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MEASURES AGAINST EARTHQUAKE POUNDING BETWEEN ADJACENT BUILDINGS

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ABSTRACT

Alternative ways, to the code specified separation distance, to deal with the problem of pounding of buildings by either filling the gaps between them with a material, or by connecting them structurally, or by using bumper walls, are examined. To study the first two ways, contact was simulated by means of spring–dashpot elements and the buildings were idealized as lumped mass, shear–type MDOF systems, with bilinear force–deformation characteristics. Results from elastic and inelastic analyses on groups of 5–story buildings, show that there is practically no reduction in either story shears or ductility factors, although there is a significant reduction in the accelerations. Moreover, the connection always penalizes one building and benefits the other. A linear elastic finite element analysis was used to study the effect of a floor mass hammering the bumper shear wall of a 5–story concrete building. Results show that the effect of pounding is mainly limited to the wall and that a maximum stress of the order of magnitude of the concrete compressive strength develops, around the contact point. These findings may lead to a design procedure, and bumper walls may provide the best way to alleviate the problem of pounding.

KEYWORDS

Pounding; impact; building collisions; bumper walls; interstructural connection; seismic separation.

INTRODUCTION

Pounding of buildings during earthquakes has been identified as a cause of damage, especially during the Mexico City earthquake in 1985. An extensive review and literature survey of the research work on the subject was given by Anagnostopoulos, 1994.

The typical measure against pounding, which is specified in various codes, is to provide a sufficient separation distance between adjacent buildings. The UBC specified separations equal to the sum of the design maximum displacements of the two buildings was found to be quite adequate for protection against pounding and so did its reduced value that was determined on the SRSS of the same displacements (Anagnostopoulos, 1988, Anagnostopoulos and Spiliopoulos, 1992, Maison and Kasai, 1992.) A more refined estimate of the required separation which works well with elastic systems has been given by Jeng *et al*, 1992.

The measure of the separation distance can not be applied, of course, to buildings that have already been constructed before any such code requirements were introduced. Moreover, even for the new construction, a big separation distance to account for pounding would result in large building separations and significant loss of usable space. This may be economically intolerable, for the owners of small lots, especially in metropolitan areas, where the cost of land is quite high. Westermo, 1989, suggested an alternative to seismic separation by connecting structurally the adjacent buildings.

It is the purpose of the present paper to examine how alternative ways to the seismic separation gap, i.e., by filling the gap with a material or by connecting the buildings structurally or by using bumper walls may influence the dynamic behaviour of a structure and if these ways could alleviate the problem of pounding.

ASSUMPTIONS AND IDEALIZATION

Each building is idealized as a series of lumped masses concentrated at the floor levels. This shear beam type model has bilinear interstory resistance characteristics. (Fig.1). Structural damping of the Rayleigh type is specified to produce modal damping 5 per cent of critical in the first two modes of vibration. Translational and rotational springs simulate the behaviour of the foundation. One translational degree of freedom is allowed for every mass, except for the mass of the foundation which can also rotate to permit rocking motion. The floor levels are the same for all the buildings and therefore collisions can only occur at the floor levels. Whenever a contact occurs the force that develops is determined through the use of a viscoelastic impact element that consists of a spring and a dashpot (Anagnostopoulos and Spiliopoulos, 1992). These impact elements are always active if an interstructural connection between two floors exists (as for example between the top floors of Fig. 1) or become active only when the two floors come into contact with each other. Such an impact element can also simulate the behaviour of a material that may fill the gap between two buildings.

