mm for the Taft and El Centro records, respectively. As noted previously, such slip must be accommodated in the slot length of the connecting plates as, otherwise, bearing of the bolts results in increased response. At F_{sb} = 640 kN slip is seen not to have occurred for both excitations, thus confirming elastic coupling of the panel stacks at this connector capacity.

Similarly, Figure 6(b) confirms that maximum shear force on the connectors is indeed limited to the capacity F_{sb}, so that elastic design of connector anchorages is possible by the prior knowledge of the maximum expected load. Tensile force in the connectors is presented in Figure 6(c), which shows that minimum tensile force is incurred for F_{sb} close to 80 kN also. At this slip load, the larger tension of 200 kN (El Centro) is easily resisted by the capacity of anticipated connector anchorages.

2. Energy Dissipation in LSB Connectors

As noted above, structural response is optimized by selecting an appropriate slip load whereby overall structural responses such as panel stress and base shear are minimized. The magnitude of the optimum slip load can also be obtained by considering the energy dissipated by the LSB connectors. The seismic energy dissipated in a single LSB connector is measured by the total area enclosed by the hysteretic loops tracing its behaviour in shear. Since behaviour is elasto-plastic, this area is equal to the product of the connector slip load and accumulated slip travel.

Energy dissipated by the LSB connector having the maximum value out of all the connectors (i.e., the critical connector) is shown in Figure 7(a) as function of the connector slip load. Energy dissipation is observed to rise to a maximum at F_{sb} = 80 kN; thus, the optimum LSB slip load for structural response also exhibits the largest potential for energy dissipation in the critical connector. Figures 7(b) and 7(c) show envelopes of energy dissipation at slip loads of 40 kN, 80 kN, 160 kN and 320 kN for El Centro and Taft, respectively, and reveal that the relationship between slip load and critical connector energy dissipation as disclosed in Figure 7(a) 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 dissipated. In contrast, the energy curves for high F_{sb} (320 kN) peak at the lower floors and thus imply reduced ability to improve seismic response.

3. Structural Integrity

Time histories of top lateral displacement of the precast wall are shown in Figure 8 for the El Centro excitation and slip loads of 0 kN, 80 kN and 640 kN. Stable response over seven seconds is demonstrated for all slip loads by the lack of perceptible drift from zero displacement. Response is markedly reduced at F_{sb} = 80 kN, for which the much improved response approaches that of elastically coupled walls.

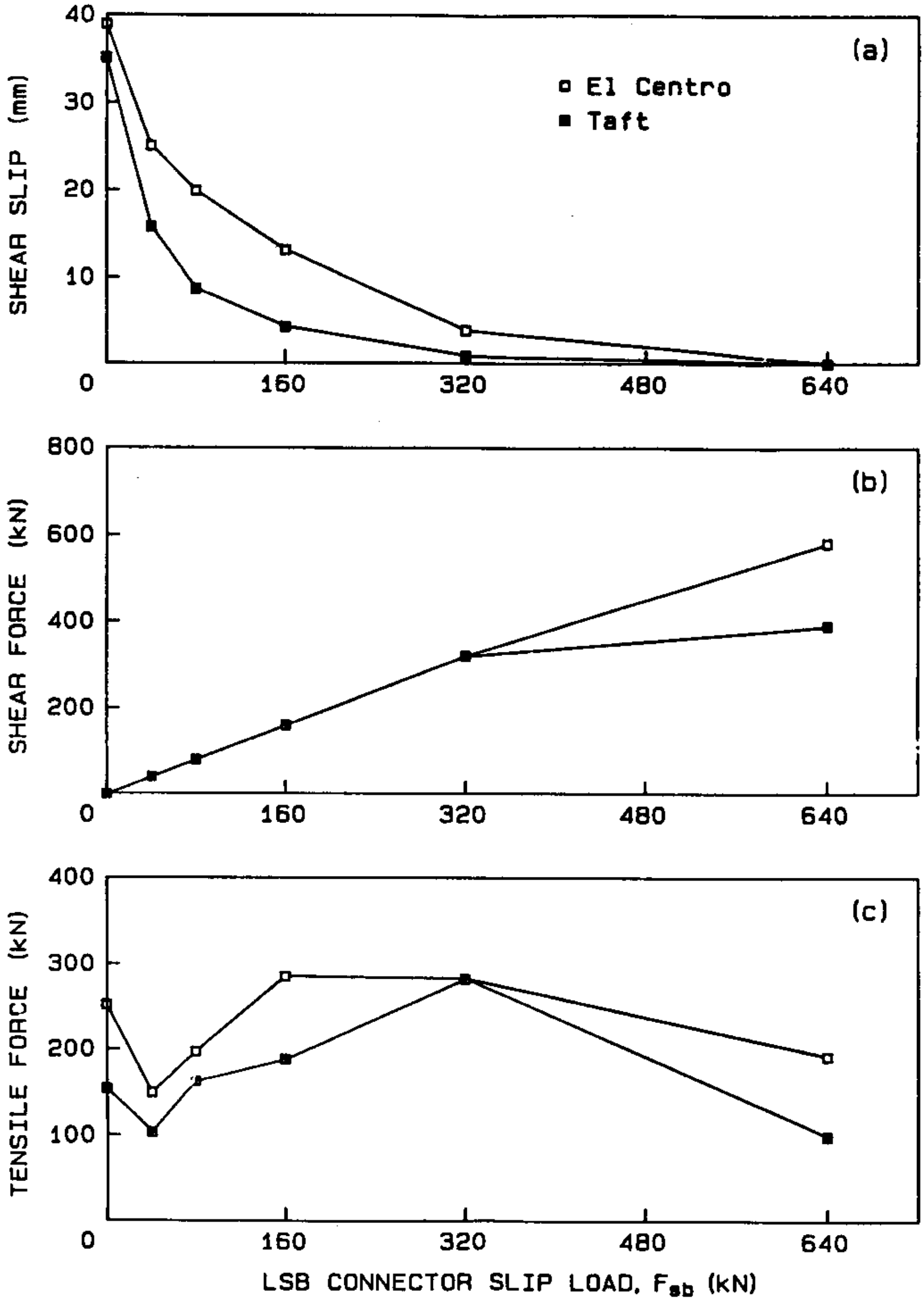


Fig. 6 Effect of slip load on response in LSB connectors

Figures 9 and 10 present the idealized deformed shapes of the wall, with the scale for deformation grossly exaggerated for clarity. Depicted in Figure 9 are the wall configurations at times of maximum positive lateral displacement. The general shapes of the wall at slip loads of 0 kN and 80 kN show little difference displaying large gap opening and vertical joint slip, although appreciably higher slip for F_{sb} = 0 kN is apparent. With F_{sb} = 640 kN, full elastic coupling along the vertical joint prevents shear slip and the configuration tends to resemble that of a single stack precast wall.

