DYNAMIC RESPONSE OF FRAMES WITH STAGGERED PANELS

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SUMMARY

This paper presents the dynamic characteristics of a new structural system, consisting of staggered discrete panels, to assess its suitability in practice. The longitudinal component of Koyna earthquake (India) of December, 1967 is considered for studying response of the staggered system in comparison with the conventional shear wall frame system. Dynamic response is evaluated for three different frame heights of 3, 11 and 19 storeys with (i) 10% damping and (ii) no damping. The staggered system is found to be superior to the conventional one for medium heights with respect to the top displacements.

INTRODUCTION

That frames with walls are advantageous for earthquake resistance has been recognised and they have been in use in earthquake resistant design of practically all high rise buildings. As for apartment buildings, if the locations of the walls could be adjusted and systematised, it would be possible for applications to be made to a variety of housing plans utilising the walls to the utmost for earthquake resistance. The present investigation aims at studying new structural forms of building frames with discrete shear pabels systematically dispositioned, Fig. 1, using the same quantity of material as in a frame with conventional shear wall extending from foundation to roof continuously, Fig. 2. It is possible that by appropriately staggering the storey-deep and baywide panels in the plane of a building frame or/and along the length of the building, the system can be made functionally more useful than a conventional shear wall frame. Staggering of panels can be varied through the combinations of the simple basic systems given in Fig. 1. In the present study two dimensional systems with planar loadings are considered. The static response was presented separately (Ref. 1). The dynamic characteristics are presented herein for the proposed staggered system, based on the stiffness approach using Macleod's pair of elements (Ref. 2), to find its suitability in actual practice. The longitudinal component of 'Koyna Earthquake' (India) for December, 1967 is considered for studying response of the proposed system in comparison with the conventional system.

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Experimental verification was limited to the study of frequencies and mode shapes only (Ref. 3). Four perspex models were tested for the purpose. The experiments validate the adequacy of the finite elements chosen and should give necessary confidence for the adoption of the proposed system by the construction industry.

METHOD OF ANALYSIS

Finite element method is recommended for the static analysis of staggered panel system as the wide column idealisation with rigid arms for the discrete panels does not simulate the real structure (Ref. 1). Further the capabilities of the present generation computers have practically removed the constraints previously encountered in the designs requiring considerations of dynamic aspects of loading and less severe idealisations in the form of finite elements representing the panels. As such the finite element procedure is adopted for the dynamic analysis of the staggered panel system using Macleod's pair of rectangular elements, (Ref. 2) which consider inplane rotation with single rotational degree of freedom at each of the four nodes. The displacement functions considered are

$$u = a_1 + a_2 x + a_3 y + a_4 xy + a_5 y^2 + a_6 xy^2 \qquad ...(1)$$

$$\text{and} \quad v = a_7 + a_8 x + a_9 y + a_{10} xy + a_{11} x^2 + a_{12} x^2 y \qquad ...(2)$$

giving full boundary compatibility. Satisfactory convergence is obtained with a mesh division consisting of 16 elements in each panel (Ref. 1). All the degrees of freedom at the internal nodes are eliminated and a condensed stiffness matrix of 12 x 12 size is obtained for a panel (Ref. 3). Using these typically condensed stiffness matrices and treating all the columns and girders as flexural line elements undergoing axial deformations, the stiffness matrix for the frame with discrete panels is formulated. The lateral flexibility matrix is generated by solving for as many unit load cases as the number of storeys using Gaussian elimination procedure and altering only the load vector without disturbing other elements while solving for different load cases. The staggered panel system has four nodes at any floor level due to condensation and hence a horizontal load of 0.25 is applied at each to add to a unit load. However, for the conventional shear wall system the wide column frame analogy method is adequate and hence used for comparison. Discretised masses are considered at floor levels which give a diagonal mass matrix. The procedure was adopted owing to the limitations of the computer facilities (ICL 1909 with an effective core storage of about 23 k) available at the Indian Institute of Technology, Delhi in 1978 during which period this investigation was undertaken. Discretization of masses at the centres of panels was not considered in view of heavier masses at floor levels due to the slabs.