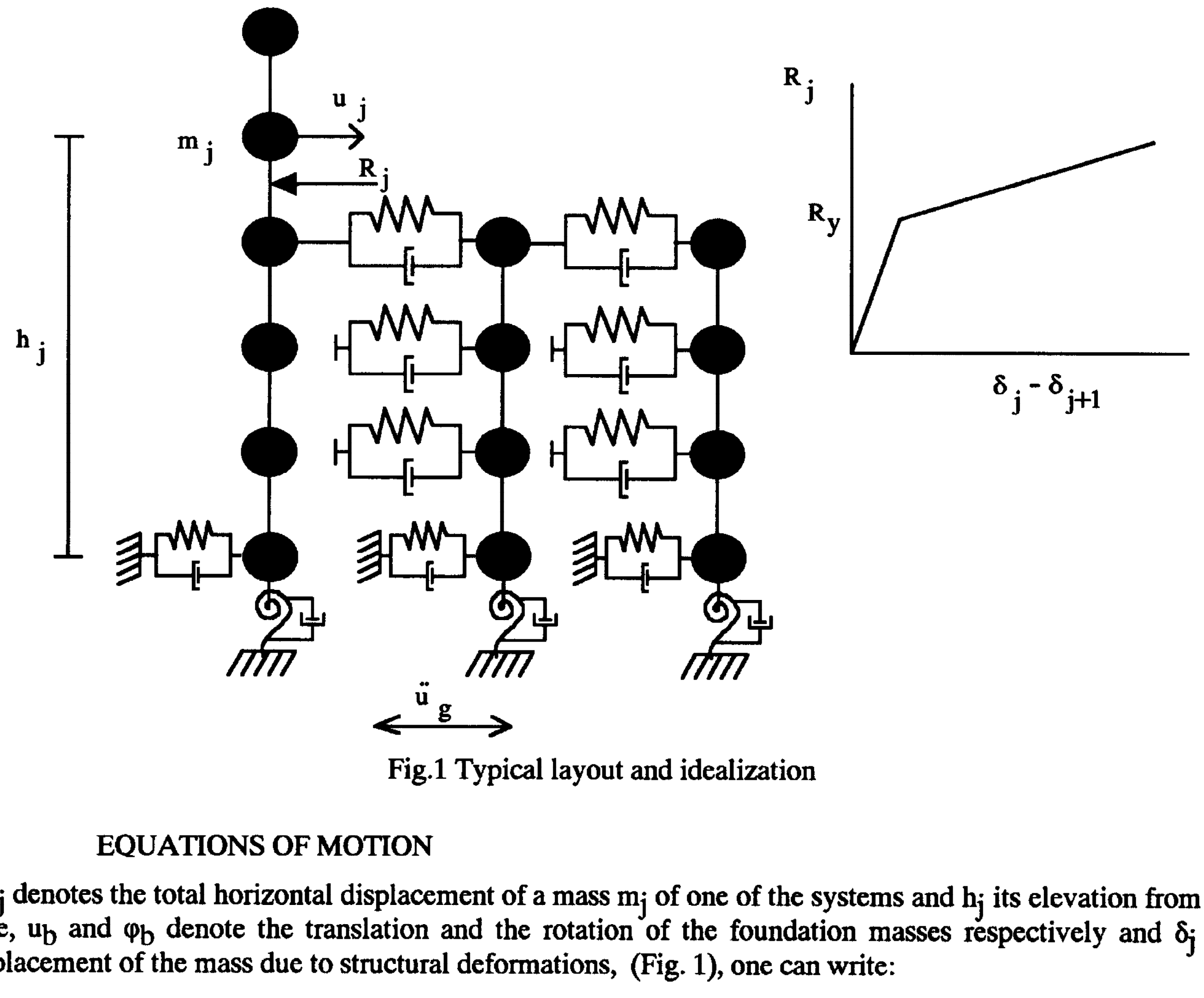

Fig.1 Typical layout and idealization

EQUATIONS OF MOTION

If u_j denotes the total horizontal displacement of a mass m_j of one of the systems and h_j its elevation from the base, u_b and φ_b denote the translation and the rotation of the foundation masses respectively and δ_j the displacement of the mass due to structural deformations, (Fig. 1), one can write:

$$u_j = \delta_j + u_b + h_j\phi_b \tag{1}$$

The dynamic equilibrium of the mass m_j can be expressed by the following equation:

$$m_j(\ddot{\delta}_j + \ddot{u}_b + h_j\ddot{\varphi}_b) + \sum_{i=1}^{n} c_{ji}\dot{\delta}_i + R_j + F_j = -m_j\ddot{u}_g \tag{2}$$

where dots indicate derivatives with respect to time, c_{ji}= damping coefficients, R_j = restoring force due to structural resistance, F_j = impact force which occurs whenever a contact occurs, n is the number of floors of the system considered, $\ddot{u}_g$ = ground acceleration.