The deformed shapes of the wall at 0.75 sec after termination of the El Centro excitation are seen in Figure 10. For both F_{sb} = 80 kN and 640 kN, the wall returns nearly to its undeformed shape. For uncoupled behaviour (F_{sb} = 0 kN), Figure 10(a) does not suggest that the structure develops severe permanent deformation, but as evident in Figure 8(a), only implies continued oscillation. In case of both uncoupled and fully coupled behaviour, however, severe compressive deformations are observed in the base horizontal joint. The excitation (El Centro) induces some permanent edge damage at the base even for the optimum slip load (Figure 10(b)). 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 study. The following sections of the paper further address this important aspect related to integrity of the horizontal joints.

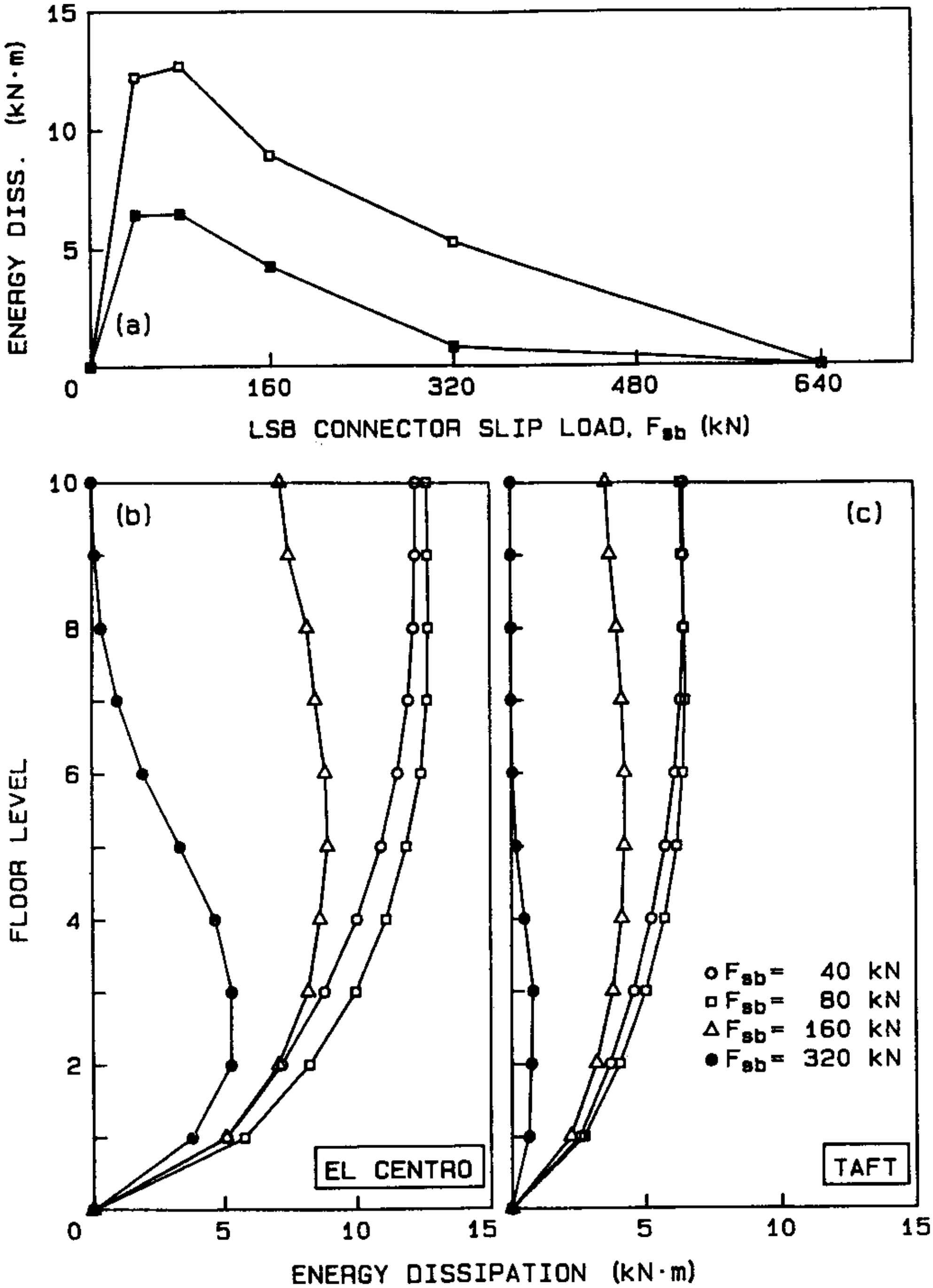


Fig. 7 Energy dissipation in LSB connectors:
(a) critical connector; (b) and (c) envelopes over height

