SEISMIC BEHAVIOR OF PRECAST WALLS COUPLED THROUGH VERTICAL CONNECTIONS

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SUMMARY

This paper explores the potential of an aseismic design concept that uses the vertical connections in large panel precast concrete walls as primary energy dissipating elements. Because it appears considerably easier to provide vertical connections with sufficient ductility than the more complex, gravity load bearing horizontal connections, this alternative to provide precast walls with energy dissipation capacity deserves serious consideration. The basic relations between vertical connection characteristics and overall response are investigated. A rule of thumb for the optimum strength of the primary energy dissipating elements is presented. It is concluded that such a design concept is viable provided that the vertical connections exhibit full and stable hysteresis loops.

ASEISMIC DESIGN CONCEPTS

The extended use of large panel precast concrete structures in seismic regions raises new questions in aseismic design. These questions center around the connections of panelized buildings, because they form, inevitably and by the very nature of the construction process, regions of both diminished strength and stiffness. This is particularly true for systems typical of North American practice (Fig.1). Both platform type horizontal connections and vertical connections using embedded, welded or bolted metal connectors are often not able to develop the panel strength. This paper explores the role of vertical connections in the seismic response of composite walls (Fig.1). Figure 2 shows some typical configurations of composite walls, i.e. simple walls coupled through vertical connections to form planar or I-, U- and box-shaped walls.

In the capacity design approach of the New Zealand Code primary energy dissipating mechanisms are chosen. The primary energy dissipating elements that participate in the mechanism, are suitably designed and detailed, and all other elements are then provided with sufficient reserve strength capacity to ensure that the chosen energy dissipating mechanisms are maintained throughout the deformations that may occur [7]. In this sense a major concern of aseismic design concepts is the establishment of favorable hierarchies of yield mechanisms [7]. In general, favorable primary energy dissipating yield mechanisms can be characterized by two properties: Such yield mechananisms are confined, i.e. do not yet represent a complete lateral collapse mechanism, and they do not make use of primary gravity load bearing members as energy dissipating elements. This allows the structure to take advantage of the beneficial effects of inelastic energy dissipation, before the ultimate lateral strength is reached and the primary gravity load bearing elements become inelastic. Examples are the yield mechanisms associated with the formation of plastic hinges in the coupling beams of coupled shear walls, in the girders of frames or in the shear walls of dual systems.

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In precast composite walls the primary inelastic action will most likely occur in the connections [1]. However, the designer obviously has the choice, whether the horizontal or vertical joints should become inelastic first. Contrary to horizontal connections, vertical connections are not, in general, gravity load bearing elements, and their inelastic deformations are confined by the walls, as long as the walls have not yet reached their ultimate strength. Vertical connections appear therefore particularly suited as primary energy dissipating elements. This paper consequently explores the suitability of a "strong horizontal, weak vertical connection" design concept which deliberately takes advantage of the energy dissipation capacity that is latent in the weak longitudinal fibres [8] created by vertical joints. In particular, it is investigated which strength and stiffness of the primary energy dissipating elements (vertical joints), relative to that of the other confining elements (walls), will lead to the best energy dissipation characteristics of the structure. A more detailed presentation of the reported results, along with an appropriate reference list, may be found in Refs.[5,9].

ELASTIC AND INELASTIC COUPLING CHARACTERISTICS

As for coupled shear walls, the general behavior of precast walls coupled through vertical connections is most simply described in terms of the continuous medium or shear medium theory [2]. The elastic coupling problem for the composite walls shown in Fig. 2 is basically governed by only two dimensionless parameters: the relative coupling stiffness α defined in Fig. 3 and the cross-sectional parameter γ defined in Fig. 4. A simple and accurate closed form expression for the fundamental period of coupled structural walls in terms of α and γ has been presented by Mueller and Becker [4,5]. Figure 5 shows a plot of the square of the ratio T/T_o, i.e. the ratio of the coupled ($\alpha \neq 0$) and uncoupled ($\alpha = 0$) fundamental periods. The figure illustrates the characteristic feature of coupled walls that nearly monolithic behavior can be achieved with very low coupling stiffness. In the low α range the fundamental period is very sensitive and in the high α range practically insensitive to the coupling stiffness.