The restoring forces R_j are computed from the bilinear force–deformation relation of each story (Fig.1)

$$R_j = k_j^t(\delta_j - \delta_{j+1}) - k_{j-1}^t(\delta_{j-1} - \delta_j) \tag{3}$$

Equation (4) is the matrix expression of equation (2), in which the equations of the dynamic equilibrium are grouped for all the floor masses as well as the foundation and rotational masses of all the buildings in the configuration:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + \{R\} + \{F_s\} = -\ddot{u}_g\{m\} \tag{4}$$

where [M]=mass matrix, {U}=displacement vector of the d.o.f., $[C]=[C]_R+[C]_I$ is the total damping matrix, $[C]_R=\alpha[M]+\beta[K]$ = structural damping matrix of Rayleigh type, [K]=elastic stiffness matrix, {R}=vector of structural resistances, {m}=right–hand side mass vector.

Three different cases of contact will be considered below: A pure pounding case, a case where the gap is filled with some material and a case where there is a permanent connection between opposite masses of adjacent buildings. All three cases can be simulated by means of an impact element which gives the contact force as a sum of an elastic part and a viscous part. The matrix $[C]_I$ denotes the contribution to the contact force of the viscous behaviour of the currently active impact elements which for all the cases is considered linear. The vector $\{F_s\}$ is the contribution to the contact force of the elastic behaviour of the currently active impact elements, which may be linear or non–linear (case of infill material).

Pure pounding case

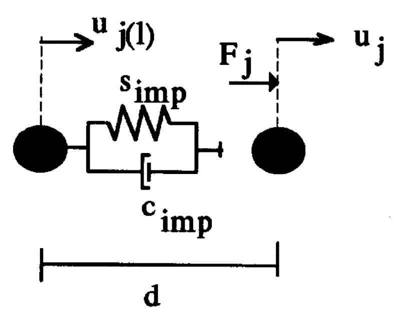

Fig.2 Impact force induced by impact element

The instantaneous distance v between the mass m_j and its neighbouring mass on the left is given by the equation:

$$v = u_{j(l)} - u_j - d \tag{5}$$

where d is the initial distance of the two masses. The condition for contact between the two masses will be v>0. In this case the impact force exerted on the mass m_j will be given by the equation:

$$F_j = s_{imp} v + c_{imp} \dot{v} \tag{6}$$

The stiffness of the impact spring s_{imp} is typically large and represents the local structural stiffness at the point of impact that will react to the shock during contact. The constant c_{imp} of the associated dashpot determines the amount of energy that is dissipated during impact and can be estimated using the following relationship (Anagnostopoulos, 1988):

$$c_{imp} = 2\xi_i\sqrt{s_{imp}\frac{m_1 + m_2}{m_1 m_2}} \tag{7}$$

where ξ_i is a damping ratio for different coefficients of restitution and m_1, m_2 are the values of the two colliding masses.

Infill material case

When the gap between two adjacent buildings is filled with a material of some kind, the behaviour of this material can be simulated by means of a viscoelastic impact element.

In this case, the instantaneous distance between the two masses shown in Fig.2 is given by the relation:

$$v = u_{j(1)} - u_j \tag{8}$$

and the impact element becomes active as soon as v>0.

The elastic behaviour of such a material is envisaged as a continuous one; therefore, when the compression v is just over zero, it starts from a minimum initial stiffness s_{mat} and when the compression exceeds the initial gap, a pure impact should occur and the stiffness should be equal to the large stiffness of an impact spring that corresponds to the case of pure pounding. (Fig. 3)

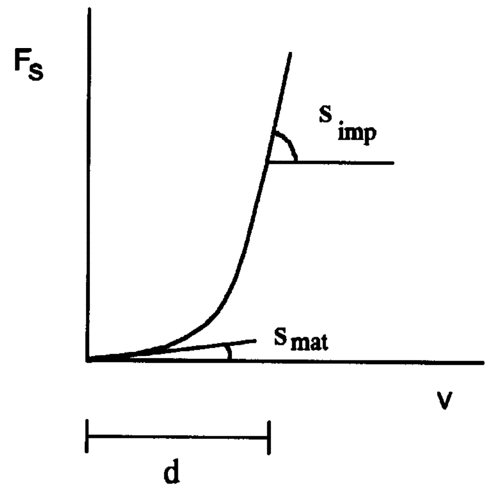

Fig.3 Assumed law of elastic force vs deformation for infill material

A cubic law for the elastic force $F_s=pv^3+qv$ can be used to approximate such a behaviour. The conditions that $dF_s/dv=s_{mat}$ at v=0 and $dF_s/dv=s_{imp}$ at v=d can determine the two constants p and q. The final expression of the contact force may therefore be given by the expression:

$$F_j = \frac{s_{imp} - s_{mat}}{3d^2} v^3 + s_{mat} v + c_{cur} \dot{v} \quad \text{if } v \le d$$

$$F_j = s_{imp} v + c_{imp} \dot{v} \quad \text{if } v > d \tag{9}$$

The relation (7) can be utilised to estimate the damping constant c_{cur} where in the place of the spring stiffness, the current slope of the force deformation curve of Fig. 3 (which is given by the derivative with respect to v of eq. (9)) can be used.