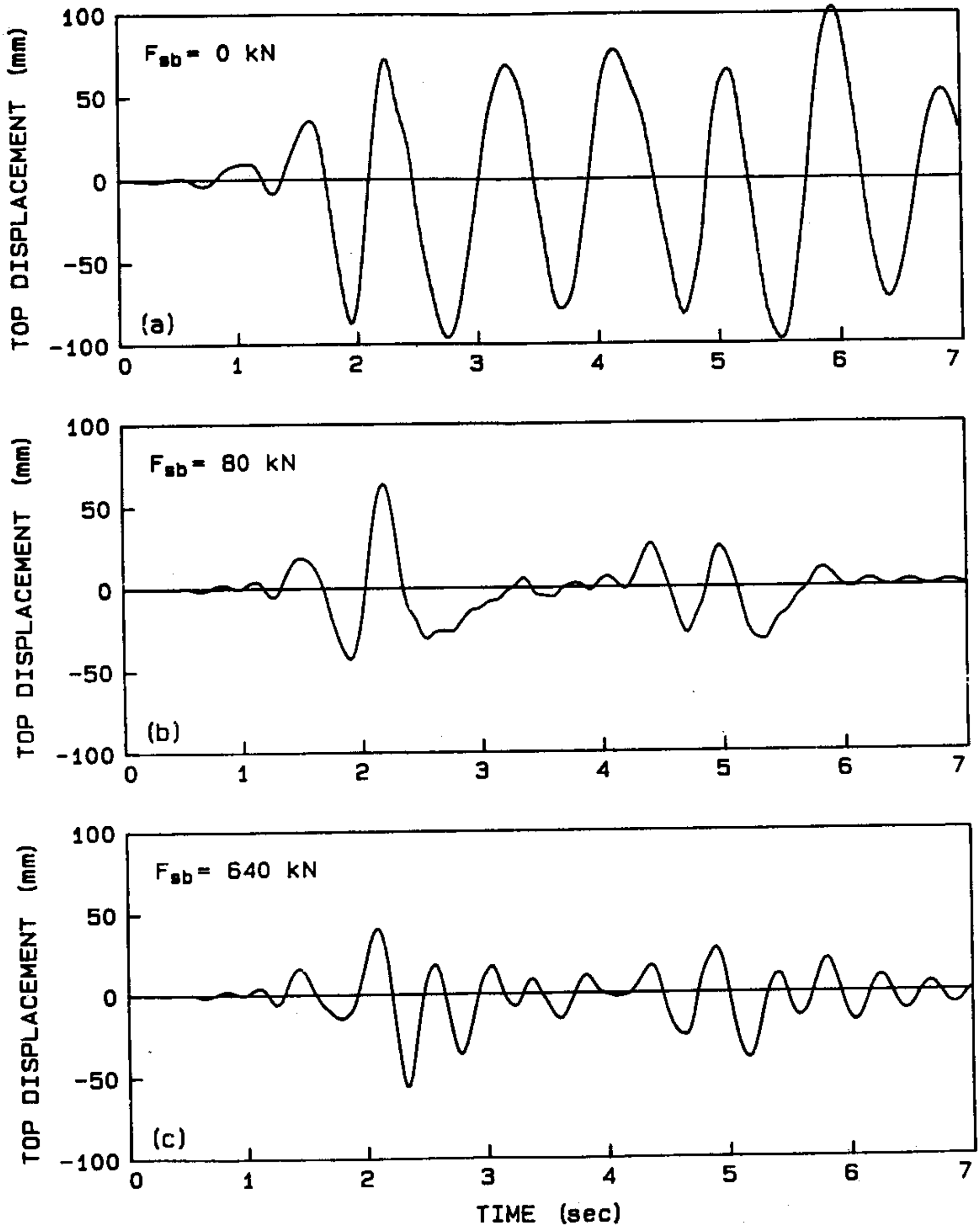


Fig. 8 Top displacement time histories for different slip loads – El Centro excitation

RESPONSE IN HORIZONTAL JOINTS

In the lower horizontal joints of precast panel structures, both the axial deformation due to rocking and the magnitude of the shear slip represent potential sources of damage. Results presented below examine both the degree and significance of these modes of response in the horizontal joints for varying vertical connector slip load F_{sb}.

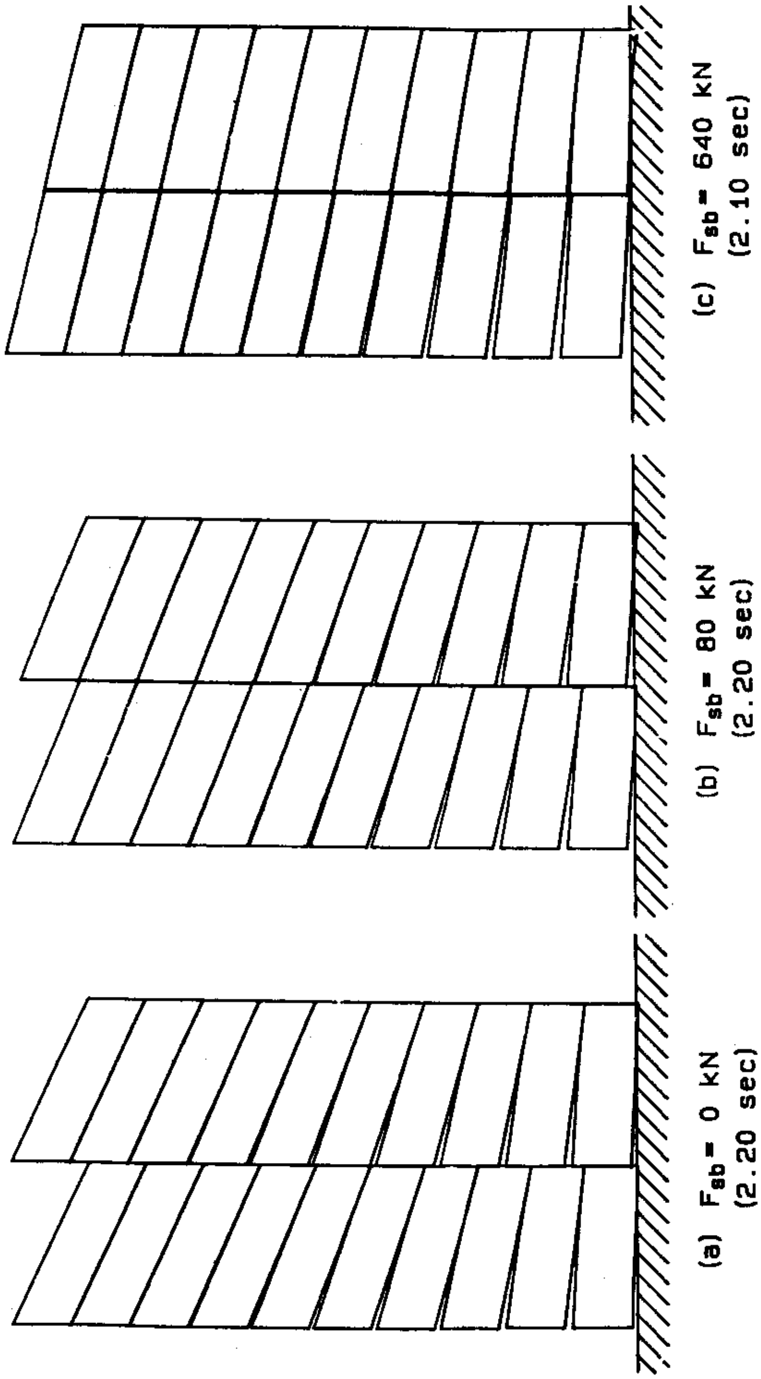


Fig. 9 Deformed wall configurations (exaggerated scale) at times of maximum displacement for different slip loads – El Centro excitation

1. Effect of Varying the Slip Load

Figures 11(a) and 11(b) plot peak values of maximum and accumulated slip in the horizontal joints versus the LSB connector slip load for the El Centro and Taft earthquake records. Maximum gap opening (or uplift) and compressive axial deformation are presented in Figures 11(c) and 11(d). As for the overall structural responses seen in Figure 5, response parameters related to the horizontal joints shown here are also minimized at a slip load close to 80 kN. At this optimum connector capacity, Figure 11(a) shows maximum slip lengths of 0.9 mm and 0.6 mm for the El Centro and Taft excitations, respectively. These magnitudes represent substantial reductions in slip action with important implications for controlling damage in the horizontal joints.

