STRUCTURAL RESPONSE TO SIMULTANEOUS MULTI-COMPONENT SEISMIC INPUTS

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SYNOPSIS

A study of the influence of simultaneous multi-component seismic input on structural response is reported. Rectangular and cruciform plan ten-storey reinforced concrete buildings were subjected to a combination of input acceleration components, including torsional ground accelerations, corresponding to several different earthquakes. The structures were analysed as elastic three dimensional space frames and time history studies were made of the external and re-entrant corner column seismic forces developed along their heights. It was found that multi-component inputs resulted in axial forces up to the sum of the maximum single component values. Shears and moments were increased due to torsional ground motion, due to eccentricity, and due to "tube" action. Preliminary design recommendations for dealing with multi-component inputs are included.

1.0 Introduction: Codes typically specify "lateral seismic forces assumed to act non-concurrently in the direction of each of the main axes of the structure..." (S.E.A.O.C., 1974). However, commentaries on these codes often contain warnings such as "particular attention should be paid to the effect of the combined stresses at the external and re-entrant corners, which are especially vulnerable to the effect of concurrent translational and torsional motions"; the meaning of the phrase "particular attention" in the context of day-to-day design is seldom spelled out. The present study attempts to shed some light on this problem.

2.0 Scope of Investigation: Five ten-storey reinforced concrete buildings were subjected to a combination of input acceleration components, including torsional excitation, corresponding to three different earthquake records. The structures were analysed as three dimensional space frames and studies were made of the corner and re-entrant column seismic stresses developed along their heights using time history methods. The work was confined to an elastic analysis.

3.0 Structures Analysed: The buildings studied included rectangular plans with and without eccentricity of mass, and a cruciform plan form having (i) peripheral frames only, (ii) frames continuous through the central core. Details and dimensions are shown in Figs. 1 and 2.

The rectangular structures have two lateral force resisting frames in the NS and four or two in the EW directions. (Buildings 1 and 2 respectively.) Eccentricity is achieved by shifting the centre of mass 10' from the centre of rigidity in the NS direction of Building 1. In the cruciform building, in one case there are discontinuous single-bay frames around the periphery, while in the other case frames are continuous through the core to give two, three-bay systems in each direction.

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4.0 Details of Analysis: The analytical procedure assumed that floors were diaphragms rigid in their own planes; frame stiffnesses were computed and assembled into a single stiffness matrix with three degrees of freedom per floor: two horizontal translations and rotation about a vertical axis. Compatibility was imposed on frames meeting at a common column.

C.I.T. digitized data(1) of the following earthquake records were used for seismic excitation:

(1) El Centro 1940: recorded N-S and E-W components.

(2) Taft 1952: recorded N21E and S69E components.

(3) C.I.T. Simulated: records D-1 and D-2 used as orthogonal horizontal components.

It was found that the El Centro earthquake is dominated by the N-S component to the extent that addition of the orthogonal component generally did not alter the peak responses. The Taft record was felt to be more truly representative of a typical earthquake (the diagonal component is of similar magnitude to the two measured orthogonal components). Consequently, in many cases, only the Taft analysis is reported. Studies with the simulated C.I.T. D-series earthquakes appear to give the same trends as the Taft input.

Investigations were made with the following combinations of input components: a single horizontal component; both horizontal components; both horizontal components and a torsional input component. The torsional ground motion was developed by the methods of Newmark, (2,3,4,5) based on a wave velocity giving a transit time of 0.20 sec; this would lead to an upper bound on the torsional response. Since the essential purpose of the investigation was to compare the response to one component of input with that to multi-directional input, it was felt that it would be adequate to use only the most severe five seconds of ground motion.

5.0 Discussion of Results: Maximum response values developed in the different structures under various input combinations are summarized in Tables I-IV. Attention is focused on external and re-entrant corner columns in the first (ground) and fifth (mid-height) stories.

5.1 Symmetric Rectangular Building

1. Adding the E-W input to the N-S input increased the axial force in the corner column by amounts varying from 58 to 107%. In each particular case the percentage increase was essentially uniform up the building height. The higher value occurred for the structure with peripheral frames only (Building 2), which had nearly equal periods in the two orthogonal directions. The peak value of response occurred some time after the peak values of excitation.

2. For N-S input the corner columns at the North end, say, are compressed while the centre column in the North face is not. This deforms the North face frame, putting shears and moments in the corner columns in the East-West plane which would be ignored in a conventional two dimensional analysis. We are referring here to the "tube action" of the structure and the attendant shear lag phenomenon; in the building studied this gave rise to forces in the order of 10% of the planar analysis forces, increasing towards the top of the building.