Permanent connectors case

In this case, whenever a permanent connection bridges the initial gap, like the top floors of Fig.1, the corresponding impact elements are continuously active throughout the entire motion of the configuration, independent of the sign of whose value is given, once again, by eqn.(8). A new elastic stiffness matrix of the configuration is therefore formed with the degrees of freedom, at the ends of the permanent connector as well as the degrees of freedom associated with the foundation masses of the corresponding buildings, coupled. The contact force that is exerted by the impact elements is given by the equation (10).

$$F_j = s_{con} v + c_{con} \dot{v} \tag{10}$$

where s_{con} is the stiffness of the connector, which can be used in eqn.(7) to determine the damping constant c_{con}. The maximum compression v must never be greater than the initial gap for meaningful results.

PERMANENT CONNECTORS BETWEEN SDOF SYSTEMS

Before proceeding to the parametric studies with the MDOF systems some of the characteristics of the interstructural connections can be seen by the analytic study of 2 SDOF systems connected together (Fig.4).

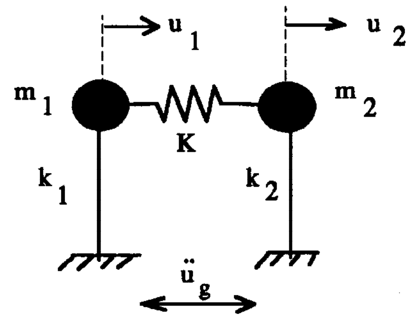

Fig.4 Two SDOF systems connected.

It one writes down the equations of motion for the coupled system, it can be proved from the resulting characteristic equation that the lowest eigenfrequency of the connected system lies between the two eigenfrequencies of the uncoupled systems, whereas the higher one is bigger than both of them.

Let us suppose that a sinusoidal type of acceleration of frequency Ω is used as input. If we assume that $m_1=m_2$, we can calculate analytically the ratio of the maximum displacements of the systems when they are coupled to the corresponding ones of the uncoupled systems. These ratios are plotted against the ratio Ω/ω_{1o}, where ω_{1o} is the eigenfrequency of the uncoupled system 1 (Fig. 5). A value of $K=0.2k_1$ and of $p=\omega_{2o}/\omega_{1o}=0.60$ was used in these plots, where ω_{2o} is the eigenfrequency of the uncoupled system 2. The left figure corresponds to a 5 per cent, whereas the right one corresponds to a 10 per cent structural damping.

It can be clearly seen from these plots that whenever the response of one of the system increases, the response of the other decreases and vice-versa. This fact holds true for any value of the connecting spring and any ratio of the initial frequencies of the systems.