To effectively use coupling elements (vertical connections, coupling beams, etc.) as primary energy dissipating elements, they must become inelastic well before the individual walls. However, it is not immediately evident which coupling strength and stiffness relative to that of the walls would lead to the best energy dissipation characteristics of the structure. Some insight may be gained from the conceptual single-degree-of-freedom (SDOF) model presented in Fig. 6. Fig. 6b shows a normalized idealized trilinear base moment versus top deflection relationship. Line AB corresponds to the elastic response with fundamental frequency ω. Along line BC the vertical connections are yielding and the apparent instantaneous frequency is assumed to be the fundamental frequency ω_0 for uncoupled response ($\alpha = 0$). At point C a plastic hinge forms at the wall base and the ultimate lateral resistance is reached. Fig. 6c shows the hysteresis loop of the SDOF-model for a steady state forced vibration with amplitude $w_y < w < w_u$, i.e. in the elastic range of the walls. Elasto-plastic hysteretic behavior is assumed for the vertical connections. One way to assess the effect of inelastic energy dissipation is to express the hysteretic damping by an equivalent viscous damping ratio for the equivalent linear elastic model with frequency ω_e (Fig. 6c). Fig. 7 shows the resulting relationship between the equivalent viscous damping ratio, the deflection amplitude and the period ratio T/T_o. Except for a constant, the equivalent viscous damping ratio represents the ratio of the area enclosed by the hysteresis loop and the shaded area in Fig. 6c.

Note, first, that the equivalent damping ratio increases with decreasing T/T_0. Thus, for a given wall configuration and, hence, uncoupled period T_0, it would seem advantageous to minimize the coupled period T, i.e to choose the relative coupling stiffness α at least at the threshold to the insensitive range in Fig. 5. Note, second, that the equivalent damping ratio exhibits a maximum. Thus, it appears advantageous to choose coupling strength and wall strength such that the deflection amplitude w_u, at which the walls become inelastic (Fig. 6b), indicates maximum damping in Fig. 7. On the one hand this choice ensures that the maximum possible value of hysteretic damping in the coupling elements is reached before the gravity load bearing walls become inelastic. On the other hand it ensures a steady increase of the equivalent damping ratio with increasing amplitude, because the walls become engaged in inelastic energy dissipation too, when hysteretic damping in the coupling elements alone is no longer effective enough as indicated by the descending portion of the curves in Fig. 7. Based on this reasoning and assuming that line AEF in Fig. 6b represents approximately the contribution of the individual walls to the base moment, the following simple rule of thumb follows for the relative coupling strength (CE/CG in Fig. 6b).

$$(T_u \cdot c)/M_u = 1 - T/T_0 \quad , \tag{1}$$

where $(T_u \cdot c)$ denotes the ultimate axial couple, M_u the total ultimate base moment and T/T_0 the ratio of the coupled and uncoupled fundamental periods. While this conceptual model gives some indication respecting the optimum coupling strength, the relative importance of the possibly conflicting effects of hysteretic damping and of softening must of course be investigated by computer studies with actual earthquake records.

COMPUTER STUDY

Fig. 8 shows the 10-story I-shaped composite wall investigated in the parametric computer study by Thiel [9], along with the force-deformation relationship for the two metal connector models used. The cross-sectional parameter γ was 0.68. Two values of relative coupling stiffness were investigated, $\alpha = 4$ and $\alpha = 12$, corresponding to coupled fundamental periods T of 0.39 and 0.35 seconds. The uncoupled period T_0 was 0.56 seconds. The lower coupling stiffness marks the threshold to the insensitive range in Fig. 5. The structure was subjected to 15 seconds of the El Centro (N.S., 1940) and an artificial earthquake created to match the Newmark-Blum-Kapur design spectra (Fig.9). Conforming with the chosen primary energy dissipating mechanism inelastic action was confined to vertical joints and the walls and horizontal joints were assumed to remain in the elastic range. The maximum response values for the elasto-plastic connector model are plotted in Fig. 10 and 11 versus the connector yield strength per story. Note that a zero connector yield level corresponds to the elastic response of the uncoupled walls and that the horizontal portion of the curves to the right represents the elastic response of the coupled walls.

