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VERIFYING THE LOCATION OF THE OPTIMUM TORSION AXIS OF MULTI-STORY BUILDINGS USING DYNAMIC ANALYSIS

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SUMMARY

The determination of the optimum torsion axis, the principal directions and the torsional stiffness radii of multistory buildings is a significant issue in the application of the simplified methods of seismic analysis. The above concepts have been discussed in previous articles (Makarios and Anastassiadis 1998a,b) [1], [2]. In the present work a numerical verification of the above concepts is achieved using static, modal and response as well as linear dynamic time-history analysis with accelerograms of different frequency content.

INTRODUCTION

The static eccentricity, the principal elasticity axes I and II and the torsional stiffness radii ρ_I, ρ_{II} of a system are defined in the single-story buildings and in special categories of multistory buildings such as the isotropic, orthotropic and shear systems, as well as systems consisting of homoaxonnic isotropic subsystems (Riddell and Vasquez 1984; Anastassiadis 1985; Makarios and Anastassiadis 1998a,b) [3],[4],[1],[2]. The above concepts constitute characteristic signs of the structure, which depend exclusively on the elastic and geometric data of the system. The static eccentricity, the principal elasticity axes I and II and the torsional stiffness radii of a system play a predominant role for the documented application of the simplified modal analysis of a seismic design which is proposed by the modern seismic Codes (Greek Seismic Code of 2003 (EAK-2003), Eurocode No8-98, NBCC-95). Also, the dynamic behavior of spatial systems depends on the above characteristics. Indeed, buildings having zero static eccentricity (coincidence of mass center CM with elastic center CR) exhibit along the principal directions I and II of the system, a complete uncoupling of the translational vibrations from the torsional vibrations of the diaphragms, while buildings with a small torsional stiffness radius and simultaneously with a small static eccentricity exhibit a strong predominance of the torsional vibration of the stories compared with the translational ones (Anastassiadis et al. 1998) [5]. The research efforts to extend the above concepts to multistory systems resulted in the following:

a. It was proved that multistory systems have not generally (except of the mentioned special cases) a vertical elastic axis or principal vertical bending planes and consequently it is not possible to define their torsional stiffness radius. The definitions of the shear torsional stiffness centers of the stories have been proved depending on the external static loading (Cheung and Tso 1986; Hejal and Chopra 1987) [6],[7].

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b. In every multistory asymmetric system, which has the required by the Codes regularity along its height, the axis of optimum torsion is defined, that is a vertical axis with the property that if the vertical loading plane of all the lateral static seismic forces is placed on this axis, then the torsion, in the whole system, is minimized (Makarios and Anastassiadis 1998a,b) [1],[2]. In this case, the rotations of the stories become negligible and consequently, within the limits of the usual approximations accepted by the simplified methods of seismic analysis, it can be assumed that the system is subjected to a translation without rotation. Also, we can find the horizontal principal directions of the building, perpendicular to each other, which approximate as much as possible the properties of the horizontal principal elasticity axes I and II. Consequently, in mixed (frame-wall) multistory asymmetric systems, the axis of optimum torsion can be considered as playing the same role of the vertical elastic axis according to the documented application of the simplified modal analysis of seismic design.

METHODOLOGY

In the present work, and among a lot of investigated cases, a ten-story mixed (frame-wall) system of single-symmetry was chosen for presentation (fig. 1). Then, the location on the plan, of the vertical z-axis of optimum torsion P_o, is determined, as well as the principal directions and the torsional stiffness radii of the system. The numerical verification of the state of optimum torsion follows by use of four different methodologies.

In the first methodology, static analysis is used and it is verified by a parametric analysis that the torsion of the system is minimized by imposing the static loading of horizontal forces of stories upon the z-axis of optimum torsion P_o.

In the second methodology, modal analysis of the system is performed and the points of application of the seismic inertia forces of the stories are determined for the fundamental coupled mode of the system. The application points of the lateral inertia seismic forces, justify the imposing of seismic loading by use of equivalent static eccentricities (dynamic eccentricities), which are defined by the simplified methods of a seismic analysis (NBCC-95, EAK-2003, Anastassiadis et al. 1998) [5]. Also, it is numerically verified that when the mass centers CM of all the stories coincide with the point P_o of the plan, from which the vertical axis of optimum torsion passes, then a very weak coupling of the torsional vibration of the floors with the translational ones appears, that is the systems mainly vibrates in translation.

In the third methodology, response spectrum analysis in used by a plateau design acceleration spectrum of EAK-2003. The resulting diagrams of the maximum (non-simultaneous) dynamic displacements of the stories completely justify the location of the optimum torsion z-axis P_o.

