Seismic response of large panel coupled wall systems

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ABSTRACT: Behaviour of large panel coupled wall systems subjected to earthquake motion is reviewed. An analytical model that accounts for inelastic action in both horizontal joints and coupling elements is described. Selected results of a parametric study are presented to illustrate significant differences between simple and coupled walls.

1 INTRODUCTION

Large-panel precast wall construction has been used extensively in Europe over the past 50 years. Large panel systems have been used in recent years in seismic regions of the USSR, Bulgaria, Romania, Japan and elsewhere. As reported by Fintel (1977) precast panel buildings showed good performance during the 1977 Romanian earthquake.

The use of large panel construction in seismic zones of North American has been limited due to concerns regarding lack of knowledge of the reliability of these systems during high intensity ground shaking. To provide necessary data, several research groups in the United States and Canada have recently reported results of analytical and experimental investigations into the seismic behaviour of large-panel systems.

In the present study an analytical model was developed to study the behaviour of large-panel wall systems with coupling beams subjected to earthquake loading. The analytical model includes the effects of inelastic action in the horizontal joints as well as in the coupling beams. The precast panels themselves are assumed to remain linear elastic.

Some difficulties associated with the use of coupling beams in large panel systems are discussed.

2 CONFIGURATION OF LARGE PANEL SYSTEMS

Large panel systems consist of precast wall panels stacked one above the other. The wall panels constitute the primary gravity load bearing system and also provide resistance to lateral loads. The floor systems are usually of precast concrete plank construction. Several methods have been used to make the horizontal connections between wall panels and floor planks at each story level. Cast-in-place grout is placed in the joint between the wall and plank elements and vertical continuity is provided by either mild reinforcement across the joint or by vertical post-tensioning between the roof and foundation levels.

3 COUPLING BETWEEN WALL SYSTEMS

Vertical continuity between large panel walls can be provided by "wet" or "dry" joints. In wet joints reinforcement hoops projecting from adjacent panels are embedded in grout with a continuous reinforcing bar passing through the hoops for the full length of the joint. Alternatively, bolted joints can be used to connect the panels. Behaviour of vertical joints has been reported by Pall et al. (1979), Pollner et al. (1975), Cholewicki (1971), Mueller and Becker (1980) and Pekau (1981).

Vertical coupling between walls can also be provided by coupling beams. Behaviour of cast-in-place walls subjected to ground shaking has been shown to be significantly improved by coupling beams (eg. Saatcioglu (1981)). By providing an energy dissipating mechanism in a non-load-bearing portion of the structure, inelastic action in the load-bearing walls can be minimized thus reducing the risk of collapse due to failure of the walls themselves.

There are two basic types of coupling beams. In slender beams, the primary method of energy dissipation is by formation of flexural hinges. Tests carried out by Barney et al. (1978) at the Portland Cement Association have shown that under cycling loading, slender coupling beams can be designed to have adequate ductility depending on amounts of longitudinal and transverse reinforcement provided, and strength of concrete and steel. For proper ductility, bond and shear failures must be avoided.

For deep beams (low span to depth ratio) with conventional flexural reinforcement, failure may occur due to diagonal cracking so that ductility is severely limited. A more effective method of reinforcement placement is in the form of diagonal struts. Tests by Pauley (1971) produced load deflection plots under cyclic loading that demonstrate good ductility and energy dissipation characteristics.

4 BEHAVIOUR OF LARGE PANEL WALL SYSTEMS

Under high intensity ground shaking, portions of large panel wall systems can be expected to enter the inelastic range of behaviour. In simple wall systems the horizontal connections are relatively weak compared to the wall panels, so that the inelastic action can be expected to be concentrated at these horizontal joints, particularly at or near the base of the wall.