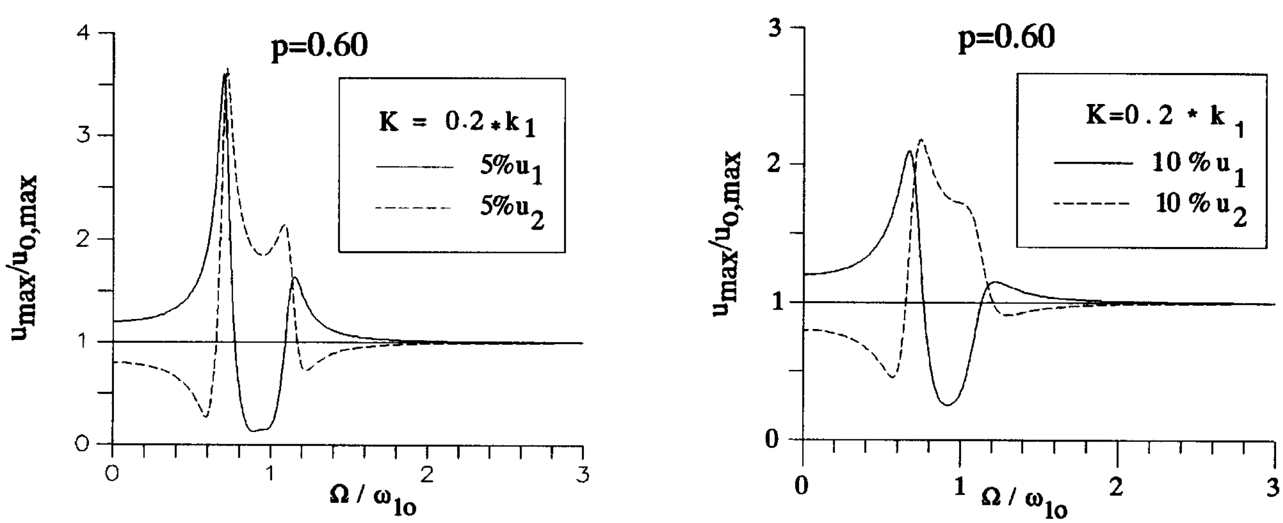

Fig.5. Variation of the maximum displacements ratio against frequency ratio

PARAMETRIC STUDIES

The effects of filling the gap with some material, as well as the possible interstructural connection of the different systems are investigated on a group of 5-story systems. Two 5-story systems with fundamental periods of 0.36sec and 0.60sec were used. Each system in the group has the same mass in a given floor, whereas the stiffness of each system was assumed to vary linearly with height. Yield levels for the inelastic solutions were taken equal to the story shears which were determined in accordance to the UBC code. For the systems studied here the UBC specified separation distance (equal to the sum of the design maximum displacements) is approximately 7cm.