3. Torsional ground motion led to increases in bending moments in the corner columns of up to 14% over those due to two horizontal components. This is most noticeable in the upper regions of the building.

5.2 Eccentric Rectangular Building

1. The second component of input motion again led to increases in axial force, this time about 26%, approximately uniform up the building height.
2. The eccentricity was in the N-S direction; therefore E-W forces, tending to rotate the building, caused shears and bending moments in the N-S frames which added to those arising from N-S excitation. This effect, which would be missed in a literal application of the code, accounted for about 25% of the N-S forces in the particular building studied.
3. Torsional excitation caused an increase of as much as 35% in column moments, which were greatest higher up in the building.

5.3 Cruciform Building with Discontinuous Frames

1. The second component of input motion again led to large increases in the axial force of the column in the re-entrant corner, which persisted for the full height of the building. With the Taft input, the increase was up to 80%, and for the simulated earthquake, up to 113%.
2. The torsional excitation caused an increase of shear in some columns of up to 30%. The effect was erratic but, again, most severe in the upper regions of the building.

5.4 Cruciform Building with Continuous Frames

1. In this case the second component of the Taft earthquake led to no significant increase in re-entrant column forces; the El Centro earthquake, surprisingly, did lead to a 22% increase in axial load.
2. Torsional effects on the re-entrant corner columns were also greatly reduced, being 5% for the Taft and 5 to 10% for the El Centro input.

It is noted that the column studied here is an interior column for the frames of which it is a member.

6.0 Discussion and Conclusions: It is stressed that the following comments are based on studies of particular buildings under particular excitations; nevertheless, it is hoped that they will be of assistance to designers concerned with routine buildings which do not warrant extensive dynamic analysis.

1. The axial force in a member which is an end column of two orthogonal frames is generally higher, throughout the building height, than is indicated by a unidirectional analysis. It has been suggested for code analysis that the larger base shear be applied in the diagonal direction; it can then be resolved into components in the principal axes, the structure can be analysed for these components, and the results added to give the force in the corner columns. (In a symmetric square building, this leads to 140% of the unidirectional analysis.) However, in this

study it was found that the maximum motion in each direction tends to persist for some little time after the responsible excitation has passed. Thus, if the fundamental periods in the two directions are similar and the damping is low, there is a strong probability that the motions will eventually be in phase when the amplitudes are still relatively high. Accordingly, if the periods are similar and damping low, the maximum stress can approach the absolute sum (200% in the square building).

2. Torsional ground motion increases the shears and moments in the corner column (but, in general, not the axial force) by an amount depending upon the eccentricity of the mass. This effect may be covered by the allowance for "accidental" eccentricity in some codes. These effects are greater at mid-height than at the base of the building.

3. In eccentric buildings, forces normal to the direction of the eccentricity cause stresses in frames parallel to the direction of eccentricity. It should not be forgotten that these must be added to the results obtained when the force is applied in the parallel direction.

4. In the cases of peripheral frames, there is a tendency for "tube" action. This may tend to reduce the axial forces somewhat, but it causes unsuspected shears and moments which are highest towards the top. In the cases studied these were of the order of 10 to 20% of the primary values.

REFERENCES

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TABLE I

SYMMETRIC RECTANGULAR BUILDINGS

TAFT 1952 EARTHQUAKE - BUILDING 1

(CIT D-1 & D-2 - BUILDING 2)

MEMBER LOCATION	MAXIMUM RESPONSE VALUE	INPUT DIRECTION		
		NS	NS+EW	NS+EW+ TORS.
GROUND FLOOR COLUMN	AXIAL LOAD (K)	158 (204)	251 (420)	252
	BASE B.M. IN NS PLANE (KF)	608 (1188)	607 (1184)	629
	BASE B.M. IN EW PLANE (KF)	3 (3)	459 (1603)	471
	SHEAR IN NS PLANE (K)	70 (40)	70 (139)	73
	SHEAR IN EW PLANE (K)	0 (1)	49 (179)	51
MID-HEIGHT COLUMN	AXIAL LOAD (K)	71 (164)	108 (330)	108
	BASE B.M. IN NS PLANE (KF)	263 (401)	259 (363)	266
	BASE B.M. IN EW PLANE (KF)	19 (32)	207 (635)	236
	SHEAR IN NS PLANE (K)	45 (56)	44 (50)	45
	SHEAR IN EW PLANE (K)	4 (6)	35 (96)	40