Previous analytical studies by Llorente et al. (1981) and by Schricker and Powell (1980) have shown that energy is absorbed by two principle mechanisms, namely rocking and slip. Rocking occurs because the joints themselves have essentially zero tensile strength. Vertical continuity reinforcement across the joints helps to constrain the rocking motion. Slipping can also take place along the horizontal connection surface. Rocking causes high concentration of compressive stress at the outer edge of the connection, while the slipping motion may lead to structural instability and large permanent deformations. The wall panels themselves are generally considered to remain linear elastic. Limited experimental work carried out for example by Oliva and Shahrooz (1984) and by Harris and Caccese (1984) have confirmed the types of deformations predicted by the analytical models.

When coupling beams are introduced a third method of energy dissipation is available. Energy dissipation may occur as a result of formation of plastic hinges in slender coupling beams or by yielding of diagonal struts in deep beams.

5 ANALYTICAL MODELLING OF COUPLED SYSTEMS

Previous analytical studies of coupled large panel wall systems, such as the study of walls coupled by limited slip bolted connections by Pall et al. (1980) and the study of walls with coupling beams by Fintel and Ghosh (1981), have considered the walls to act monolithically. In other words no inelastic action was permitted in the horizontal joints. It is however difficult to ensure that only linear elastic behaviour occurs in the horizontal joints under intense ground shaking. For an economical design it may be necessary to allow some inelastic action in the horizontal joints. The modelling techniques used in this study permit an evaluation of the distribution of energy dissipation between the horizontal joints and the coupling beams. For the coupling beams to be effective, a certain amount of shear must be transferred across the horizontal joints near the base of the structure after the coupling beams enter the inelastic range of behaviour. Premature sliding along horizontal connections may prevent the coupling beams from functioning as locations for energy dissipation.

For the present study the analytical modelling techniques developed by Llorente et al. for simple walls were extended to coupled wall systems. Wall panel elements and horizontal connection elements were incorporated into a general purpose computer programme, DRAIN-2D, developed by Kanaan and Powell (1975) for seismic analysis of planar systems. Slender coupling beams were modelled using the DRAIN-2D reinforced concrete beam element, while deep beams were modelled using the DRAIN-2D inelastic strut element to represent the diagonal struts of the deep beam. Full details of the modelling techniques used are given in a report by Kianoush and Scanlon (1986). The main aspects of modelling are summarized as follows:

1. Wall Panels:
   - Linear elastic isoparametric plane stress elements

2. Horizontal Connection Material
   (a) Axial behaviour:
   - Multi-linear stress-strain relationship with softening in compression
   - Zero-tension

   (b) Shear behaviour:
   - Shear-friction model with mild reinforcement for vertical continuity
   - Shear-slip model with post-tensioning for vertical continuity.

3. Vertical Continuity Steel
   (a) Mild reinforcement:
   - Elasto-plastic in tension and compression

   (b) Post-tensioning:
   - Linear-elastic

4. Coupling Beams
   (a) Slender Beams:
   - Hinge inelastic moment-rotation model

   (b) Deep Beams:
   - Truss model with yielding in tension and compression.

A typical discretization of a multi-storey coupled wall system is shown in Fig. 1. A single beam line element is used to represent slender coupling beams while truss elements are used to represent diagonal reinforcing bars in deep coupling beams. To minimize computational effort, substructuring can be used to eliminate internal degrees of freedom in the linear elastic panel elements, as was done by Llorente et al. (1981) in their study of simple wall systems. However this particular refinement has not yet been incorporated in the version of DRAIN-2D used in this investigation.