DYNAMIC RESPONSE FOR KOYNA EARTHQUAKE

Accelerogram record for the Koyna earthquake recorded the

longitudinal component of peak ground acceleration equal to 63% of gravity (Ref. 4). For the proposed and conventional systems, dynamic responses are obtained for the longitudinal component of the Koyna earthquake considering the contribution of the first three modes of vibration and the results compared. The digitised accelerogram data as obtained by School of Research and Training in Earthquake Engineering, University of Roorkee based on accelerogram record is used for the study of dynamic response.

Dynamic response is evaluated at the end of 5.6 seconds with (i) no damping and (ii) 10% damping. Three different frame heights 3, 11 and 19 storeys are considered for investigation as representative. For the first two heights, conventional system and all the three cases of staggered panel system are considered. For the 19 storey height, case 1 of the proposed staggered system, Fig. 1a, has been compared with the conventional one. Time step adopted is 0.0053 second.

COMPARISON OF METHODS OF ANALYSIS

Two methods, (i) the modal superposition method using Simpson's rule for evaluating Duhamel integral and (ii) the step method (β =1/6) are used for the evaluation of the dynamic response. The first three modes are considered in evaluating the response by modal superposition. The results obtained from modal analysis are verified with those from step method. They are in agreement as expected (Ref. 3).

RESPONSE COMPARISON

Storey Displacements

The maximum top displacement in respect of the different cases of the staggered system have been compared with those for conventional shear wall system in Table 1. The maximum top displacements are considerably less for cases 2 and 3 of the staggered system and they are comparable, except for 19 storey frame with no damping, for case 1 with those for conventional system. The effect of damping is observed to be about the same in both the systems.

Inertial Forces and Mode Shapes

Contribution to displacements from the second mode, especially in the lower storeys, is significant besides that from the first mode, Fig. 3. As a result of this significant influence of the second mode on the deflections the floor inertial loads do not continuously increase, Fig. 4. In fact in some of the cases investigated, there is a change of sign in the inertial loads along the height.

The mode shapes for the staggered panel system consist of zigzag lines, especially for higher modes, Fig. 5, unlike in the conventional system for which they are smooth curves. This is due to the discontinuity in the shear wall and provision of discrete panels. In such modes sway deformations are small as compared to panel rotations and the adjoining story panels have the direction of rigid body rotations reversed. The inplane rotation in a discrete panel causes opposite nature of

movement in the top and bottom edges of the panel, Fig. 6. There
can be a change of a sign in the horizontal deformations of top
and bottom corners of a panel. This feature makes the mode shapes
zigzag in nature for the proposed system. As an illustration, for
a 11-storey frame 10 reversals take place in sixth mode, Fig. 5.
Because the masses are assumed to act at floor levels, the eigen-
vectors are computed with respect to these levels. Based on the
above discretization the mode shape with respect to the centroids
of the discrete panel is also shown in Fig. 5.

Table 1 — Comparison of Maximum top Displacements between the
proposed and conventional systems

Description	Proposed System		
	Case 1	Case 2	Case 3
a) 3 Storey frames			
i) No damping	Less 7.98%	Less 56.48%	Less 56.48%
ii) 10% damping	Less 4.95%	Less 36.56%	Less 36.56%
b) 11 Storey frames			
i) No damping	More 6.85%	Less 44.7%	Less 44.75%
ii) 10% damping	More 1.98%	Less 28.24%	Less 30.21%
c) 19 Storey frame			
i) No damping	More 17.97%		
ii) 10% damping	More 6.36%		

Base Shears

The maximum base shear need not necessarily occur at the
instant when the maximum top displacement occurs. In the present
investigation, it has been observed that the maximum base shear
and maximum top displacement do not occur simultaneously except
for the 3 storey frames. The values are compared with the corres-
ponding results for a conventional system in Table 2. The maximum
base shear in case 1 of the staggered system is comparable with that
for a conventional system for all the heights considered. In
respect of cases 2 and 3 of the staggered system, the values are
comparable for 3 storey frames; but are considerably more for
11 storey frames.

Table 2 - Comparison of maximum base shears between the proposed
and conventional systems (with 10% damping)

	Description	Proposed System		
		Case 1	Case 2	Case 3
a)	3 Storey frames	Less 4.83%	Less 3.39%	Less 3.39%
b)	11 Storey frames	More 2.71%	More 51.56%	More 49.93%
c)	19 Storey frames	More 1.73%		

Displacement Time History for Top Storey

The variation in top displacement with time is presented in
Fig. 7 for case 1 of the proposed staggered system and the conven-
tional system for the height of 19 storeys. It can be observed
that the responses in both the systems are similar and magnitudes
comparable.