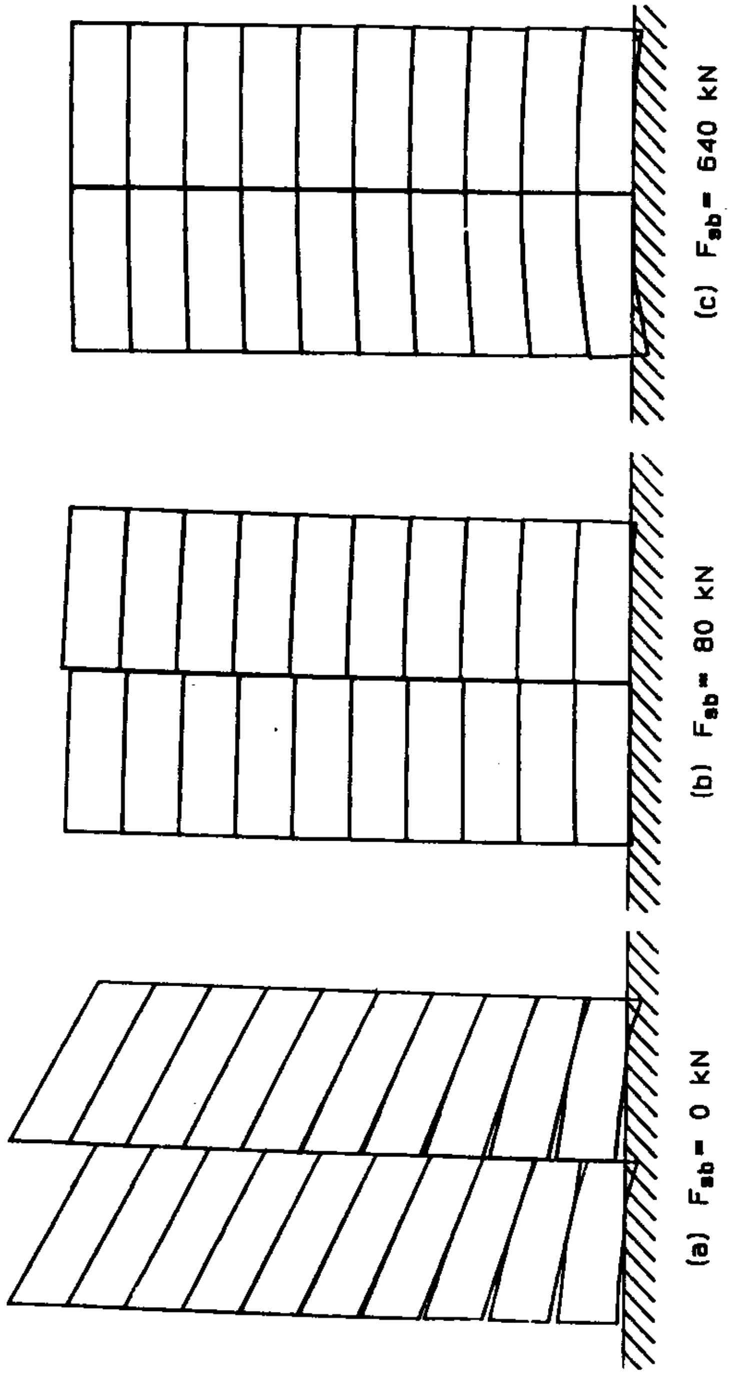


Fig. 10 Deformed wall configurations (exaggerated scale) after earthquake for different slip loads – El Centro excitation

Shear tests on full-scale European "Vranica" type horizontal joints by Verbic and Terzic (1978) indicated nearly elastic behaviour at deformations up to approximately 1 mm, for which the ultimate static strength had not yet been reached. Under applied normal force to simulate gravity loading, cyclic shear behaviour at amplitudes of 20 mm was shown to be stable with negligible degradation in either stiffness or strength. In similar shear tests on 3/32 scale American platform joints, Harris and Abboud (1981) observed several cycles of elasto-plastic behaviour at slip amplitude of 4 mm prior to failure.

Furthermore, the horizontal joint slip of the present study is "localized" in nature and not the more or less "global" slip of the above tests. In seismic response, rocking causes slip to be confined to a relatively small region of the horizontal joint, which for analytical purposes implies slip in one element, while others belonging to the same joint remain elastic. Global slip is more serious in terms of joint degradation, however, since all points along the joint are in contact and reach the ultimate strength. Thus, the slip observed above at optimum F_{sb} implies little damage due to the combined effects of its relatively low magnitude (Figure 11(a)) and localized nature.

More important for the present structure is the extent to which gap opening occurs. At all slip loads, substantial uplift is observed. With F_{sb} = 80 kN, however, reductions in gap opening and related axial deformation are significant as demonstrated in Figures 11(c) and 11(d) respectively. For the more critical El Centro ground motion, values are 47 % and 52 %, less than for the isolated walls and 34 % and 64 % less than for the elastically coupled walls, for gap opening and compressive deformation, respectively. The similarity between the two figures shows the effect that joint opening, indicative of rocking, has on compressive deformation. The ultimate compressive strength f_c' of the composite horizontal joints, reduced to 14.5 MPa for the detail of Figure 2(b), corresponds to axial deformation of 0.42 mm (or 0.0021 strain for the 200 mm deep joints) and is seen to be exceeded at all slip loads for the El Centro earthquake. However, for the Taft excitation the optimum connector capacity F_{sb} = 80 kN is just adequate to prevent incipient crushing. Nevertheless, axial deformation and consequent degradation in the joint associated with strains beyond that at ultimate strength are seen to be much more pronounced for the isolated and elastically coupled walls.

2. Envelopes of Joint Response

Envelopes of maximum horizontal joint response are presented in Figure 12 for the El Centro excitation. Uniform slip action is apparent over the full height of the structure at F_{sb} = 80 kN, as indicated by envelopes of maximum and accumulated local slip in Figures 12(a) and 12(b). Particularly important is the large reduction in response realized at the critical lowermost levels, which as noted previously, is sufficient to prevent shear degradation in the joints.

Substantially lower magnitudes of gap opening at all levels are also noted for F_{sb} = 80 kN, as shown in Figure 12(c). A nearly linear increase in gap opening is demonstrated at all slip loads from top to bottom. Associated rocking is thus more severe at the lower joints, where accompanying normal joint forces are also notably greater. This results in concentration of compressive force at the ends of the lowermost horizontal joints.