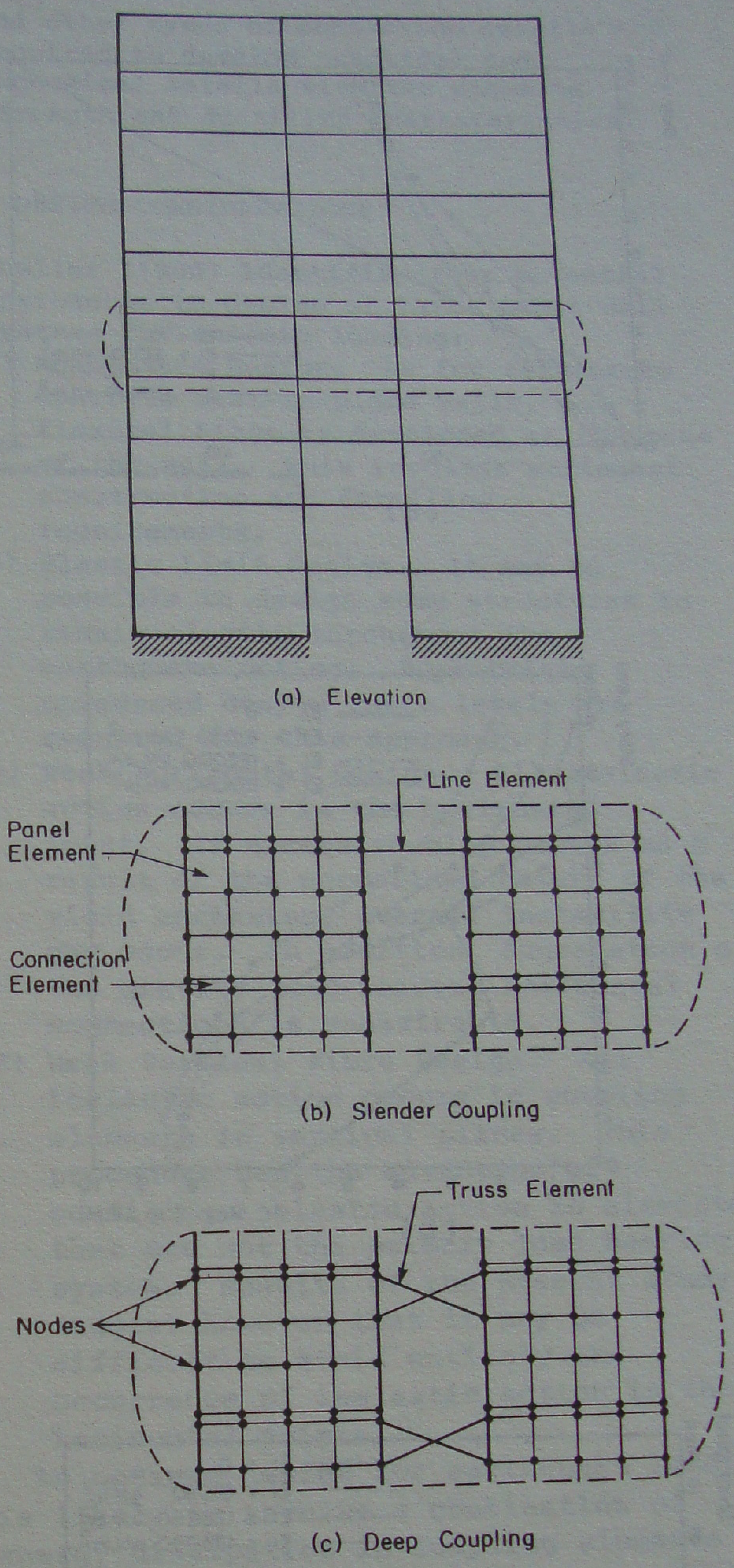

Figure 1. Discretization of Ten Story Coupled Wall System

6 APPLICATION OF THE ANALYTICAL MODEL

Using the analytical model described above, a parametric study was undertaken to determine the effects of several significant parameters on response of coupled walls to seismic loading. Applying a high intensity ground acceleration time history to a 10 story coupled wall system, effects of variations in strength and stiffness of coupling beams, and method of providing vertical continuity (either mild reinforcement, or post-tensioning) were investigated. Typical results are shown in Fig. 2 for effects of variation in initial beam stiffness (EI) with post-tensioning used for vertical continuity. The case, EI = 0, represents a simple wall with no coupling beams.

