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AN EFFICIENT MODEL FOR PREDICTION OF THE TORSIONAL EFFECT OF MULTISTOREY BUILDING STRUCTURES

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SUMMARY

Presented in this paper is an efficient model for prediction of the torsional effect of multistory building structures subjected to an earthquake. The model is represented by an assemblage of two dimensional unit structures interconnected by a rigid diaphragm at each floor level. Torsional effect can be predicted from the first mode shape or by applying static analysis, modal analysis or time history analysis procedures to the proposed model.

INTRODUCTION

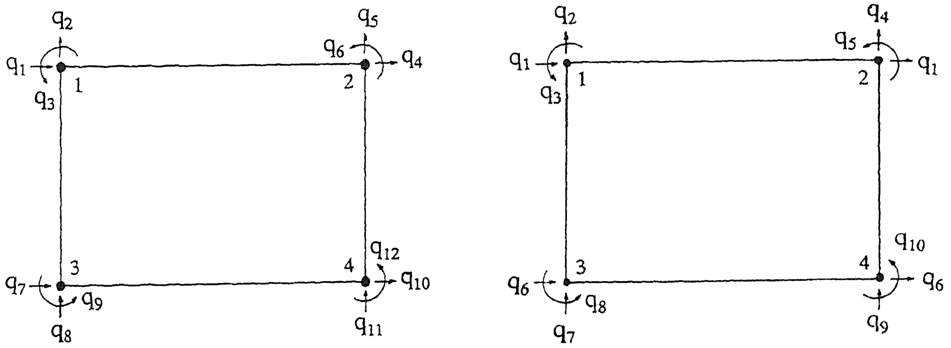
One of the principles in earthquake resistant design of multistory buildings is to reduce or eliminate the torsional effect from the seismic response of a structure. However, in many cases, multistory building structures have unsymmetric distribution of mass and/or stiffness which may result in the incorporation of the torsional effects in the response of a structure subjected to an earthquake ground motion.

In previous studies on the coupled lateral-torsional response of buildings, the response of a multistory building structure caused by an earthquake had been determined by the study of a torsionally coupled one-story system together with a torsionally uncoupled multistory counterpart of a building structure(Refs. 1,2,3). These studies included parametric studies of a one-story system to investigate the effects of torsional coupling on the response.

The objective of this study is to develop an efficient analysis model for prediction of the contribution of the torsional coupling on the response of a multistory building structure. Three parameters such as torsion ratio, torsion factor and displacement ratio are introduced for torsional effect assessment. A set of three 10 story structure with different types of torsional coupling have been used to demonstrate the use of the proposed torsional effect parameters.

DEVELOPMENT OF THE REDUCED 3D MODEL

A multistory building structure is idealized as an assemblage of a series of two dimensional (2D) frame-wall systems interconnected by a rigid diaphragm at each floor level. A plane stress element with 12 degrees of freedom (W12 element) had been modified to the W10 element with 10 degrees of freedom in the modelling of 2D systems(Fig. 1). These elements have the advantage of deformation compatibility with a 2D beam element and enhanced accuracy in the distribution of stresses(Ref. 4).



a) W12 element b) W10 element

Fig. 1 Plane Stress Elements for Shear Walls

The story-by-story matrix condensation technique is employed to obtain the stiffness matrix with one degree of freedom per floor for each 2D system. The condensed stiffness matrices are assembled into the stiffness matrix of the reduced 3D model idealizing the total structure with two lateral and one torsional degrees of freedom at each floor level. The mass lumped to each floor level in 2D models are assembled to the story mass and mass moment of inertia of the reduced 3D model.

The equation of motion for a reduced 3D model is

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = -[M]\{I\}\ddot{u}_g \tag{1}$$

where [M],[C] and [K] are mass, damping and stiffness matrices of the order of 3N×3N, in which N is the number of stories of the building. The story displacement vector {U} in Eq.(1) is constructed as follows;

$$\{U\}^T = \{ u_1, v_1, \theta_1, \ldots, u_i, v_i, \theta_i, \ldots, u_N, v_N, \theta_N \} \tag{2}$$

Where u_i and v_i are story displacements in x and y direction and θ_i is the rotation of i^{th} floor with respect to the vertical axis. The ground motion $\ddot{u}_g(t)$ is assumed to be applied in horizontal direction only. Therefore the vector {I} used to generate the seismic story force is a vector filled with unities to the degrees of freedom corresponding to the direction of applied ground motion and nulls otherwise.

