OPTIMUM SEISMIC RESISTANCE OF LARGE PANEL STRUCTURES USING LIMITED SLIP BOLTED JOINTS

by

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SUMMARY

Precast concrete large panel construction is widely adopted for apartment type buildings. In seismic regions, traditional jointing procedures for such construction pose many serious problems, which can be overcome by the use of limited slip friction bolted joints. During severe seismic excitations, the limited slippage in the joints provides a mechanism for the dissipation of energy by means of friction. By locating these connections in the vertical joint lines only, permanent deformations and damage can be minimized.

Nonlinear time-history dynamic analysis has been used to study and to demonstrate how a building can be "tuned" for optimum seismic response. The proposed joints act in effect as both safety valves and structural dampers.

INTRODUCTION

During strong ground motions, a large amount of seismic energy is fed into the structure. If a major portion of this vibrational energy can be dissipated during building motion, the level of distress can be considerably minimized. In cast-in-place concrete or steel framed buildings, reliance is placed on the ductility of the structure to dissipate energy while undergoing inelastic deformations. In large panel construction the development of flexural ductility is extremely difficult to achieve due to the absence of continuity in vertical steel, and hence the suitability of this construction system for seismic regions is often questioned.

Joints in a panelized building are its weakest links and naturally are the first to crack during severe earthquake excitations, with little damage in the panels. Cracking and slipping along these planes of weakness provides a mechanism for energy dissipation comparable to that due to inelastic deformations of ductile structures. The panels being large basically remain in the elastic range and, therefore, the joints are the only location where energy can be dissipated. Hence, these very planes of weakness, if properly harnessed, can be advantageously used to control the seismic response. The challenge therefore lies not only in providing joints of sufficient strength but in maximizing their capacity for energy dissipation.

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It has been concluded earlier (1, 2) that the vertical joints are by far the most suitable location of a mechanism for energy dissipation. Unlike horizontal joints, the vertical joints, after necessary slippage to dissipate energy, return to their original alignment under the elastic action of cantilevers with little or no permanent set. Even in extreme loading cases, the failure of the connections is not likely to threaten the overall stability of the structure as these are not the gravity load carrying joints.

The vertical joints that may be utilized are the continuous joints between the end walls, the connections between corridor lintels and the right angle joints between wall panels in I , T , L , [, and box sections around stair shafts or elevators.

PROPOSED JOINT

A joint possessing "elasto-plastic" behaviour and a stable hysteretic character over a number of cycles of reversals, as expected during a severe earthquake, is the ideal as a means of energy dissipation. It should also be able to accommodate relatively large deformations to dissipate sufficient energy without permanent damage. None of the jointing sytems presently being used meet all of these requirements.

A slipping friction joint can be engineered to simulate "elasto-plastic" behaviour and with the proper choice of sliding surface, a stable hysteretic character can be asssured. The connection chosen consists of steel plates or sections, with slotted holes, connected by high strength steel bolts to steel inserts anchored in the concrete panels. The length of the slot accommodates normal fabrication and erection tolerances with an additional clearance on either side of the bolt to allow the desired slip for necessary energy dissipation. A typical wall-to-wall vertical joint is shown in Fig. 1. The limited slip bolted (LSB) joints are designed not to slip under loads in service, but are expected to slip during severe seismic excitations and so they will not be grouted but sealed by other appropriate means. Attention will however need to be paid to the details of floor joints and other finishes along the slip planes to accommodate the differential movement of the walls.

Static and dynamic cyclic tests have been conducted on several connections using different faying surface treatments to determine their performance (3, 4). A predictable and repeatable load is the most important requirement to ensure predictable response of the structure. The best behaviour is provided by heavy duty brake lining pads inserted between sliding steel plates. This joint exhibits a constant, repeatable slip load and simulates near "elasto-plastic" behaviour with negligible degradation. The hysteresis loop of the joint, using 12.5 mm diameter high strength bolts (ASTM A325), is shown in Fig. 2.

OPTIMIZATION OF SEISMIC RESPONSE

The seismic response of a panelized structure is determined by the amount of seismic energy fed-in and energy dissipated. The optimization of seismic response, therefore, consists of minimizing the difference between the input energy and energy dissipated.