The significant difference in behaviour between simple and coupled wall systems is evident. Maximum horizontal displacements and width of gap opening are significantly greater for the simple wall. However the maximum slip at each story level is

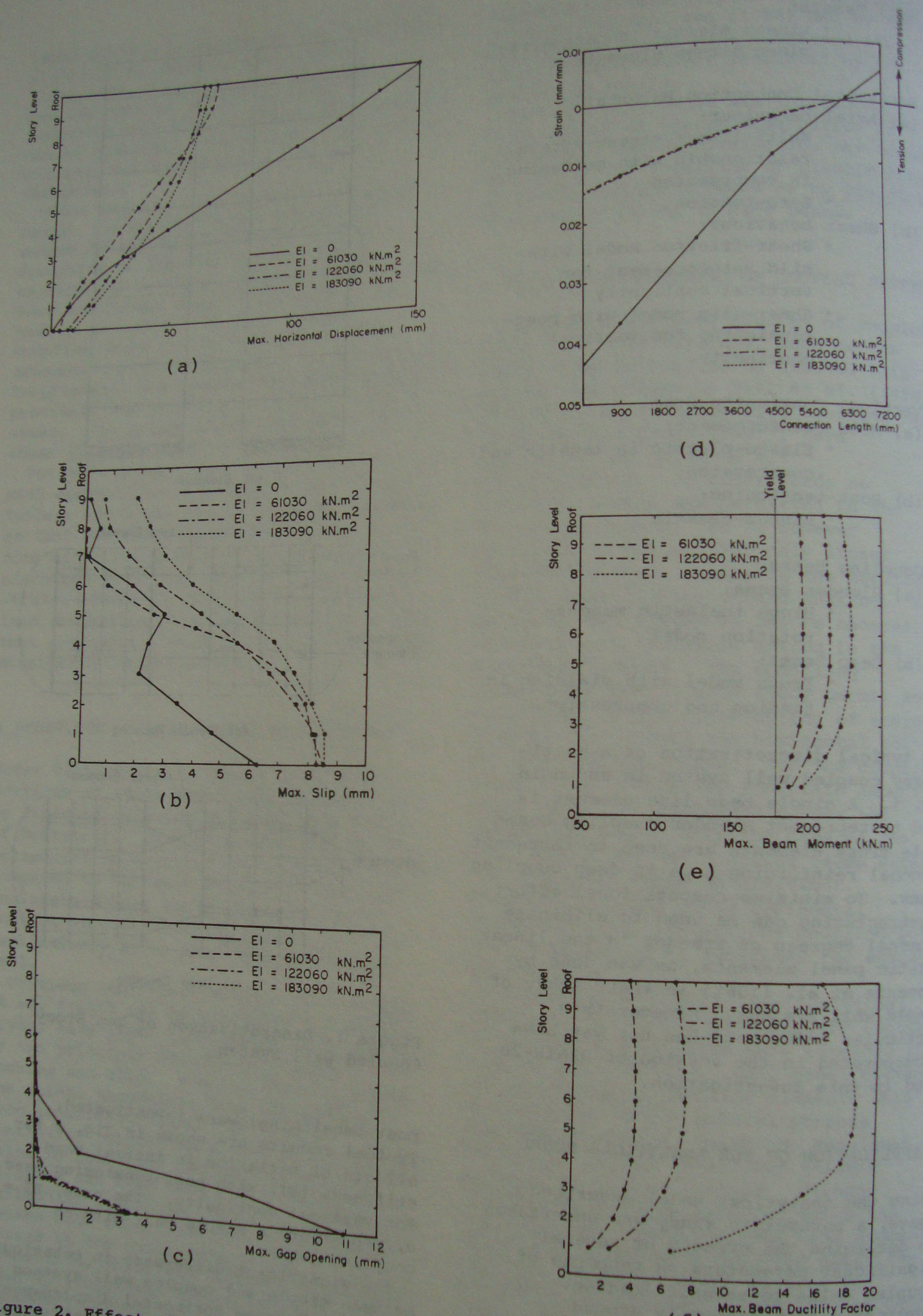

Figure 2. Effect of Beam Stiffness on a) Maximum Horizontal Displacement b) Maximum Slip c) Maximum Gap Opening d) Maximum Strain in Connection e) Maximum Beam Moment and f) Maximum Beam Ductility Factor

generally greater for the coupled wall system.