TORSIONAL EFFECT PARAMETERS

Three parameters are introduced to predict and assess the torsional effect of a multistory building structure.

Torsion Ratio Torsional effect can be predicted from the first mode shape of a reduced 3D model. The first mode shape, $\{\Phi_1\}$, of a reduced 3D model is obtained in the following manner;

$$\{\Phi_1\}^T = \{ \phi_{u1}, \phi_{v1}, \phi_{\theta 1}, \ldots, \phi_{ui}, \phi_{vi}, \phi_{\theta i}, \ldots, \phi_{uN}, \phi_{vN}, \phi_{\theta N} \} \tag{3}$$

For the simplicity in calculating torsion ratios and torsion factors, the first mode shape is rearranged as follows;

$$\{\Phi_1\}^T = \{ \Phi_u, \Phi_v, \Phi_\theta \} = \{ \phi_{u1}, \ldots, \phi_{uN}, \phi_{v1}, \ldots, \phi_{vN}, \phi_{\theta 1}, \ldots, \phi_{\theta N} \} \tag{4}$$

Where Φ_u and Φ_v are translational modes in x and y direction and Φ_θ is the torsional mode. The ratio of the displacement component of the 2D system located at the farthest location from the mass center to the displacement component of the mass center is defined as the torsion ratio of each floor. Torsion ratio, λ_i, for the i^{th} floor can be calculated from the first mode shape as follows;

$$\lambda_i = \frac{\phi_{\theta i} \times d}{\phi_{yi}} \tag{5}$$

where $\phi_{\theta i}$ and ϕ_{yi} are the rotational and translational component of the first mode shape for the i^{th} floor and d is the distance from the mass center to the location of the farthest 2D system. For structures with symmetric dynamic properties, the torsion ratio of each floor will be zero.

Torsion Factor As a parameter for torsional effect prediction for a multistory building structure the average of the absolute value of torsion ratios of every floor is introduced and defined as a torsion factor. A multistory building with larger torsion factor is expected to experience larger incorporation of torsional effect in the response during an earthquake.

Displacement Ratio Torsional effect can be predicted by using the results of static analysis, modal analysis or time history analysis of a reduced 3D model. The displacement ratio defined as the maximum story displacement of each floor of a 2D system normalized by the story displacement of the corresponding reference model due to the same static loads or ground acceleration can be used to assess the torsional effects in the seismic response of a multistory building structure. A reference model is obtained by restraining the rotation of each floor in the corresponding reduced 3D model.

PERFORMANCE OF REDUCED 3D MODEL

The performance of the reduced 3D model has been verified by applying static or dynamic loads to several types of structures with different configuration and torsional coupling. Analysis results obtained using reduced 3D models and 3D finite element models were in such good agreement that the maximum difference of story displacement in all the cases studied was less than 2 percent. A five story structure shown in Fig. 2 is used as an example for the assessment of the performance of the reduced 3D model. Vibration frequencies of the example structure obtained using the reduced 3D model and a 3D finite element model are listed in Table 1.