NS INPUT = TAFT 1952, N21E COMPONENT; CIT D-1
EW INPUT = TAFT 1952, S69E COMPONENT; CIT D-2

TABLE II

ECCENTRIC RECTANGULAR BUILDING

TAFT 1952 EARTHQUAKE

MEMBER LOCATION	MAXIMUM RESPONSE VALUE	INPUT DIRECTION		
		NS	NS+EW	NS+EW+ TORS.
GROUND FLOOR COLUMN	AXIAL LOAD (K)	158	200	203
	BASE B.M. IN NS PLANE (KF)	608	824	841
	BASE B.M. IN EW PLANE (KF)	3	247	324
	SHEAR IN NS PLANE (K)	70	96	97
	SHEAR IN EW PLANE (K)	0	28	36
MID-HEIGHT COLUMN	AXIAL LOAD (K)	71	98	100
	BASE B.M. IN NS PLANE (KF)	250	353	369
	BASE B.M. IN EW PLANE (KF)	20	113	152
	SHEAR IN NS PLANE (K)	45	61	62
	SHEAR IN EW PLANE (K)	3	20	26

NS INPUT = TAFT 1952, N21E COMPONENT
EW INPUT = TAFT 1952, S69E COMPONENT

TABLE III

CRUCIFORM BUILDING WITH DISCONTINUOUS FRAMES

TAFT 1952 EARTHQUAKE

(CIT D-1 & D-2)

MEMBER LOCATION	MAXIMUM RESPONSE VALUE	INPUT DIRECTION		
		NS	NS+EW	NS+EW+ TORS.
GROUND FLOOR COLUMN	AXIAL LOAD (K)	125 (152)	225 (365)	225
	BASE B.M. IN NS PLANE (KF)	430 (901)	435 (904)	441
	BASE B.M. IN EW PLANE (KF)	7 (8)	365 (1087)	376
	SHEAR IN NS PLANE (K)	48 (104)	49 (105)	49
	SHEAR IN EW PLANE (K)	2 (2)	42 (128)	43
MID-HEIGHT COLUMN	AXIAL LOAD (K)	59 (136)	103 (271)	103
	BASE B.M. IN NS PLANE (KF)	230 (319)	270 (502)	272
	BASE B.M. IN EW PLANE (KF)	50 (84)	259 (684)	270
	SHEAR IN NS PLANE (K)	39 (48)	46 (63)	53
	SHEAR IN EW PLANE (K)	9 (15)	44 (108)	58

NS INPUT = TAFT 1952, N21E COMPONENT; CIT D-1
EW INPUT = TAFT 1952, S69E COMPONENT; CIT D-2

TABLE IV

CRUCIFORM BUILDING WITH CONTINUOUS FRAMES

EL CENTRO 1940 EARTHQUAKE

MEMBER LOCATION	MAXIMUM RESPONSE VALUE	INPUT DIRECTION		
		NS	NS+EW	NS+EW+ TORS.
GROUND FLOOR COLUMN	AXIAL LOAD (K)	48	58	58
	BASE B.M. IN NS PLANE (KF)	1320	1350	1370
	BASE B.M. IN EW PLANE (KF)	10	630	700
	SHEAR IN NS PLANE (K)	176	176	185
	SHEAR IN EW PLANE (K)	2	85	90
MID-HEIGHT COLUMN	AXIAL LOAD (K)	37	45	45
	BASE B.M. IN NS PLANE (KF)	1125	1125	1200
	BASE B.M. IN EW PLANE (KF)	60	350	360
	SHEAR IN NS PLANE (K)	188	188	200
	SHEAR IN EW PLANE (K)	10	58	63