The connector yield level or coupling strength is the most important factor governing the seismic response of the composite wall. Whether softening of the structure leads to higher (El Centro) or lower (Artificial) seismic forces, there exists an optimal connector yield level (~ 100kN), for which the seismic forces are considerably reduced (Fig. 10), but the deflections (Fig. 11a) do not increase relative to the elastic response. For the optimum yield level of 100 kN, the percentages of the total base moment resisted by the axial couple are 32% (El Centro, α = 4), 28% (Artificial, α = 4), 37% (El Centro, α = 12) and 31% (Artificial, α = 12). These results compare satisfactorily with the relative coupling strength indicated by Eq. (1), namely 32% for α = 4 and 37% for α = 12. Eq. (1) is also confirmed by several other computer studies [4,6] and by experiments [3]. In these experiments the walls yielded too. Minimum top deflection was observed for specimens conforming most closely with Eq. (1). As might be expected from Fig. 5, increasing the relative coupling stiffness from α = 4 to α = 12 (corresponding to a 9-fold increase in connector stiffness) has no significant effect on maximum top deflection (Fig. 11a), base shear, base overturning moment and inelastic connector deformations (Fig. 11c), because the overall stiffness is insensitive to α in this range. The main effects of the increase of the coupling stiffness over the threshold to the insensitive range are detrimental: a drastic increase of the connector ductility demands (Fig. 11b) and of the number of yield excursions (Fig. 11d).

The results for the degrading connector model (Fig. 8) are given in Refs. [5,9]. For such strongly degrading connector characteristics, maximum web wall moment and top deflection are higher for inelastic than for linear elastic connector behavior, but still lower than for isolated uncoupled walls. On the one hand this indicates that a deliberate weak vertical connection design requires vertical connections that exhibit full and stable hysteresis loops. On the other hand it shows that even minimal residual inelastic coupling stiffness and strength can contribute to an improved seismic behavior relative to simple isolated walls or composite walls with brittle vertical connections. Thus prevention of a premature brittle connection failure, such as a pullout failure of a metal connector embeddment, is of primary importance.

CONCLUSIONS

In composite walls with strong vertical connections that are able to develop their full monolithic strength, the inelastic deformations will most likely concentrate in the horizontal connections that are crucial for both the overall stability and the integrity of the structure. Because of this concentration and because it appears difficult to provide horizontal joints with ductility, panelized buildings are often conceived as rather brittle structures. A viable alternative to provide precast structural walls with energy dissipation capacity is a "weak vertical joint, strong horizontal joint" design. The presented results show that the energy dissipation mechanism along weak vertical joints is efficient enough to compensate and even override the conflicting effects of softening. In general, the mechanism is more efficient for taller walls with longer periods and less efficient for shorter walls with shorter periods. Practical implementation of the concept requires vertical connections that exhibit full and stable hysteresis loops, and a structural system that allows for the relative vertical displacements without jeopardizing the structural integrity. The results concerning the optimum coupling strength may also give some indication concerning the optimum contribution to lateral resistance of primary energy dissipating elements in other types of structural systems. In particular they show that in inelastic aseismic design member strength should not follow the linear elastic force distribution, if certain yield mechanisms are to be enforced.

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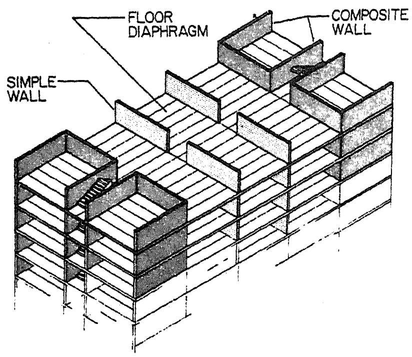