The energy input is basically dependent upon the natural period of the structure and the dynamic characteristics of the earthquake motion. The period of the composite wall is influenced by the stiffness and the slip load of the joints. The introduction of LSB joints will result in a period, intermediate between that of a monolithic wall and that of two separate walls, which will vary with the slip load and with the amplitude of the oscillation (Fig. 3).

The energy dissipated in the joint is proportional to the product of slip load and the slip travel during each excursion. For a high slip load and for a low slip load the energy dissipated will be negligible. Between these extremes there is a value to give maximum energy dissipation. The effect of the slip load on the hysteretic behaviour of a single story wall is conceptually shown in Fig. 4.

Softening of the structure, due to slipping of the joints, can mean an invitation to either higher or lower seismic forces depending upon its relation to the frequency content of the ground motion. The beneficial effects of energy dissipation must thus be combined with the positive or negative effects of the prolonged period of vibration on the energy input. By the proper selection of the joint slip load it is, therefore, possible to "tune" the response of the structure to an optimum value.

EXAMPLE ANALYSIS

To demonstrate the influence of LSB joints on the seismic response, a simple end wall of a cross wall type panelized apartment building was chosen for analysis. The wall width of 14.3 m was made up of two panels (7.3 m x 2.65 m x 0.2 m) coupled with a single vertical joint. The mass per story was 64 tonnes. Analyses were carried out for different wall heights and parametric studies included the effect of joint stiffness, joint slip load, slot length and seismic intensity.

Nonlinear time-history dynamic analysis was carried out using the computer program "Drain-2D", developed at the University of California, which was modified to incorporate the behaviour of LSB joints. The earthquake record of El Centro 1940 (N.S Component), was used in these studies. The analysis was conducted for a duration of seven seconds which includes the most severe motion, followed by zero acceleration for two seconds. It is known that different earthquake records, even though of the same intensity, give widely varying structural responses, and response obtained using a single record may not be conclusive.

Structural Model

The coupled walls were idealized as an equivalent wide column frame. The influence of the finite width of the wall was incorporated by rigid arms which connect the ends of LSB joints to the centroidal axis of the walls. Effects of flexure, axial and shear deformations were taken into account. Each stack of wall panels was considered as a continuous elastic cantilever. The influence of horizontal joints, was neglected, and the nonlinear behaviour of the wall was limited to the vertical joints only.

These joints were modeled as axial elements yielding both in tension and compression to conform to the idealized behaviour of the LSB joint shown in Fig. 5.

Viscous damping corresponding to 5% of critical was assumed for the elastic walls. Energy dissipation due to hysteretic damping of LSB joints was looked after in the computer program. Rigid foundations were assumed.

RESULTS OF ANALYSIS

a) *Effect of Joint Stiffness:* The variation in the initial stiffness of the joint assembly, within the practical range for such joints, does not cause appreciable change in the response.

b) *Effect of Slot Length:* No advantage was gained by restricting the slot length of the joint. On the contrary, permanent damage can result in panels due to the sudden increase in forces caused by the closing of the joint and shear failure of the bolt. It is, therefore, advisable to keep some margin of clearance when deciding the slot lengths.

c) *Effect of Joint Slip Load:* For a given earthquake intensity and wall height, the slip load of the joint was the variable which most influenced the seismic response. The influence of the slip load on the maximum bending stress at the base is shown in Fig. 6. The slip load which gave the minimum bending stress also gives minimum overturning moment, deflection, story shears and accelerations. The optimum slip load value varied directly with the seismic intensity. Using an artificial earthquake, generated to match Newmark-Blume-Kapur response spectrum, it was observed that although the response differed widely from that of El Centro record, the value of the optimum slip load was the same for a given seismic intensity but was independent of the time-history of an earthquake motion.

d) *Effect of Building Period:* For El Centro record, the response of short period structures, say less than 0.5 seconds (5 and 10 story walls), was distinctly different from those of longer period structures (15 and 20 story walls). In short period structures the benefit of energy dissipation was countered by the negative effect of the increased seismic forces caused by moving the natural frequency towards the dominant frequency of the earthquake, while for longer period structures the benefit of energy dissipation was added to that of reduced seismic forces due to the softening of the structure. The limiting building period, however, depends upon the dominant frequency content of the earthquake motion.