GENERAL

It is desirable that the analytical results obtained by a
proposed method in respect of a new structural form are further
confirmed by experimental investigations. To study the overall
behaviour of the proposed system, both static and dynamic tests
were carried on 4 perspex models; and 3 reinforced concrete panels
were tested to examine and behaviour of the panel at its connections
with the skeletal members (Ref. 3).

CONCLUSIONS

The feasibility of staggered panel system has been assessed
in comparison with the conventional shear wall system. The dynamic
characteristics for medium rise frames with staggered panels are in
no way inferior to those provided with continuous shear walls.

Cases 2 and 3 of the proposed staggered system are superior
to the conventional one in respect of displacements for frames of
moderate heights. The displacements in case 1 are comparable with
those for the conventional shear wall frame.

The displacement time history of the top storey is similar and comparable between the staggered panel system, case 1 and the conventional shear wall system.

The maximum base shears are comparable for case 1. For cases 2 and 3 they are comparable for the 3 storey frames and are higher for the 11 storey frames.

The presence of discrete panels makes the mode shapes, especially for the higher modes, zigzag in nature for the staggered panel system.

The contribution of second mode is not insignificant in the case of tall frames. Other higher modes are not important.

The effect of damping is about the same in the proposed and the conventional systems.

The discrete shear panels can be made functional and at the same time to the best advantage of earthquake resistant design by appropriate dispositioning of the panels.

REFERENCES

1. Prasada Rao, K. N. V., and Seetharamulu, K., "Staggered Shear Panels in Tall Buildings", Jnl. of Structural Engineering, ASCE, Vol. 109, No. 5, May, 1983, pp. 1174-1193.

2. Macleod, I. A., "New Rectangular Finite Element for Shear Wall Analysis", Proc. ASCE, Vol. 95, No. ST3 March 1969, pp. 399-409.

3. Prasada Rao, K. N. V., "Tall Buildings with Staggered Shear Walls", Thesis presented to the IIT Delhi, India in 1978 in fulfilment of the requirements for the degree of Doctor of Philosophy.

4. Chandrasekharan, A. R., and Saini, S. S., "Spectral Analysis of Koyna Earthquake of December 11, 1967", Jnl. Instn. of Engrs. (India), Vol. 48, pp. 1601-1612.
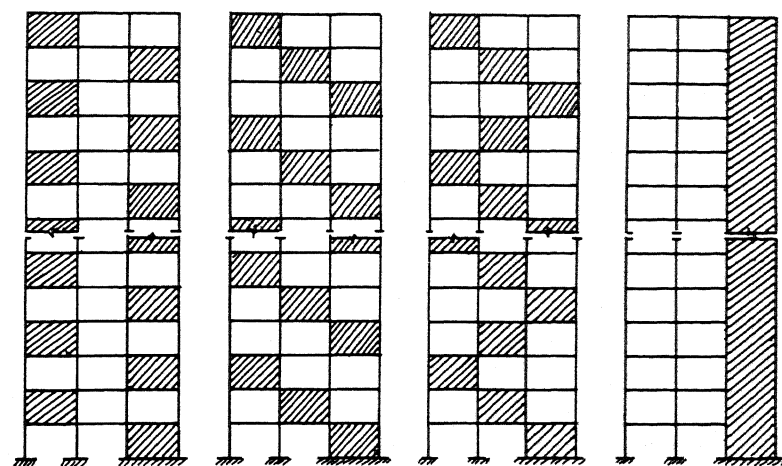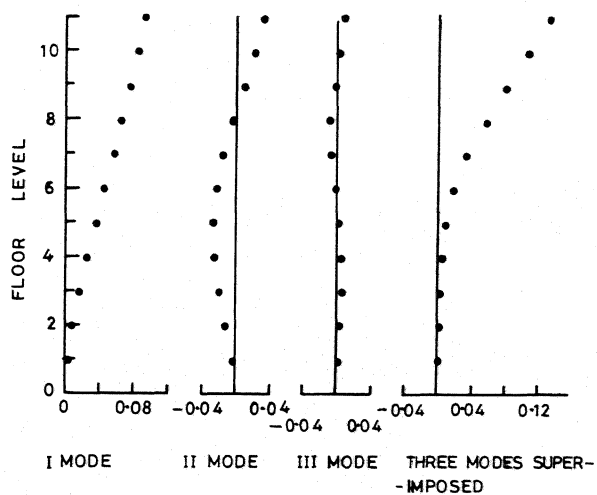
(a) CASE 1   (b) CASE 2   (c) CASE 3