FIGURE 1 BASIC STRUCTURAL ELEMENTS OF LARGE PANEL PRECAST CONCRETE BUILDINGS

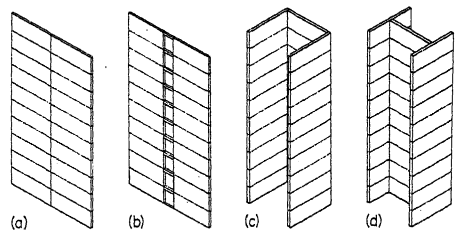

FIGURE 2 TYPICAL PRECAST COMPOSITE WALLS

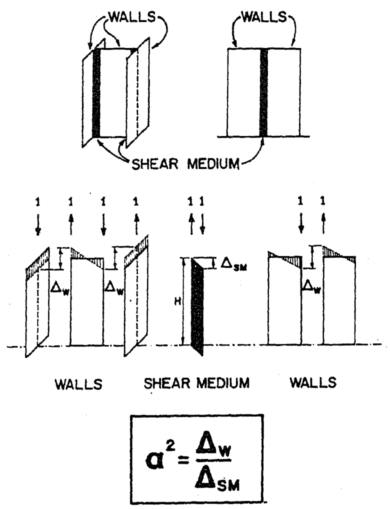

FIGURE 3 RELATIVE COUPLING STIFFNESS α

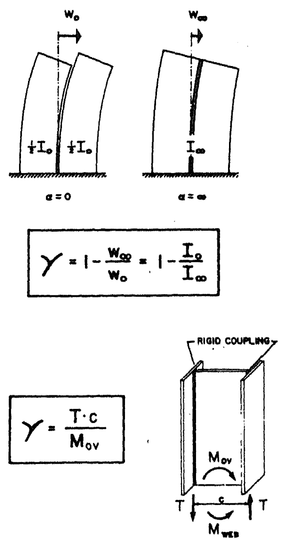

FIGURE 4 CROSS-SECTIONAL PARAMETER γ

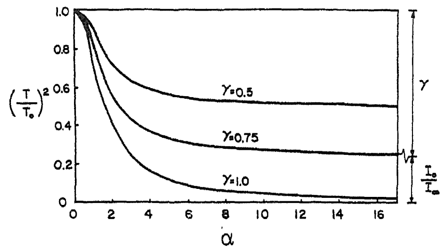

FIGURE 5 FUNDAMENTAL PERIOD OF COUPLED WALLS

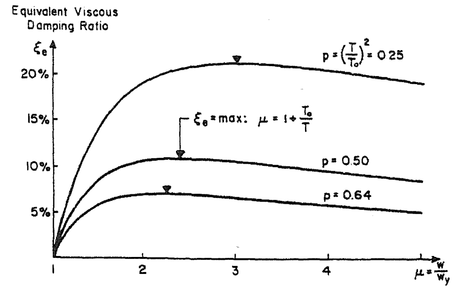

FIGURE 7 EQUIVALENT VISCOUS DAMPING RATIO