The effect of the coupling beams is clearly to reduce rocking motion in the individual walls. However there is a corresponding tendency for increased slip to occur in the horizontal joints. Slipping at horizontal joints can be reduced by providing mild steel reinforcement across the joint. The shear friction forces developed reduce the tendency for slip to occur. However rocking motion tends to increase with a resulting increase in ductility demand in the coupling beams. The effect of initial beam stiffness on behaviour is to produce an increase in beam ductility demand with increasing stiffness.

Based on these and other results of the parametric study it was concluded that the presence of coupling beams has a significant effect on seismic response of large-panel precast wall systems. It was also found that the method of providing vertical continuity has a significant effect on response. Further details of the parametric study are given in the report by Kianoush and Scanlon (1986).

7 CONSTRUCTION DETAILS

While the results of this study confirm that coupling beams can be used to improve seismic response of large panel systems, a number of practical problems need to be addressed. Coupling beams can be cast monolithically with the panels in the precast plant to provide essentially the same system as used in cast-in-place construction. However the size and arrangement of the combined precast unit may require the use of special frames to support the unit to prevent damage during transportation and erection.

Mueller (1981) suggests that each half of a coupling beam could be cast integrally with a wall panel with a point of inflection at the joint designed for shear transfer, or that steel shapes used as floor plank supports could be developed into coupling beams.

The panels and beams could be fabricated separately and connected together in the field. Laboratory tests are required to assess the strength and ductility of such connections under cyclic loading. Bhatt and Kirk (1985) tested welded beam-column connections for precast concrete elements under cyclic loading and showed that adequate strength and ductility can be obtained although tolerance requirements are quite severe. Further tests of welded and other types of connection details are required to develop practical and economical details with the required strength and ductility characteristics.

8 DESIGN CONSIDERATIONS

Mueller (1980) identifies four potential approaches to design of large panel wall systems for seismic loading:

a) Monolithic Design. As for reinforced concrete cast-in-place walls, a flexural hinge is developed at the base of the wall. This involves stringent construction and detailing requirements.
b) Elastic Limit Design. It may be possible to design some structures to remain elastic throughout the earthquake motion. Appropriate unreduced design force levels are required for this approach.
c) Weak Horizontal Design. All inelastic action occurs in the horizontal joint. If excessive slip occurs as a result of the unconfined nature of the yield mechanism, overall instability may occur. In addition, degradation of the gravity load-bearing horizontal connections is undesirable.
d) Weak Vertical Fibre Design. All inelastic action occurs in coupling elements in vertical planes. This procedure has the advantage of confining inelastic action in elements that are not the primary load bearing system. Results of the present study suggest however that it may be difficult to avoid entirely the occurrence of inelastic action in the horizontal joints.

An optimum design for earthquake loading is likely to involve a combination of energy dissipation in coupling elements (beams or connectors) with some controlled amount of inelastic action permitted in the horizontal joints. Further studies will be required to develop a sound basis for design along these lines.

It is also conceivable that design could be based directly on dynamic inelastic analysis of the type described in this paper if appropriate earthquake and structural characteristics can be defined.

9 SUMMARY AND CONCLUSIONS

Lateral load resisting characteristics of large panel precast wall systems have been reviewed. An analytical model to simulate behaviour of inelastic horizontal connections and coupling beams was described. Selected results of a parametric study were presented to emphasize the differences in behaviour between simple and coupled wall systems.

It was concluded that coupling beams can effectively improve the seismic response of large panel precast wall systems. Further work is required to develop practical and effective coupling beam details for precast systems, and to extend the parametric study to provide the basis for guidelines on design of coupled wall systems for appropriate earthquake intensity levels.

ACKNOWLEDGEMENT

Financial support provided by the Natural Sciences and Engineering Research Council through Operating Grant A5153 is gratefully acknowledged.

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