The corresponding envelopes of maximum compressive deformation in the horizontal joints of Figure 12(d) indicate the consequent crushing which occurs in the lowermost joints, where normal strain exceeds that corresponding to the ultimate strength. However, it is noted that the optimized LSB connector slip load of 80 kN limits the expected damage to the base joint only, whereas at F_{sb} = 0 kN the ultimate deformation of 0.42 mm is exceeded up to level 2.

Tests have shown that compressive strain in excess of 0.004 for equivalent low-strength concrete (14.5 MPa and ultimate strain of approximately 0.002) can be sustained prior to failure (Freedman 1985). This corresponds to a deformation of about 0.8 mm for the joints employed in this study, implying a ductility capacity of approximately 2. The test results for platform joints reported by Harris and Iyengar (1980) also suggest similar ductility capacity, although strains beyond a ductility factor of one were not recorded due to potential instrumentation damage. Compared with this predicted although limited ductility capacity of the joints in compression, the data of Figure 12(d) correspond to excessively large ductility factors 11.2 and 8.5 at the base for elastically coupled and uncoupled walls, respectively, whereas, optimum F_{sb} = 80 kN reduces the required ductility factor to 4.0 or approximately only twice that needed to cause some local damage in the lowermost joint.

3. Time Histories of Slip and Axial Deformation

Figure 13 shows time histories of localized horizontal joint shear slip for F_{sb} = 0 kN, 80 kN and 640 kN and the El Centro excitation. The results are presented for slip at the far left edge of the level 1 horizontal joint, although similar behaviour can be observed at corresponding edges of other floor levels as evidenced by the envelopes of Figure 12 for slip action.