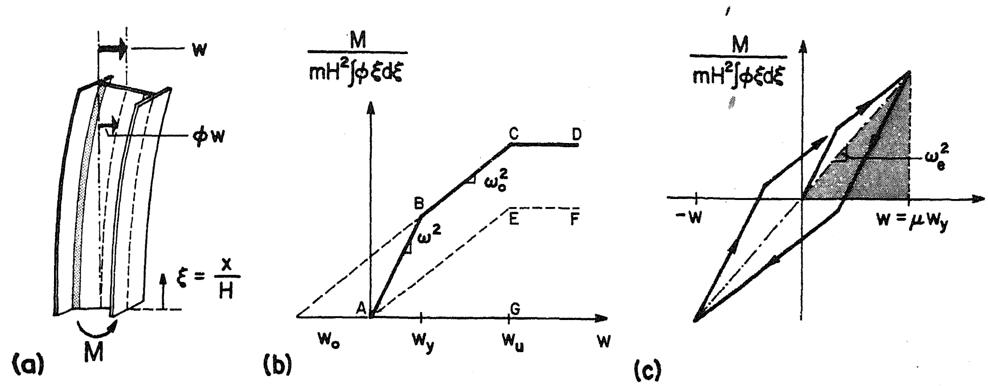

FIGURE 6 CONCEPTUAL MODEL

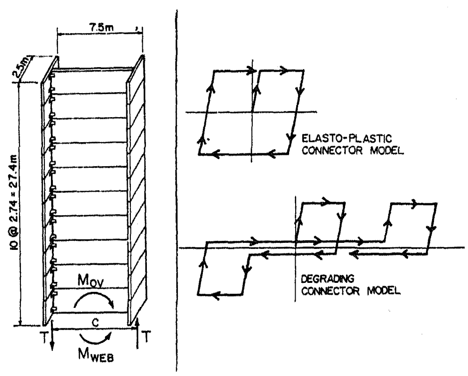

FIGURE 8 COMPOSITE WALL AND VERTICAL CONNECTOR MODELS

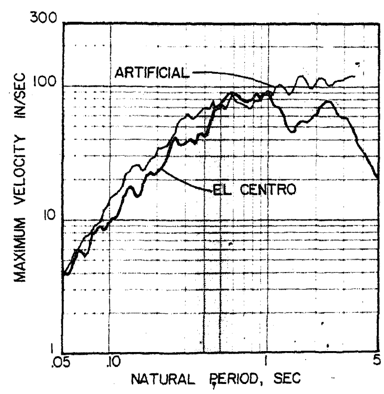

FIGURE 9 RESPONSE SPECTRA, 1.0g, 5% DAMPING

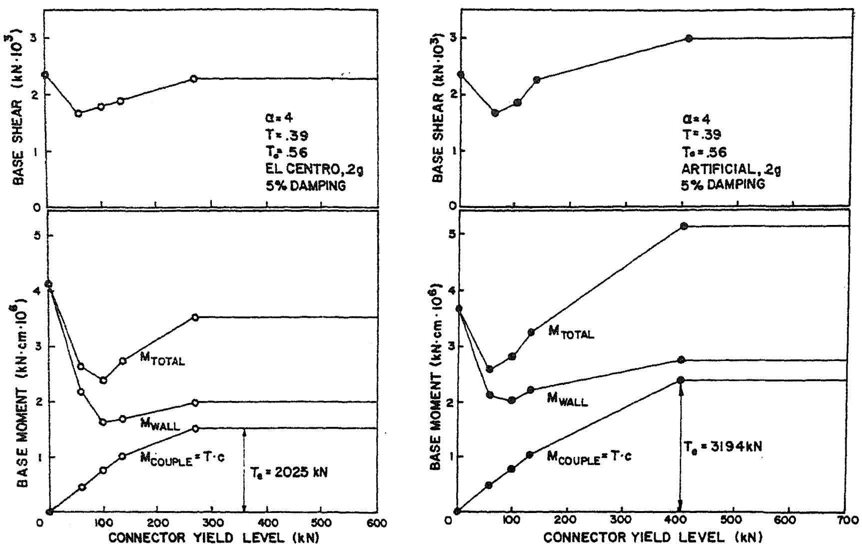

FIGURE 10 MAXIMUM BASE SHEAR AND MOMENT VS. CONNECTOR YIELD LEVEL

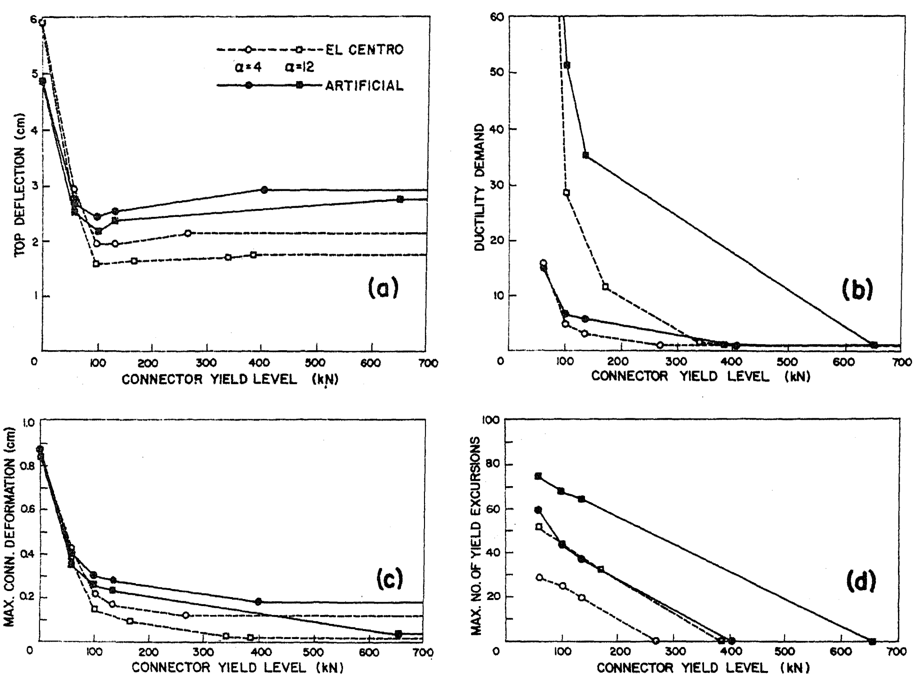

FIGURE 11 MAXIMUM TOP DEFLECTION AND CONNECTOR RESPONSE VS. CONNECTOR YIELD LEVEL (0.20g)