NS INPUT = EL CENTRO 1940, S00E COMPONENT
EW INPUT = EL CENTRO 1940, S90W COMPONENT

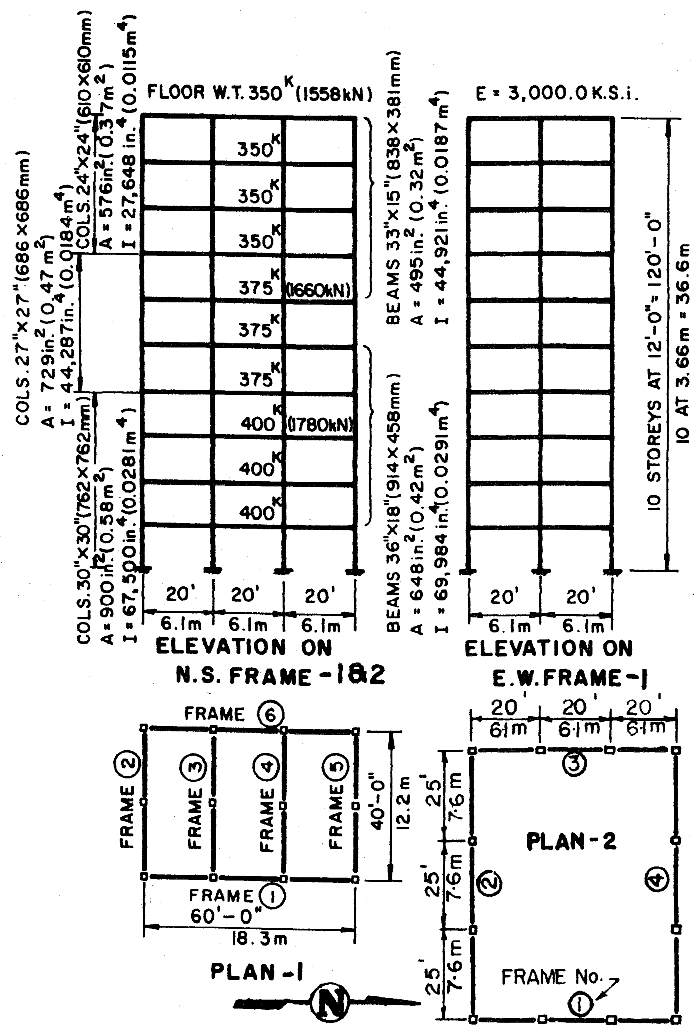

FIG. 1 DETAILS OF TEN STOREY RECTANGULAR BUILDINGS.

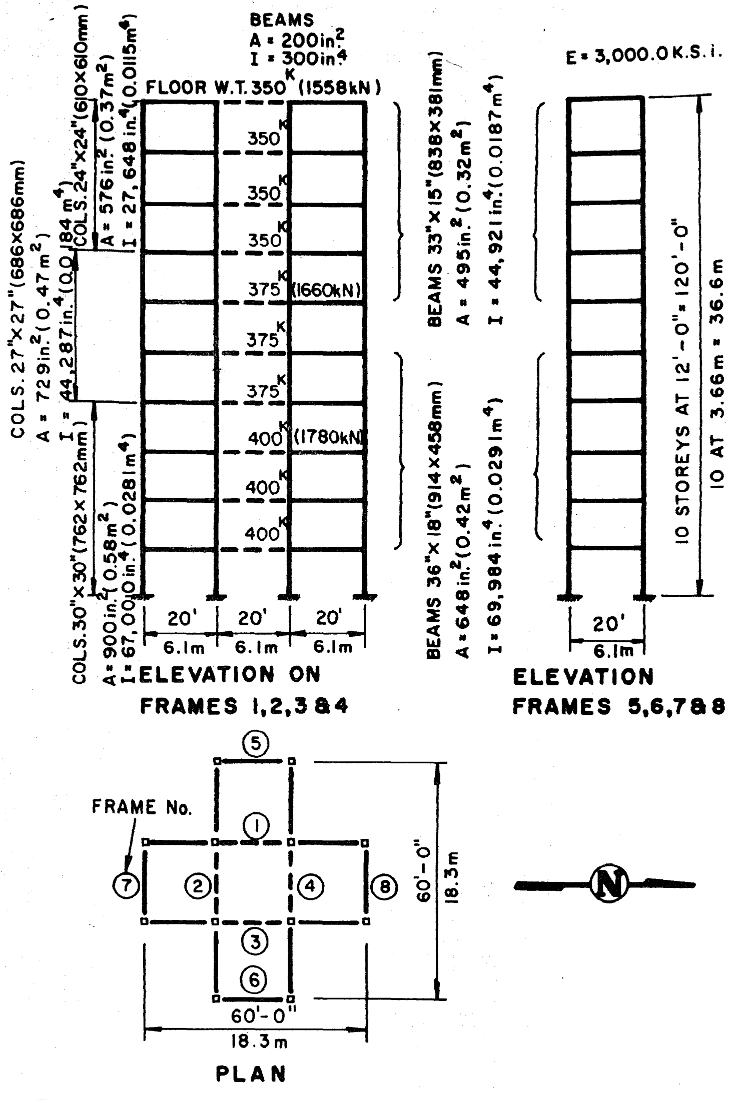

FIG. 2 DETAILS OF TEN STOREY CRUCIFORM BUILDINGS.