e) *Forces in Joints:* The distribution of forces in the LSB joints and strong nonslipping elastic joints (conventional joints), for 10 and 20 story walls, are shown in Fig. 10. The force in nonslipping joints varied over the building height and increased with an increasing severity of earthquake. In the case of LSB joints, as the connections slipped redistribution of forces took place until they became almost uniform throughout the height. One of the advantages of slipping joints was, therefore, to provide a predetermined limit to the load independent of seismic intensity. It also allowed the full capacity of all the connections to be utilized. Since the force level in LSB joints was far less than that in non-slipping joints, no damage would have been caused to the anchorages or the panels.

f) *Response:* The optimum response of LSB jointed walls, as compared to those of isolated walls (zero slip load) and walls with strong non-slipping joints, are shown in Table-I and Figs. 7 to 9. It is seen that for 5 and 10 story walls the response of LSB jointed walls was considerably improved over that of the isolated walls. The maximum base shear, bending stress, deflection and overturning moment of LSB jointed walls were about 65%, 35%, 20% and 60% respectively of isolated walls, while it was nearly the same as that for wall with nonslipping joints. In case of 15 and 20 story walls, the response of LSB jointed wall was improved over both isolated walls and walls with non slipping joints. The maximum base shear, bending stress, deflection and overturning moment of LSB jointed wall were about 65%, 70%, 60% and 80% respectively of isolated walls and, 35%, 35%, 65% and 25% respectively of walls with nonslipping joints.

g) *Time-Histories:* Typical time-histories for deflection at the top of 10 and 20 story walls, for a seismic intensity of 0.33 g, are shown in Fig. 11. For the 10 story wall, the peak amplitude of the LSB jointed wall was far less than that for isolated walls but was almost the same as that of the walls with nonslipping joints. However, since the effective period of vibration of the LSB jointed walls was longer than the walls with nonslipping joints, the accelerations experienced by this wall were less. The effectiveness of the hysteretic damping of the LSB jointed wall was more clearly seen in the case of 20 story wall. The amplitude of vibration and accelerations were considerably less than for both isolated walls and walls with nonslipping joints. It was observed that the effective period of vibration of LSB jointed walls changed with the amplitude of vibration i.e. with the increasing severity of earthquake, resonance of the structure is thus more difficult to establish.

h) *Equivalent System Ductility:* For LSB jointed walls the equivalent system ductility may here be defined as the ratio of maximum deflection at the top when the limiting stress is reached at the base of the wall to the deflection at the top when approximately half of the joints have slipped i.e. the onset of significant nonlinearity. For the optimum slip load in the simple coupled walls, the value is about 4 (4). This compares with 2 - 3 for a well detailed cast-in-place shear walls, but in the present case it is achieved with no structural damage or permanent set.

i) *Damping:* The hysteretic damping in terms of equivalent viscous damping of the equivalent linear elastic model is nearly 20% of critical (4). This is very high compared to 3 - 5% available in conventional buildings.

CONCLUSIONS

The results of the present studies have shown that the use of the limited slip bolted connections in the vertical lines of joints can significantly improve the overall seismic response of large panel structures.

Briefly the concept is of particular importance as: a) the process of energy dissipation acts over the full height rather than being localized; b) the joint strength can be uniform; c) the building is softened without losing its elasticity and recovers with little or no permanent set; d) the joints act as structural dampers to control the amplitude and as safety valves to limit the load exerted; e) the effective period of vibration changes with the severity of earthquake motion thus the resonance of the structure is more difficult to establish; f) the amplitudes of vibration and accelerations are considerably reduced thus secondary damage is minimized; g) the building can be "tuned" for optimum response without resorting to other expensive devices; h) there is no yielding of materials involved in the process of energy dissipation, hence no damage is caused and the structure is ready to face future earthquakes with the same efficiency.