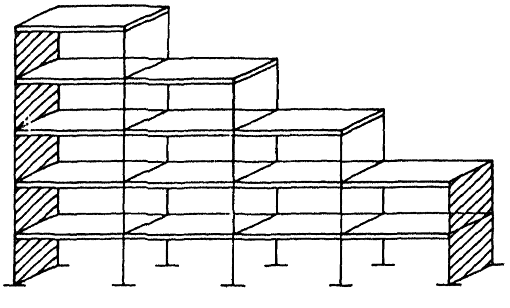


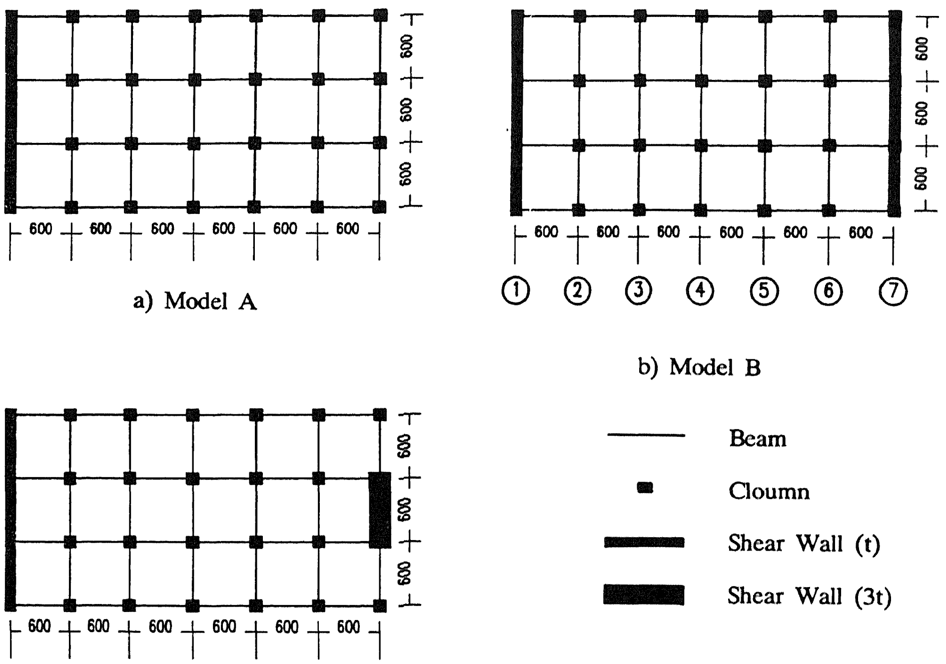
Fig. 2 Five Story Structure

Table 1 Frequencies Obtained Using The Reduced 3D Model and A 3D Finite Element Model. (Hz)

Mode No.	Reduced 3D Model	Finite Element Model
1	0.0570	0.0570
2	0.1017	0.1052
3	0.1372	0.1411
4	0.1963	0.2028
5	0.2687	0.2687
6	0.3118	0.3235
7	0.4426	0.4426
8	0.8072	0.7826
9	0.9101	0.8890
10	1.4372	1.4102

EFFECT OF TORSIONAL COUPLING

Example Structures Plans of three types of ten-story building structures used as examples for the prediction of torsional effect are shown in Fig. 3. They are reinforced concrete structures with 6-bays in x-direction and 3-bays in y-direction. Shear walls are added to moment resisting frames to increase the lateral resistance. When the shear wall is located at only one side of the structure as model A, the seismic response will be significantly influenced by the torsional effect. The model A is modified to models B and C to reduce the torsional effect on the seismic response. Model B is a symmetric structure with two identical shear walls located at both sides of the structure. Thus no torsional effect is expected for this model when ground motion or seismic load is applied in y-direction only. Another type of torsional effect reduction is represented by the model C which is obtained by adding a shear wall at the other side of the structures. The shear wall added to model C has three times of thickness and one third of length of the existing wall. In this case the torsional effect will be reduced significantly. However there will be minor torsional effect remaining because of the difference of shear and bending resistance of the walls located at both ends.



a) Model A

b) Model B

c) Model C

Fig. 3 Example Structures

Applied Loads The example structures had been idealized as reduced 3D models and torsional effect prediction were performed by static analysis, modal analysis, and time history analysis. Equivalent static loads have been determined according to the Uniform Building Code('88) for each model. The ground acceleration record used for time history analysis is the S00E component of the El Centro earthquake of 1940. The spectrum used for modal analysis was obtained from the same El Centro earthquake records. Since the major interest of present study was prediction of the torsional effect, the ground acceleration records were used without any modification.

Results Listed in Table 2 are rearranged first mode shape of three models. Since the model B is a symmetric structure, the translational mode is uncoupled to the rotational mode. Torsion ratios and torsion factors obtained from the first mode shapes are compared to those obtained from time history analysis of reduced 3D models in Table 3. Torsional effects on seismic response of example structures are shown in Figs. 4,5,6,7 in terms of displacement ratios. Torsional effects predicted using modal analysis procedure are reasonably close to those obtained from time history analysis in all cases while the prediction by static analysis procedure exaggerated torsional effect significantly. The exaggeration of torsional effect prediction by static analysis procedure is considered to be caused by the fact that the effect of the mass moment of inertia of each floor is ignored in static analysis.