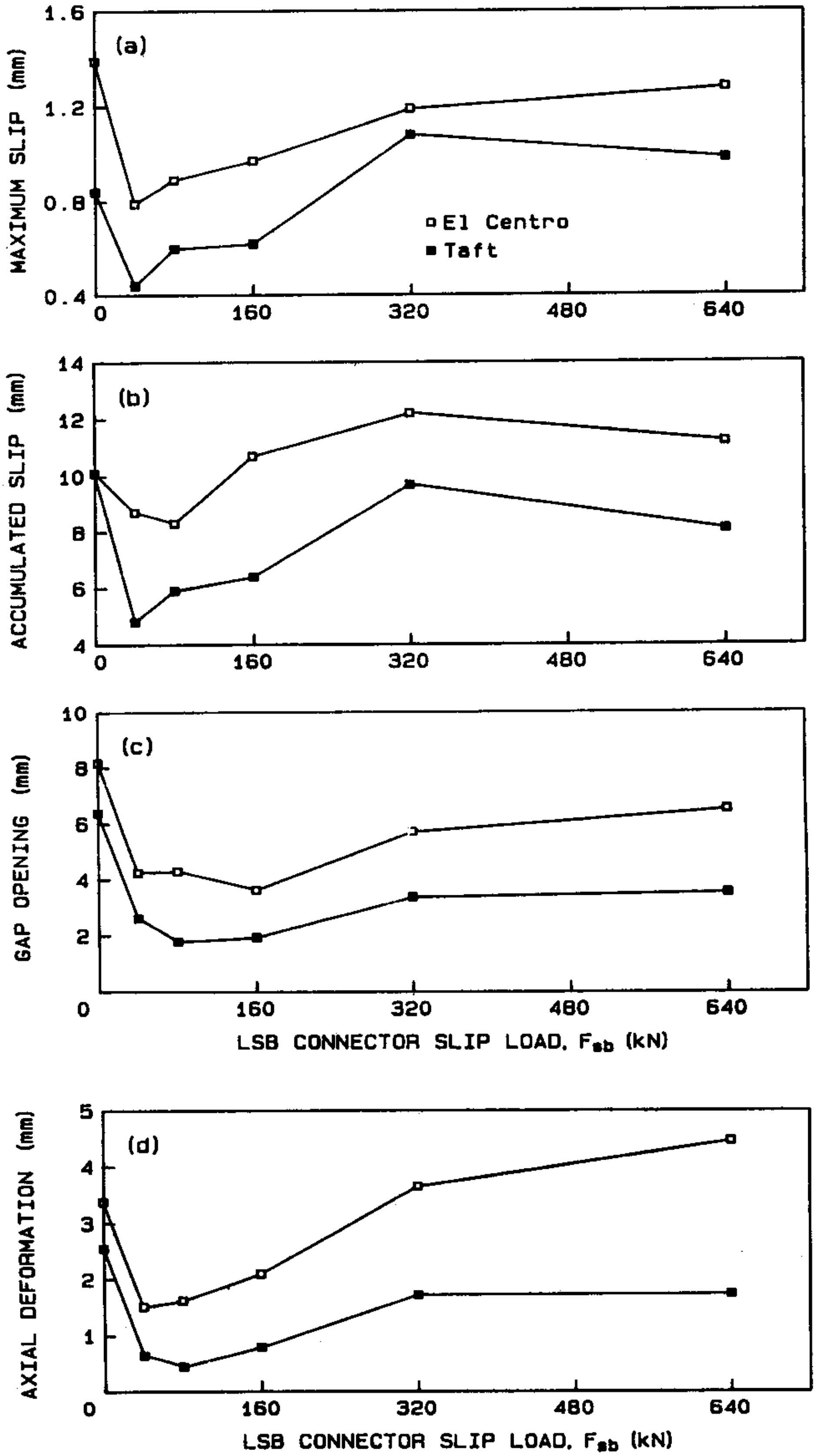


Fig. 11 Effect of connector slip load on maximum response in horizontal joints

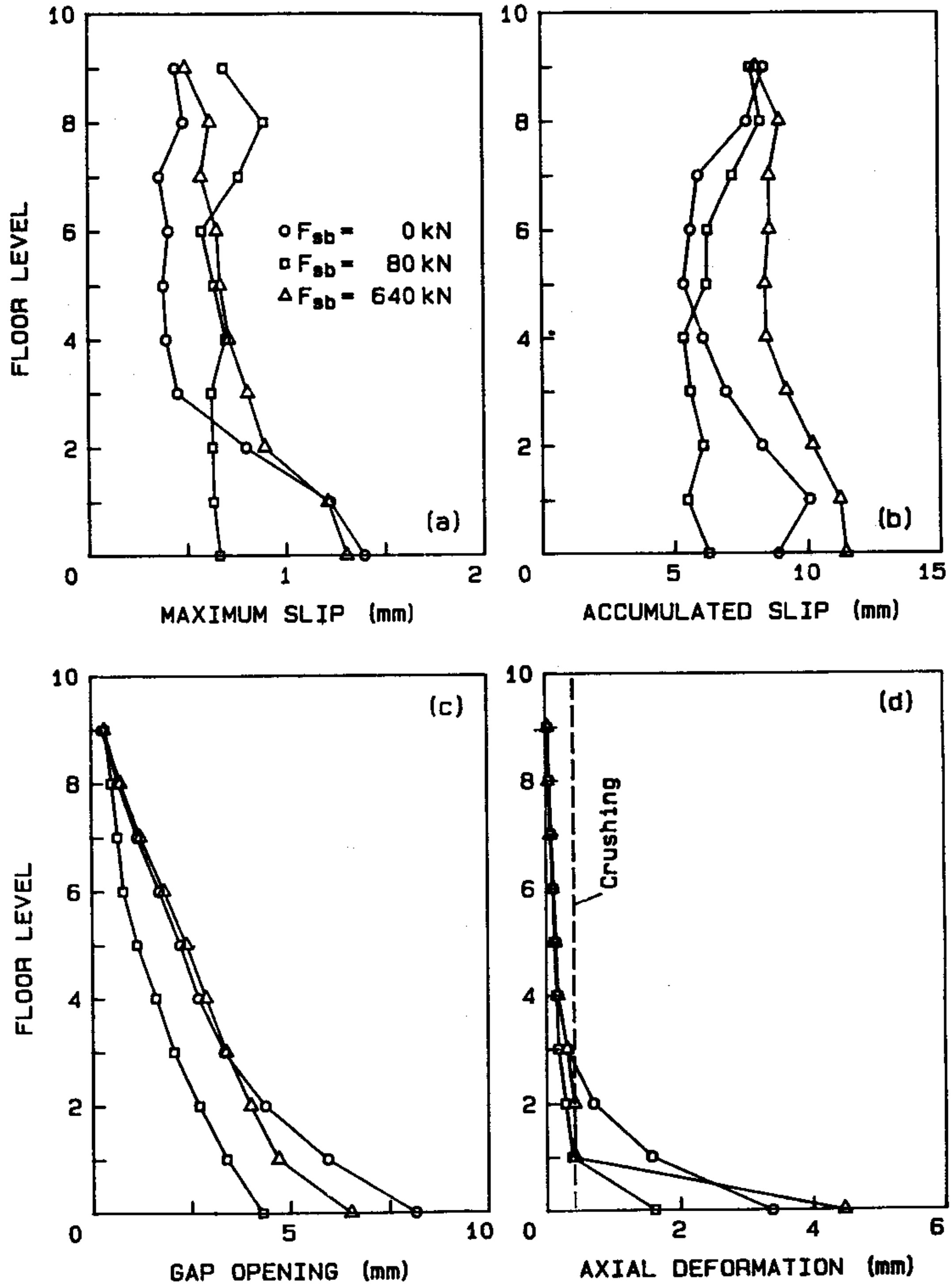


Fig. 12 Envelopes of maximum response in horizontal joints for different slip loads – El Centro excitation

The data of Figure 13 demonstrates an essentially monotonic increase in slip with time. This lack of major reversal in slip direction, combined with the pronounced reduction in magnitude realized in Figure 13(b) for F_{sb} = 80 kN, confirms that shear degradation poses no danger for the present LSB equipped prototype structure.

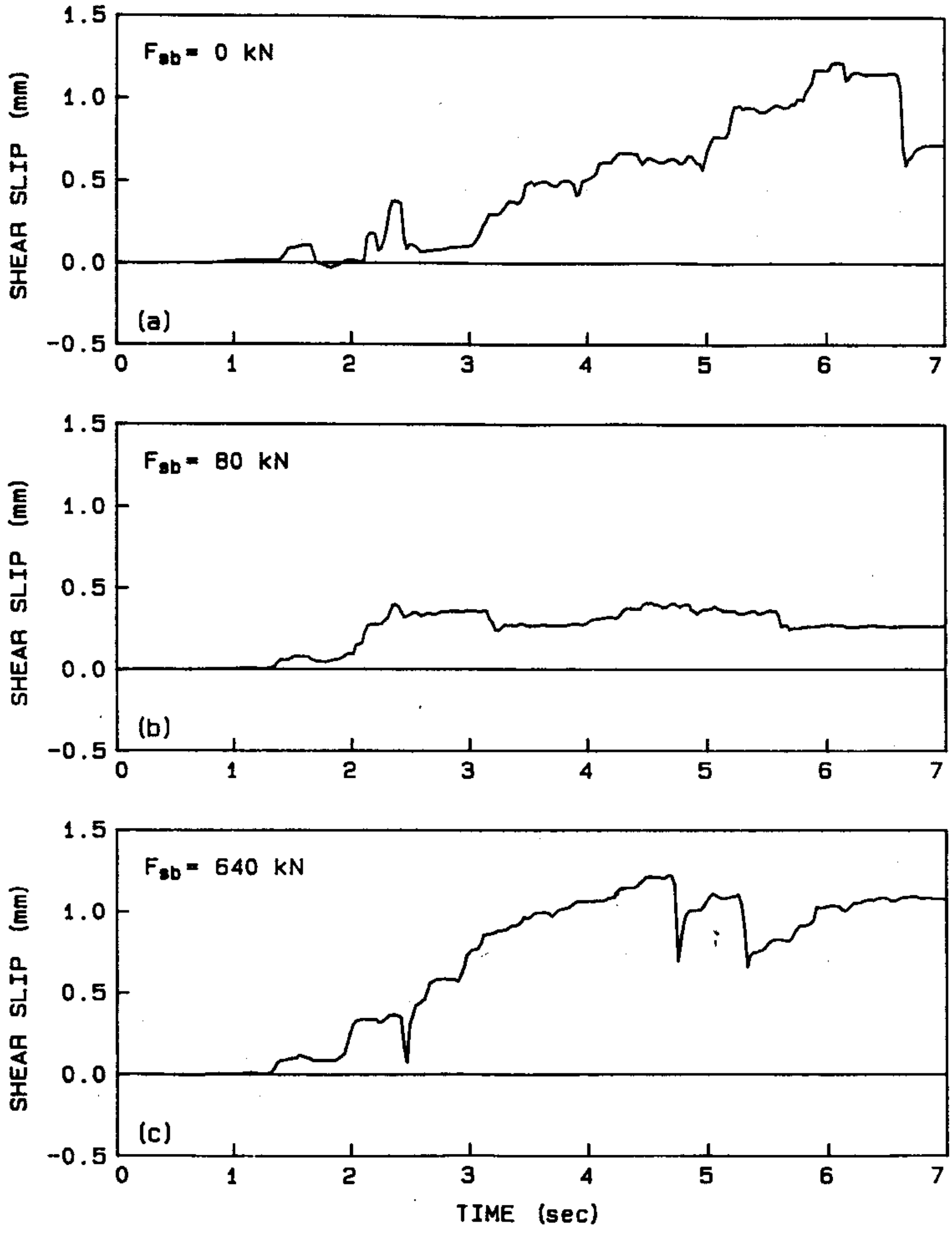


Fig. 13 Time histories of local horizontal joint shear slip at level 1 for different slip loads – El Centro excitation