The concept of energy dissipation through friction in slipping joints can be easily extended to framed buildings clad with precast concrete curtain walls. In this case slipping may be allowed in horizontal joints as these are not the gravity load carrying joints. LSB joints can also be conveniently and inexpensively incorporated in tall cast-in-place shear walls to increase the flexibility of the otherwise rigid walls and to dissipate energy, resulting in overall improved seismic response (5). Since large amounts of seismic energy can be dissipated in friction alone, ductility demand, which is associated with structural and secondary damage, can be considerably reduced.

ACKNOWLEDGEMENTS

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REFERENCES

1. Pall, A.S., Marsh, C., "Seismic Response of Large Panel Structures Using Limited Slip Bolted Joints", Proc. of the Third Canadian Conference on Earthquake Engineering, Montreal, 1979, pp. 899-916.

2. Mueller, P., Becker, J.M., "Seismic Characteristics of Composite Precast Walls", Proc. of the Third Canadian Conference on Earthquake Engineering, Montreal, 1979, pp. 1169-1199.

3. Pall, A.S., Marsh, C., Fazio, P., "Limited Slip Bolted Joints for Large Panel Concrete Structures", Proc. International Symposium, Behaviour of Building Systems and Building Components, Vanderbilt University, Nashville, Tenn., USA, 1979, pp. 385-404.

4. Pall, A.S., "Limited Slip Bolted Joints - A Device to Control the Seismic Response of Large Panel Structures", Ph.D. Thesis, Centre for Building Studies, Concordia University, Montreal, September, 1979.

5. Pall, A.S., Marsh, C., Fazio, P., "Friction Damped Concrete Shear Walls", *paper submitted to the Journal of American Concrete Institute.*

TABLE I. RELATIVE SEISMIC RESPONSE OF LSB JOINTED WALLS, (0.33g)

Type of Response	Response of LSB Jointed Walls, Percentage of							
	Two isolated walls				Walls with nonslipping joints			
	5 story	10 story	15 story	20 story	5 story	10 story	15 story	20 story
Shear	70	65	65	65	100	100	35	35
Bending	40	35	50	70	100	100	40	35
Deflection	30	20	45	60	100	105	75	65
Overturning	95	60	60	80	100	80	25	25