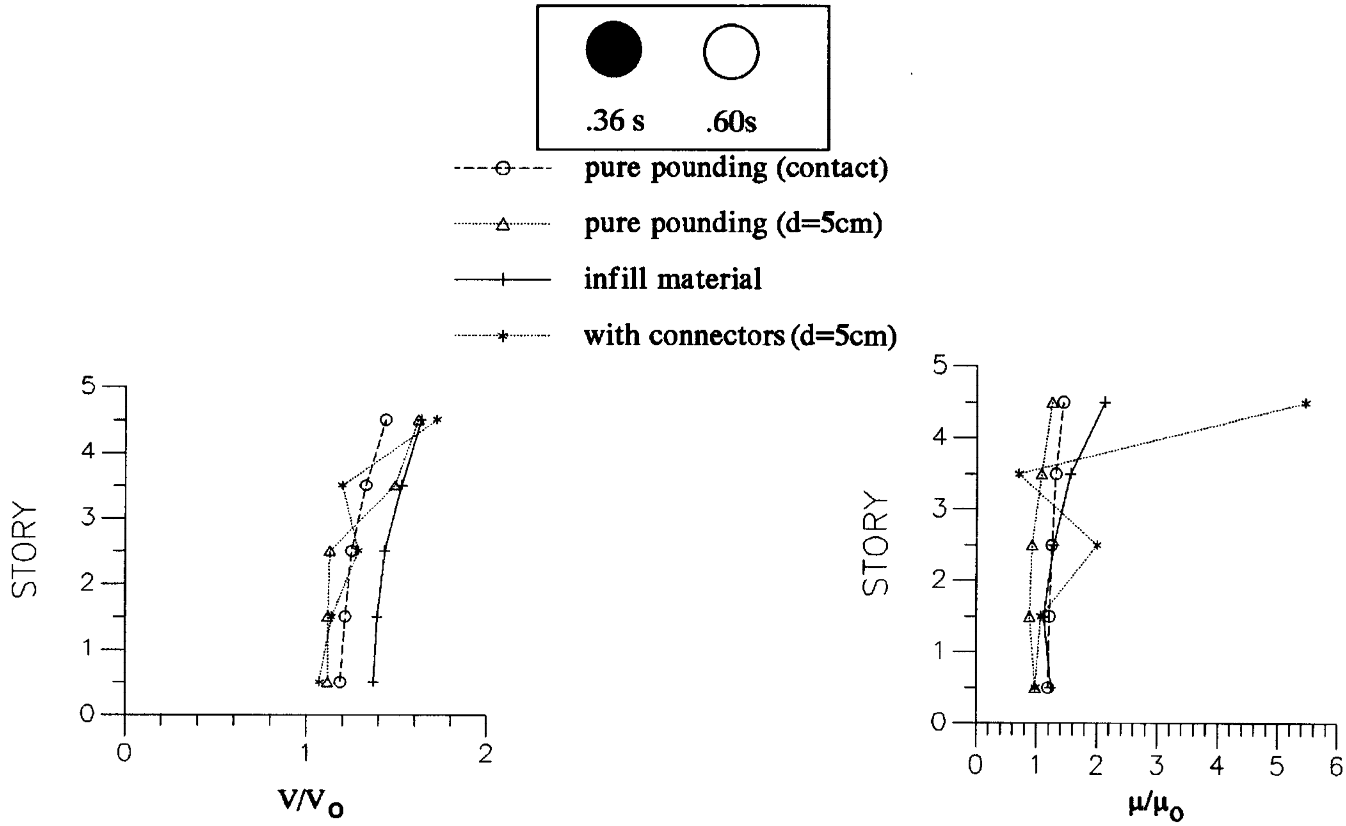

Fig.6 Effects of pounding, infill material and interstructural connection on the elastic and inelastic response of a 5–story system in a 2–system group.