Similarly, Figure 14 depicts the time histories of axial deformation at the left edge of the base horizontal joint. Compared to uncoupled and elastically coupled walls, F_{sb} = 80 kN is observed to result in dramatically reduced cyclic crushing (negative deformation) over the full duration of the excitation.

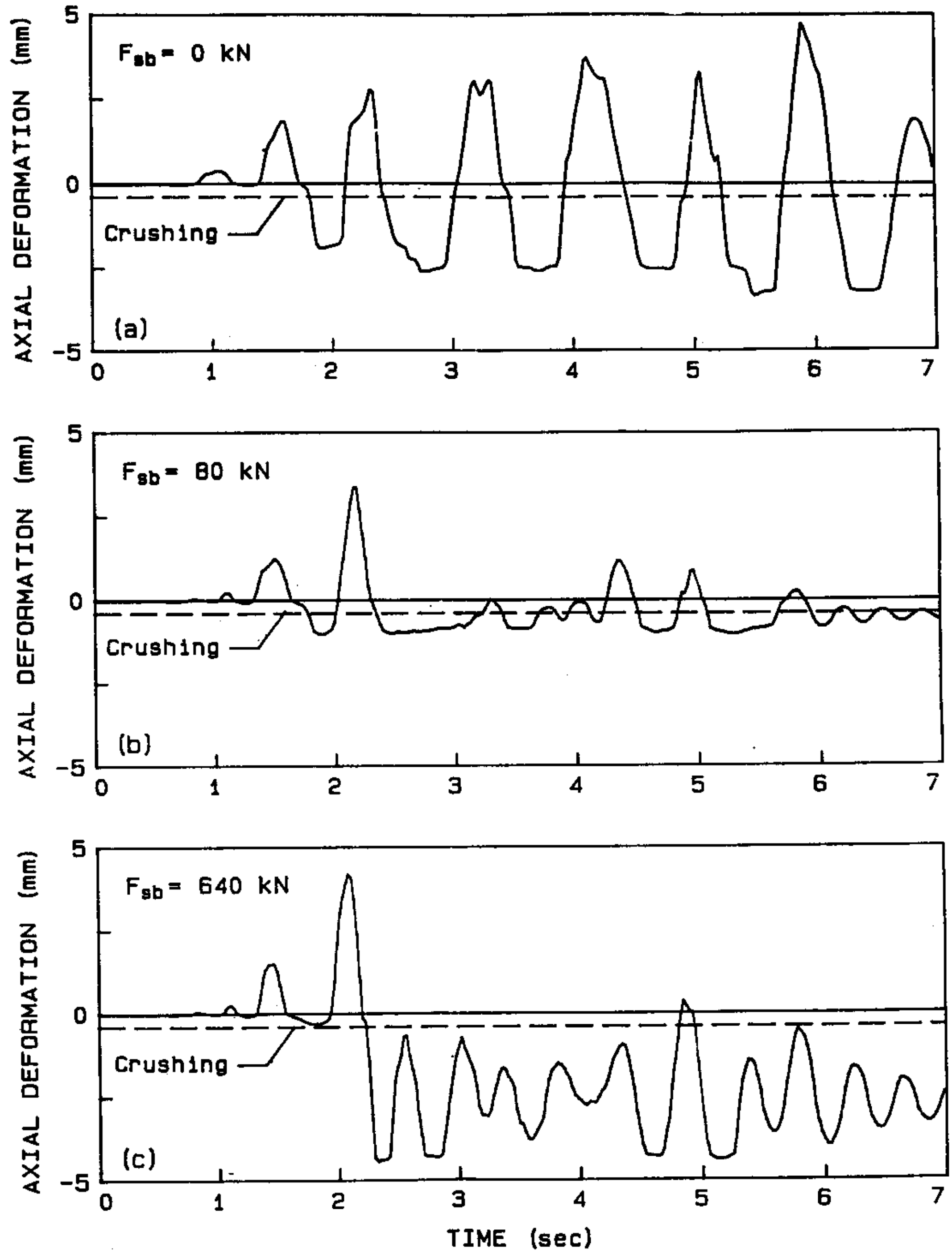


Fig. 14 Time histories of axial deformation at edge of base horizontal joint for different slip loads – El Centro excitation

FINAL DAMAGE IN HORIZONTAL JOINTS OF THE TUNED LSB STRUCTURE

The foregoing results have shown that seismic performance of the present prototype shear wall is optimized through use of tuned vertical joint LSB connectors. However, some damage due to corner crushing in the lowermost joint was noted to accompany the otherwise much improved performance.