FIG.1 STAGGERED SHEAR PANEL SYSTEMS   FIG.2 CONVENTIONAL SHEAR
                                                   WALL SYSTEM

I MODE   II MODE   III MODE   THREE MODES SUPER-
                                                        -IMPOSED

11 Storey staggered panel frame — case 1

FIG.3 STOREY DISPLACEMENTS — CONTRIBUTION OF   FIG.4 FLOOR INERTIAL LOADS
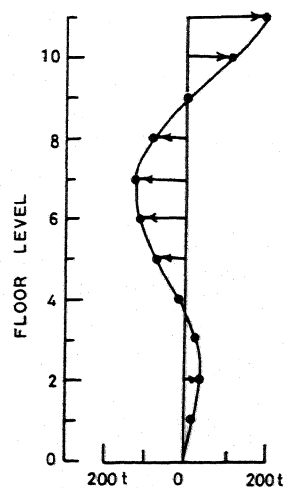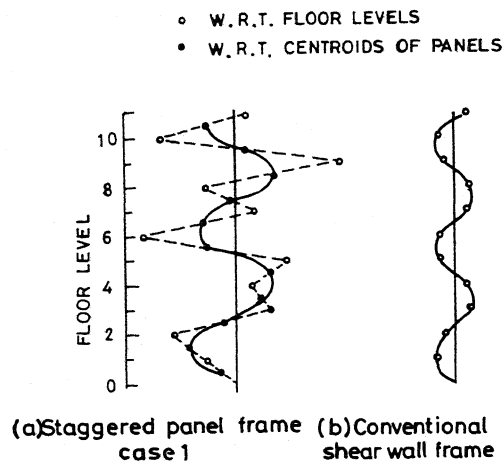   DIFFERENT MODES   STAGGERED PANEL FRAME
                                                            CASE 1

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(a)Staggered panel frame   (b)Conventional
        case 1   shear wall frame

FIG.5 SIXTH MODE SHAPE-11 STOREY FRAME

FIG.6. ZIGZAG MODESHAPE

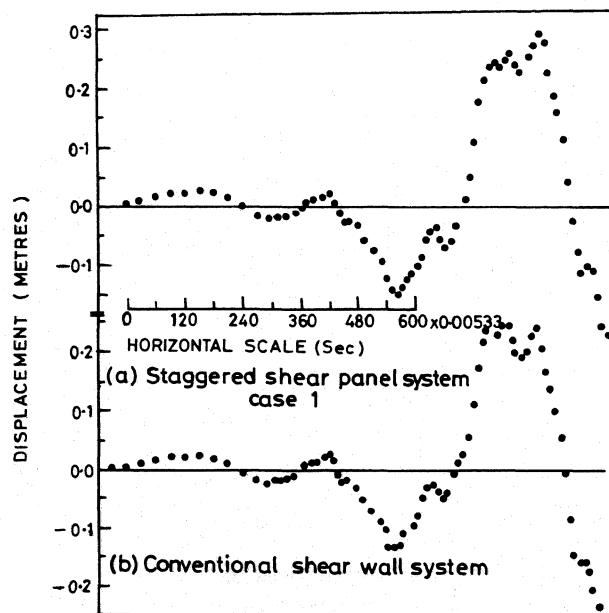(a) Staggered shear panel system
        case 1

(b) Conventional shear wall system
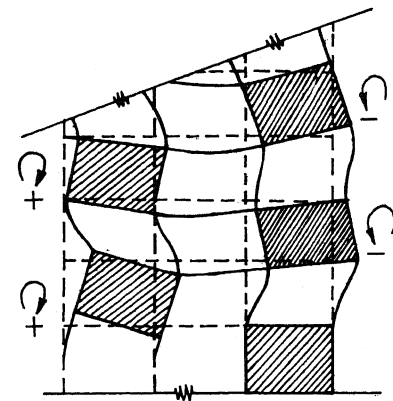
FIG.7 RESPONSE OF TOP STOREY TO KOYNA EARTHQUAKE