Table 2 Rearranged First Mode Shape of Each Model

	Translational Mode $\{\Phi_v\}$			Torsional Mode $\{\Phi_\theta\}$		
Story	Model A	Model B	Model C	Model A	Model B	Model C
10	1.0000000	1.0000000	1.0000000	.0005498	.0000000	.0004437
9	.9474432	.8839092	.8690580	.0005213	.0000000	.0003838
8	.8518338	.7635506	.7367398	.0004689	.0000000	.0003237
7	.7545169	.6410644	.6054244	.0004155	.0000000	.0002643
6	.6336013	.5188088	.4774993	.0003490	.0000000	.0002069
5	.5199410	.4003795	.3568069	.0002865	.0000000	.0001530
4	.3941984	.2889997	.2467817	.0002173	.0000000	.0001044
3	.2772825	.1889226	.1518645	.0001529	.0000000	.0000629
2	.1579881	.1039162	.0759837	.0000872	.0000000	.0000303
1	.0571102	.0384823	.0236477	.0000315	.0000000	.0000087

Table 3 Torsion Ratio Obtained from The First Mode Shape and Time History Analysis

	First Mode Shape			Time History Analysis		
Story	Model A	Model B	Model C	Model A	Model B	Model C
10	.989	.000	.798	1.144	.000	.850
9	.990	.000	.794	1.111	.000	.839
8	.990	.000	.790	1.014	.000	.823
7	.991	.000	.785	0.924	.000	.812
6	.991	.000	.779	0.900	.000	.795
5	.991	.000	.772	0.905	.000	.780
4	.992	.000	.761	0.917	.000	.757
3	.992	.000	.745	0.933	.000	.722
2	.993	.000	.718	0.941	.000	.662
1	.993	.000	.660	0.941	.000	.531
Torsion Factor	.991	.000	.760	0.973	.000	.757

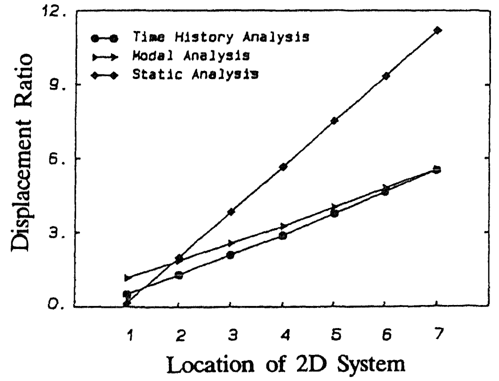


Fig. 4 Torsional Effect at 10th Floor (Model A)

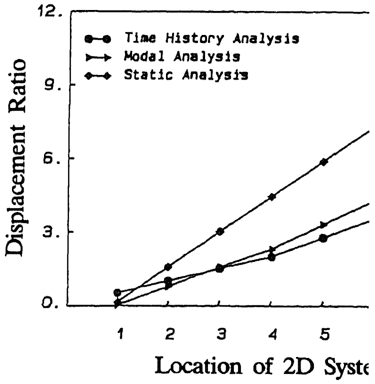


Fig. 5 Torsional Effect at 5th Flo

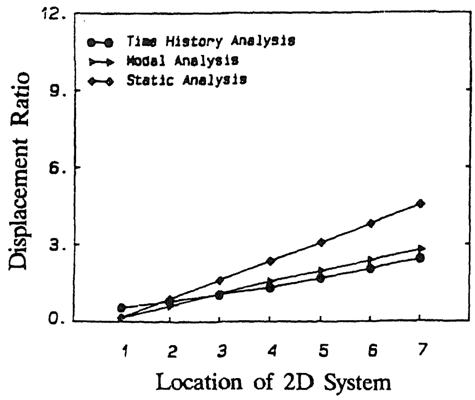


Fig. 6 Torsional Effect at 10th Floor (Model C)

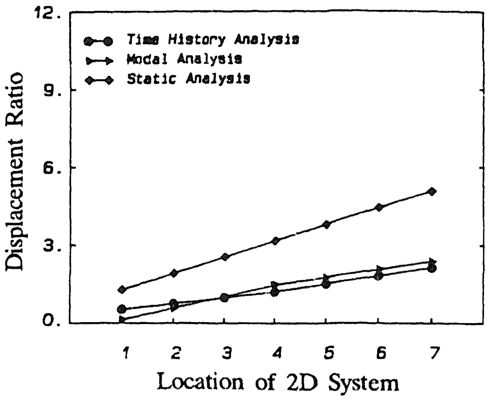


Fig. 7 Torsional Effect at 5th Floor (Model C)

CONCLUSIONS

Prediction of torsional effect can be performed with the advantage of significant reduction in computation time and memory size required by using the reduced 3D model proposed in this study. Torsion ratio and torsion factor obtained from the first mode shape can be useful parameters for the preliminary prediction of the torsional effect and displacement ratio obtained from the results of modal analysis can be a simple measure of torsional effect in a multistory building structure. The use of static analysis turned out to be not adequate for torsional effect prediction because static analysis can not account for the torsional dynamic properties of a structure.

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