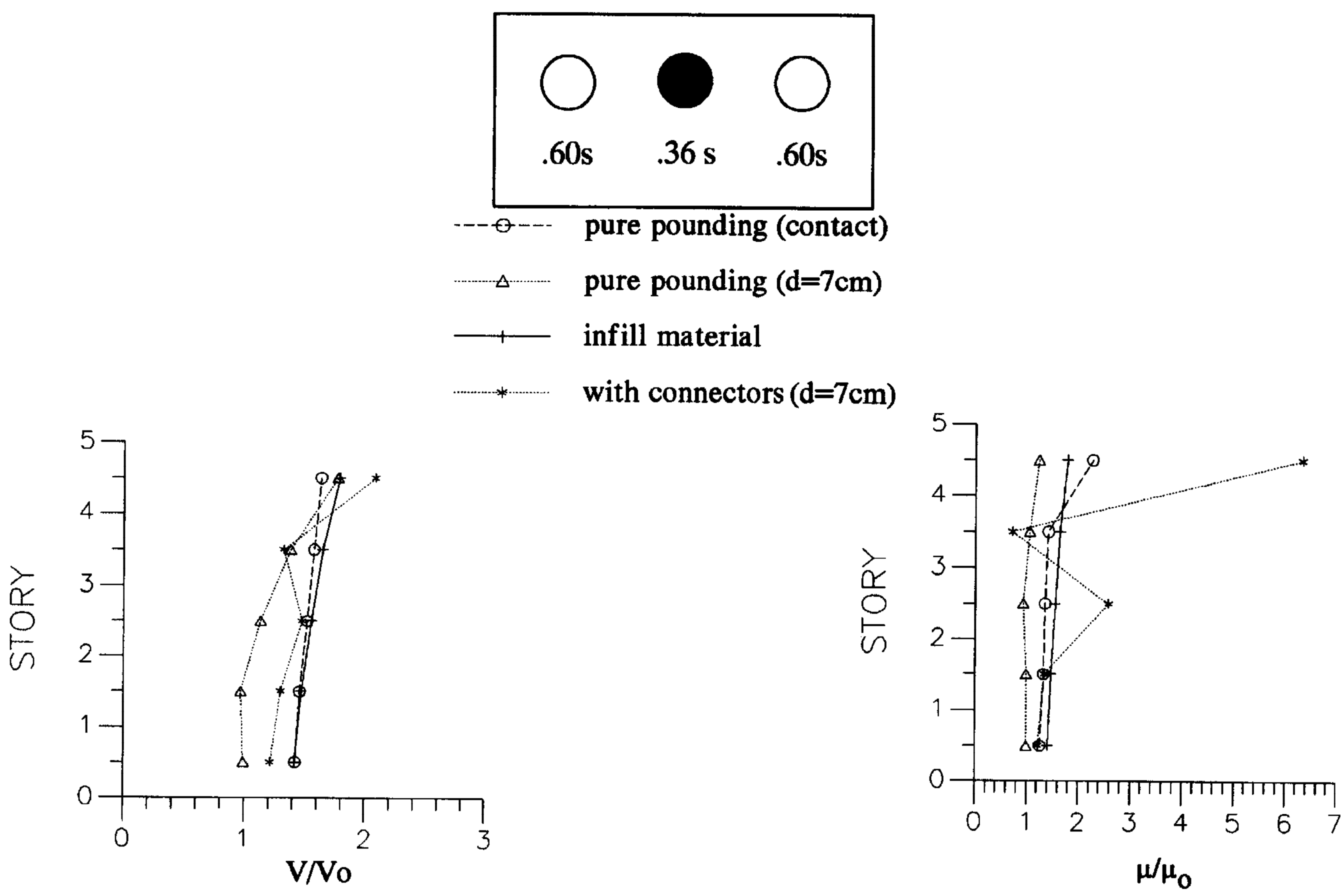

Fig.7 Effects of pounding, infill material and interstructural connection on the elastic and inelastic response of a 5–story system in a 3–system group.

Elastic and inelastic analyses have been performed for the 5 earthquake records listed in Table 1. The scale in the last column of the Table was computed by equating the Arias intensities of these motions to the Arias intensity of the El Centro record. Results for the elastic analyses are presented in terms of mean values of the ratios (V/V_0) and for the inelastic analyses in terms of mean values of ratios (μ/μ_0), for the 5 motions. V and μ are the maximum story shear and ductility factor of the pounding building respectively, whereas V_0 and μ_0 are the corresponding maximum story shear and ductility factor of the same building without pounding.

Table 1. Earthquake motions used in analyses

Record	$\ddot{u}_g$ max (g)	Duration (sec)	Scale
El Centro(1940) – NS	0.35	10	1.00
Taft(1952)–S69E	0.18	15	1.75
Eureka(1954)–N79E	0.26	10	1.33
Olympia (1949)–N86E	0.28	23	1.25
Parkfield (1966)–65E (Array No. 2)	0.49	10	0.82

A two and a three system configurations were examined as one can see at the insets at the top of Fig.6 and Fig.7. Each system is characterized by its fundamental period T(sec), while the system whose results are plotted herein is shown in black.

Four different cases are shown in each of the two figures. Two pure pounding cases were considered for both the 2–system and the 3–system groups; one in contact with each other and the second by introducing a gap of 5cm (less than the UBC specification) for the 2–system and a gap of 7cm (equal to the UBC specification) for the 3–system group, respectively. Results indicate that the code specified separation is quite adequate.

For the infill material an initial stiffness $s_{mat} \approx 1/5$ of the average stiffness of all the stories of one of the buildings was used. There is a small increase in the responses shown in the figures if a 1/10 to 1/100 of this average value is used instead. As can be seen from both the figures and subject to the assumptions of the model of the infill material behaviour that was explained above, the infill material does not seem to produce any beneficial effect. Nevertheless, it was found that there is more than 80% reduction to the accelerations.

For the permanent connectors, the value of the linear spring constant was also taken equal to 1/5 of the average stiffness among all the stories of a building. To avoid pounding at any level both the top and the middle floors were connected. As it can be seen from both the figures there is a substantial increase to the response of the stiffer building, especially for the inelastic case; at the same time, just like the SDOF systems, the response of the other connected system was found to reduce (a fact also mentioned by Westermo, 1989).

BUMPER WALLS

The use of shear walls that are constructed at right angles to the dividing line between two buildings in contact, so that they can be used as bumper elements in the case of pounding, has been suggested by Anagnostopoulos and Spiliopoulos, 1992.

A typical 5–story concrete building with a bumper shear wall was considered in order to study the effect of pounding in such a case (Fig.8). The dimensions of the shear wall were taken as 25x200 cm whereas the dimensions of the beams and columns were taken as 25x60 and 60x60 cm respectively. Quadrilateral finite elements were used to model the shear wall, whereas beam elements to model the beams and columns.

Each floor was assumed to have a mass of 200000 kg, which was distributed as concentrated lumped masses at the nodes of the structure. It was assumed that the floor of an adjacent building which was taken as a concentrated mass of also 200000 kg strikes the building, at the mid–height between the fourth and fifth story, at a seismic velocity of $\dot{v}_0 = 0.5$ m/sec.

An elastic analysis was performed using MSC/NASTRAN, 1994. The results show that the bigger values of stresses occur at the elements around the point of impact. The maximum stresses in the wall were obtained at the elements just above and below the point of impact and are of the value of about 33 N/mm^2 (von Mises stresses), which is of the order of magnitude of the compressive strength of concrete. Moreover, since the stresses obtained in the rest of the wall are substantially lower and in the beams and columns are quite low, the phenomenon appears to be a rather local one, which is promising for design purposes.