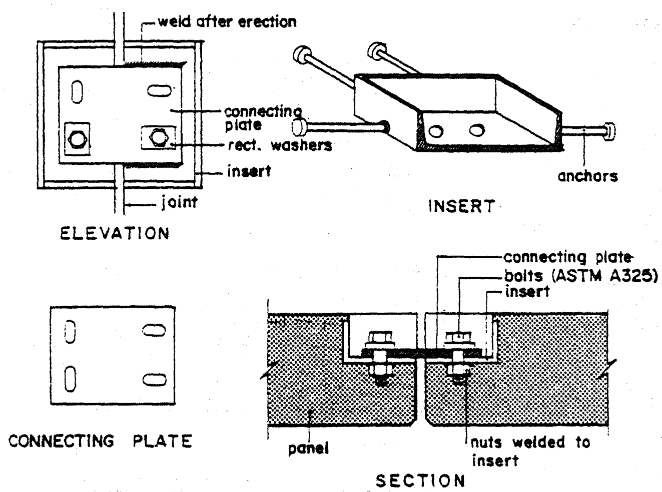

FIG. 1. LIMITED SLIP BOLTED (LSB) JOINT, TYPICAL

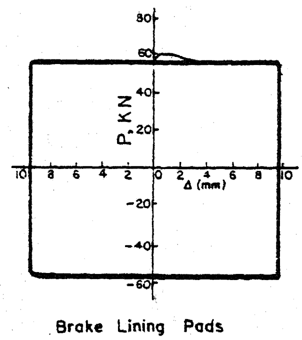

FIG. 2. HYSTERESIS LOOP USING BRAKE LINING PADS

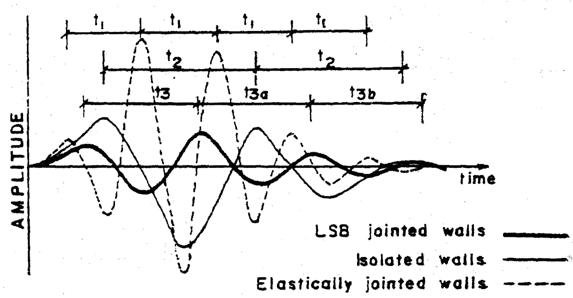

FIG. 3. OSCILLATION OF WALLS

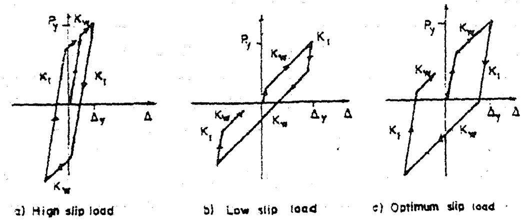

FIG. 4. EFFECT OF SLIP LOAD ON HYSTERETIC BEHAVIOUR OF COUPLED WALLS

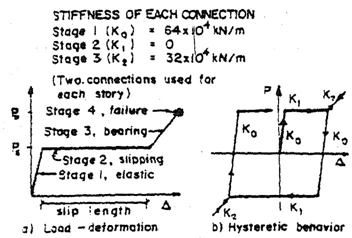

FIG. 5. IDEALIZED BEHAVIOUR OF LSB JOINT

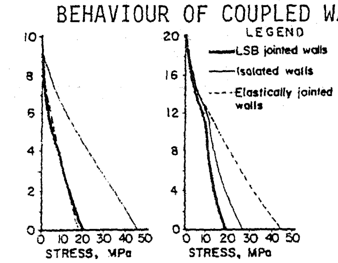

FIG. 7. BENDING STRESS, 0.33g

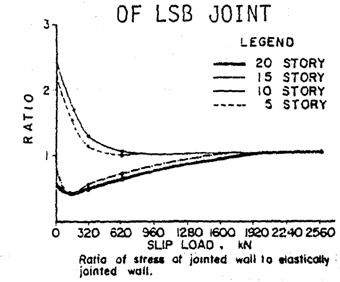

FIG. 6. EFFECT OF SLIP LOAD ON BENDING STRESS IN WALLS

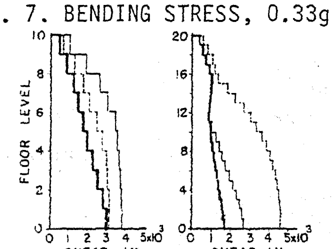

FIG. 8. SHEAR ENVELOPE, 0.33g

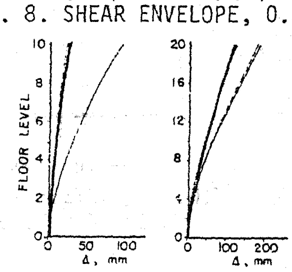

FIG. 9. DEFLECTION ENVELOPE, 0.33g

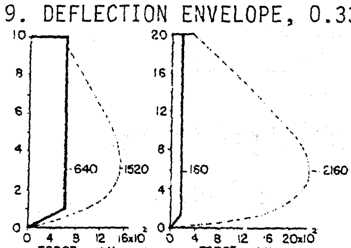

FIG. 10. FORCES ON JOINT, 0.33g

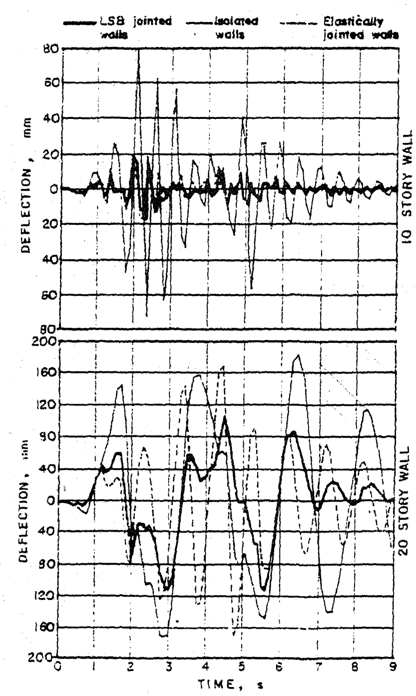

FIG. 11. TIME-HISTORIES FOR WALL DEFLECTION AT TOP, 0.33g