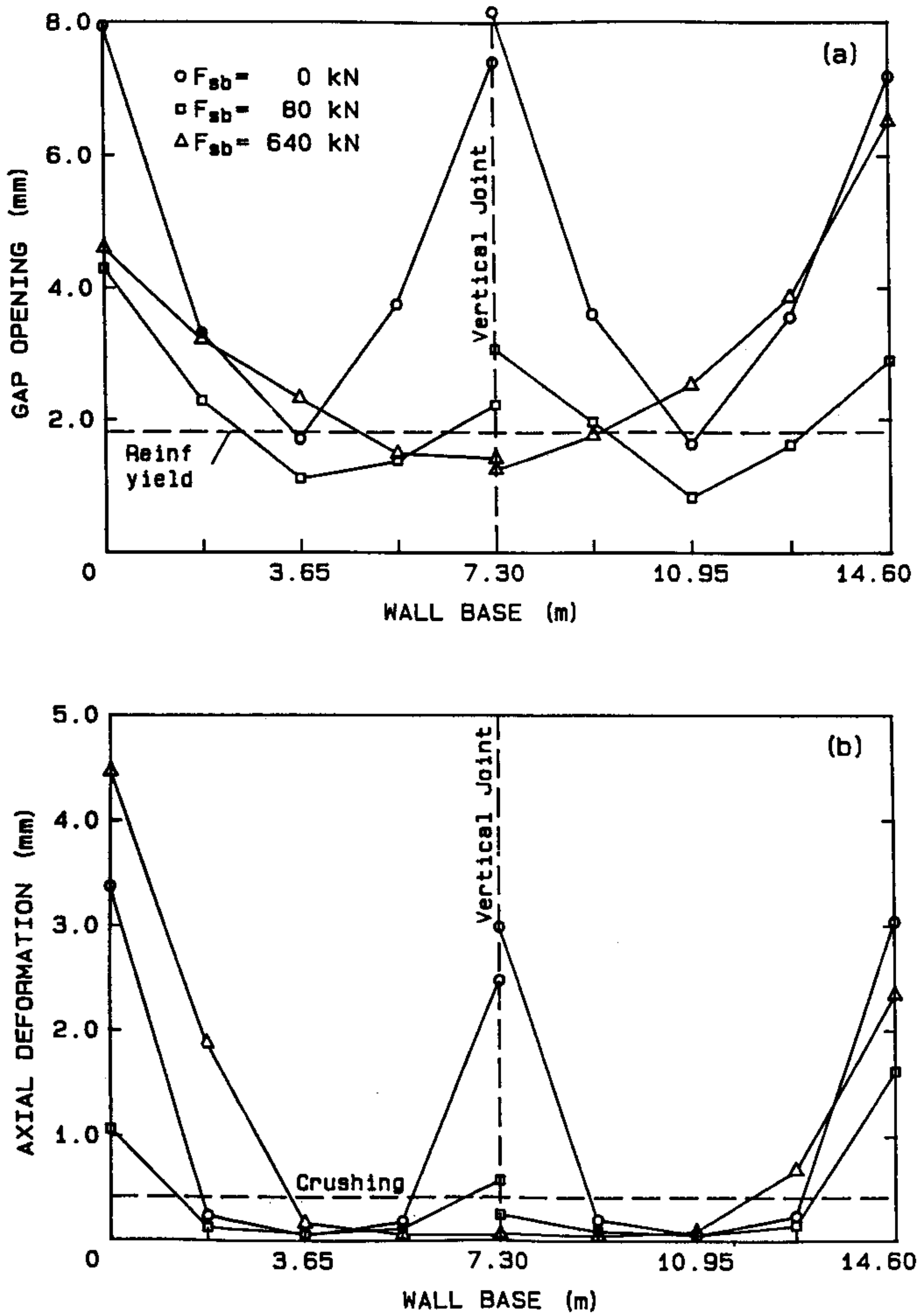


Fig. 15 Envelopes of maximum response across base horizontal joint for different earthquake excitations –optimum connector slip load

Of concern also is the possibility of vertical reinforcement yielding as a result of gap opening. Gap opening in the horizontal joints has thus far been discussed mainly as related to its influence on the anticipated compressive deformation. However, with the provision of vertical reinforcement across the joints, the magnitude of the uplift becomes important in itself. Stretching of the steel reinforcing bars beyond their yield point occurs when the magnitude of joint opening becomes large. Yield stress $f_y = 450$ MPa for the reinforcing steel allows a maximum elastic strain of 0.0023. Assuming a total unbonded length of 800 mm, based on the 200 mm depth of joints and approximately 12 bar diameters unbonded within adjoining panels (Cheema and Klingner 1985), allows a maximum deformation of 1.8 mm prior to yield. Since reinforcement is assumed to remain elastic in this study, further reference to the problem of yielding relates to minimization of gap opening in order to restrict the deformation in steel within elastic range.

Figure 15 shows response envelopes across the base horizontal joint for the four earthquake excitations described earlier and F_{sb} = 80 kN. Despite scaling each earthquake acceleration record to match the intensity of the El Centro excitation, base response still varies substantially between the four records. Figure 15 (a) shows, that with the exception of the El Centro excitation, gap opening is under 1.8 mm across the entire base for all earthquakes, while Figure 15(b) reveals that the associated compressive deformation is at or below the crushing level of 0.42 mm.

Thus, except for the El Centro record, damage at the base using the optimum slip load has virtually been eliminated by the "tuned" LSB connectors, both in terms of reinforcement yielding and horizontal joint crushing. Indeed, even for the apparently severe effect of the El Centro earthquake record of ground shaking, the damage is limited to only some edge crushing at the lowermost joint corners.

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 minimizes seismic response and this optimum slip load appears independent of the ground motion. "Tuning" of buildings for optimal behaviour by adjusting the vertical connector slip load thus involves consideration only of the properties of the building itself. This behaviour is in general agreement with predictions from Pall et al. (1980) obtained using idealized continuous wall cantilevers coupled through LSB connectors. Because of the inherent lateral stiffness of precast concrete walls, the optimization in the present study was performed based on the response parameters concerning energy dissipation, panel stress, base shear and horizontal joint damage.
2. Energy dissipation in the LSB connectors is maximized over the height of the wall at the optimum slip, and almost all the connectors contribute equally toward energy dissipation.
3. Seismic behaviour of the LSB jointed prototype structure is characterized by panel rocking and vertical joint shear slip. While the latter is noted to improve considerably the expected seismic performance through efficient energy dissipation by the LSB connectors, rocking results in both gap opening and associated compressive stress concentration in the lower horizontal joints. This may result in crushing at the lowermost joint edges as well as yielding of the vertical reinforcing bars. Although these problems are not completely eliminated for all earthquakes at optimum LSB connector slip load, markedly improved performance at tuned F_{sb} is nevertheless obtained.
4. The above problem of some remaining edge damage was encountered only for the apparently severe case of the El Centro excitation. The other three earthquakes employed, scaled to match the intensity of El Centro, resulted in essentially damage-free response of the tuned LSB jointed prototype structure.
5. For the LSB optimized structure shear slip is relatively low in magnitude, which combined with its essentially monotonic variation over time, ensures low likelihood of damage in the horizontal joints due to this mode of response also.
6. Although results (not presented) for 1.5 times the El Centro record indicated identical optimum slip load for the LSB connectors, further studies are nevertheless needed to confirm performance under different intensity and frequency conditions, as well as for other values of the various parameters characterizing the precast panel structure.

In summary, the prototype structure equipped with tuned LSB vertical joint connectors has been shown to respond essentially without damage in either the vertical or the horizontal joints for ground motions other than the apparently severe El Centro excitation. Thus, while some localized edge damage is to be anticipated for particularly severe earthquakes, the relative economy of the LSB connectors together with the pronounced reductions in response makes their use attractive for enhancing the earthquake resistance of precast concrete panel structures.

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