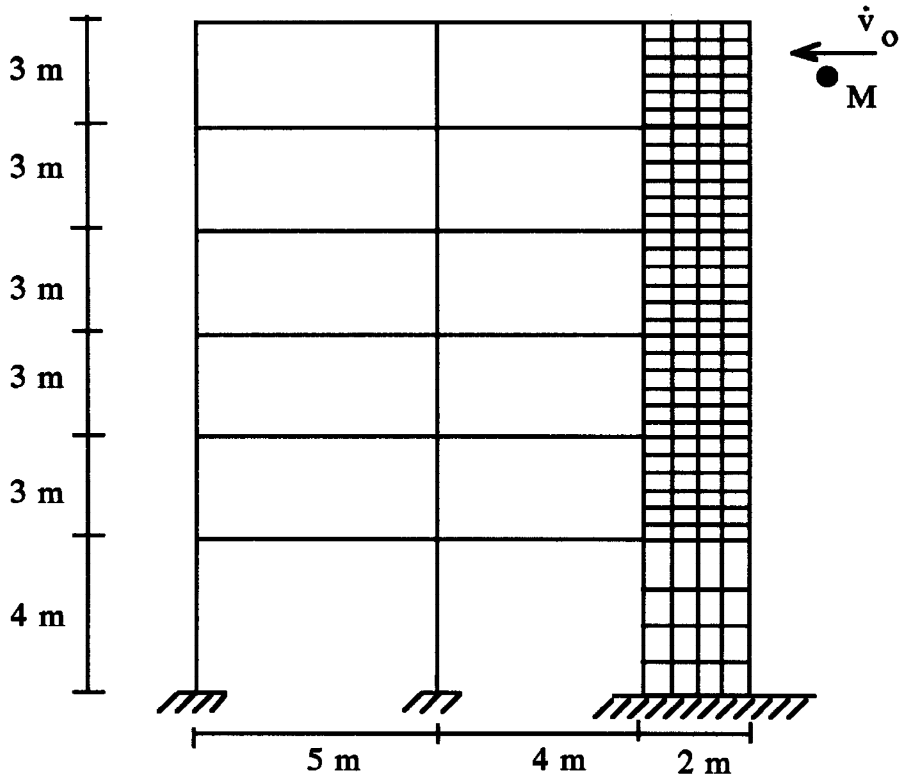

Fig. 8. Finite element modelling of a 5–story building with a bumper wall

CONCLUSIONS

In the case of insufficient separation distances and under the assumption that collisions are limited only between floor masses, the filling of the gap with an impact absorbing material does not seem to produce any favourable effects on the response, although the accelerations are greatly reduced. Structural connection is not an acceptable measure as not only increases the response but also will often penalize one of the two structures, while benefiting the other.

Since the most severe situation is midheight column pounding, bumper walls seem to be the best alternative to the seismic separation problem. It appears from a finite element linear elastic analysis of a concrete building with a bumper shear wall impacted by a floor slab, that pounding affects mainly the wall locally and the stress that is developed is of the order of magnitude of the concrete compressive stress. These results may lead to a design procedure.

REFERENCES

Anagnostopoulos, S.A. (1988). Pounding of buildings in series during earthquakes. *Earthq. eng. struct. dyn.*, 16, 443–456.

Anagnostopoulos, S.A. and Spiliopoulos, K.V. (1992). An investigation of earthquake induced pounding between adjacent buildings. *Earthq. eng. struct. dyn.*, 21, 289–302.

Anagnostopoulos, S.A. (1994). Earthquake induced pounding: State of the art. *Proc. 10th European conf. earthquake eng.*, Vienna, 897–905.

Jeng, V., Kasai, K. and Maison, B. (1992). A spectral difference method to estimate building separations to avoid pounding. *Earthq. spectra.* 8,2, 201–223.

Maison, B.F. and Kasai, K. (1992). Dynamics of pounding when two buildings collide. *Earthq. eng. struct. dyn.*, 21, 771–786.

MSC/NASTRAN, (1994), Reference manual (Version 68), *MacNeal–Schwendler Corporation*, USA

Westermo, B.D. (1989). The dynamics of interstructural connection to prevent pounding. *Earthq. eng struct. dyn.*, 18, 687–699.