Finally, in the fourth methodology, a linear dynamic time-history analysis is performed with three accelerograms of different frequency content. The maximum results from these analyses are obtained according to the section 1631.6.1 of UBC-1997. The resulting diagrams of the maximum (non-simultaneous) dynamic time-history story displacements, also justify the location of the optimum torsion z-axis P_o.

ANALYSIS

General

The ten-story system of single symmetry in figure 1, has the following geometric and elastic characteristics (SI units): Building height H =10×3.00m = 30.0m, columns of a constant section (0.50m)×(0.50m) in all the stories, structural walls of a constant section (0.25m)×(4.50m) in all the stories, inertia moment of beam sections $I_b = 0.006m^4$, elasticity modulus E = 29Gpa, seismic design acceleration $R_d(T) = 0.171 \cdot g$ for every period T (plateu design spectrum), story mass M = 375.0 t (SI) and mass inertia moment J_m around a vertical axis passing through the mass center CM, J_m = 32562.5 tm^2. The mass center CM of the stories does not coincide with the geometric center of the diaphragm, but it has coordinates (8.50, 0.00) in the reference axes Oxyz (fig. 1).

This mixed (frame-wall) ten-story system of single-symmetry is considered as formed by the superposition of two spatial subsystems, the bending subsystem and the shear one, which co work with each other by means of the diaphragm behavior of its stories. By assuming that, these subsystems maintain invariable, elastic and geometric characteristics along their height, then we can always define in them the corresponding elastic centers CR and CS.

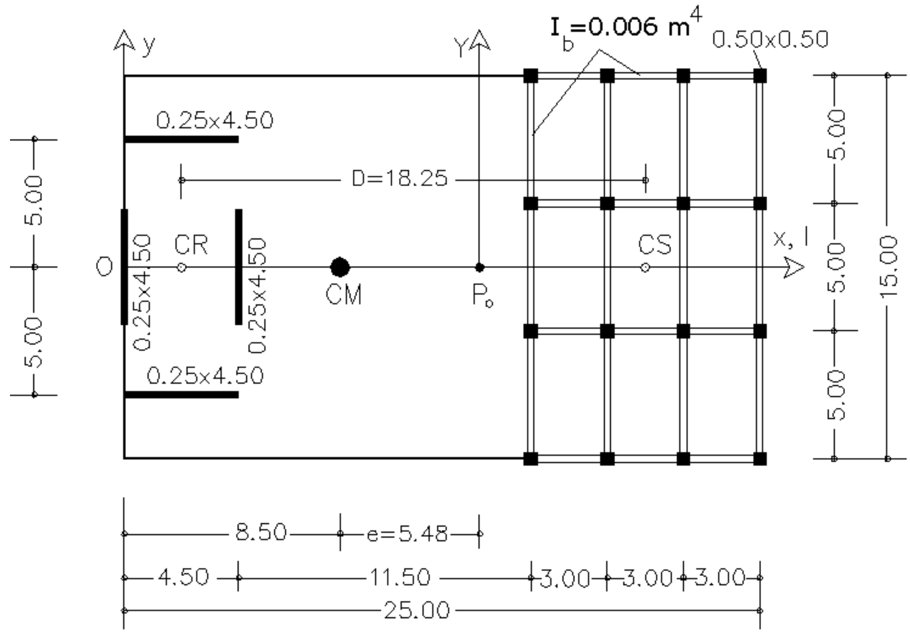


Figure 1: Plan of the ten-story system

The optimum torsion axis is determined by the static analysis of the system. We assume that all the lateral external static forces lie on the same vertical loading plane and follow a triangular distribution over building's height. From previous investigations, it has been noticed that the distribution of the horizontal static forces over building's height (triangular or uniform or according to fundamental mode) has a minimal affect on the location of the z-axis of optimum torsion P_o in the plan (Makarios and Anastassiadis 1998a, b) [1],[2]. By imposing the loading plane of vector **F** of the forces F_i within the interval $\overline{(CR)(CS)} = D$, perpendicularly to the symmetry axis x of the system, it results that the story rotations of the bending subsystem around the CR have opposite trend from the story rotations of the shear subsystem around the CS (fig. 2). So there is, at the maximum possible degree, a competition operation of the two subsystems during the torsion of the system. This competition operation is attributed on one hand, to the different torsion type (bending versus shear) of the two subsystems and, on the other hand, to the opposite trend rotations they have to each other. In this case, it has been pointed out that it is always possible for the rotation around a vertical axis within a story level to have a zero value, and consequently the story levels lying above the level of zero rotation, rotate with opposite trend from all the rest of story levels of the system (Makarios and Anastassiadis 1998a) [1]. In order to minimize the rotation of the system, that is to achieve the state of optimum rotation, it has been proposed, as a most appropriate criterion, to minimize the quantity $\overline{\theta}^2$ (Makarios and Anastassiadis 1998a) [1]:

$$\overline{\theta}^2 = \left(\theta_1^2 + \theta_2^2 + \ldots + \theta_N^2\right)/N \qquad (1)$$

where θ_i the rotation of story level i (i = 1,2, … , N) and N the number of stories. The formula (1) is approximately satisfied when the rotation becomes zero at the level z_o = 0.8H of the system. The location of the optimum torsion axis always lies within the interval D. As the interval D becomes smaller, the state of optimum torsion approximates to the state of zero torsion, which appears in the limit state of CR coinciding with CS.

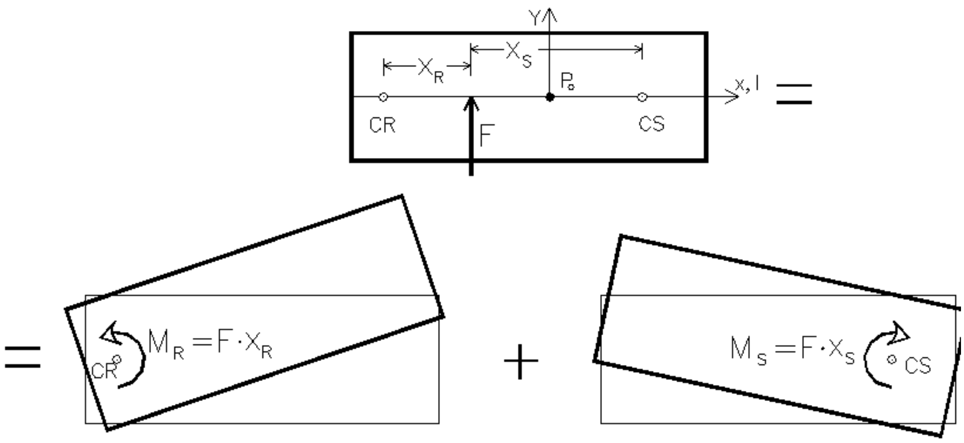


Figure 2: The competitive torsion of the two subsystems

The axis of optimum torsion satisfies the following limit conditions:

a. Its location within the plan always approaches the stiffness center of the corresponding, with respect to the plan, single-story system (that is, when in the regular over its height frame-wall multistory system, the number of stories is gradually reduced) and coincides with CR in the limit case that the multi-story system turns to a single-story one.

b. Its location within the plan always approaches the elastic center CR of the respective bending subsystem, as the structural walls in the mixed multi-story system increase and coincides with the CR when the system turns to a completely bending one (isotropic).

c. Its location within the plan always approaches the elastic center CS of the respective shear subsystem, when the structural walls are successively removed from the mixed multi-story system and coincides with CS when the building turns to a completely shear one (isotropic).

d. By the increase of stories number, the location of the optimum torsion axis approaches the elastic center CS of the shear subsystem, because more and more the shear subsystem predominates compared to the bending one.

Determination of the optimum torsion axis

At the beginning of the analysis, the principal directions of the building and the respective base shear forces are unknown. For this reason, we choose an arbitrary right-rotating system of reference axes Oxyz and give to the base shear an arbitrary value e.g. V_o = 10000kN, which is triangularly distributed over building's height, thus determining the story forces F_i. Then, the vector **M** of twisting moments of same sign is formed, which result as couples of the above forces with a unit lever arm ($M_i = 1 \cdot F_i$):

$M_{10} = 1 \cdot F_{10} = 1818.18$ kN·m	$M_5 = 1 \cdot F_5 = 909.09$ kN·m
$M_9 = 1 \cdot F_9 = 1636.36$ kN·m	$M_4 = 1 \cdot F_4 = 727.27$ kN·m
$M_8 = 1 \cdot F_8 = 1454.55$ kN·m	$M_3 = 1 \cdot F_3 = 545.45$ kN·m
$M_7 = 1 \cdot F_7 = 1272.73$ kN·m	$M_2 = 1 \cdot F_2 = 363.64$ kN·m
$M_6 = 1 \cdot F_6 = 1090.91$ kN·m	$M_1 = 1 \cdot F_1 = 181.82$ kN·m

From the loading of the spatial system by the vector **M**, the displacements of point 0 (0.0, 0.0, 24.0) that is of 8th story result (z_o = 0.80H):

u_{x8}	0.0 m
u_{y8}	- 0.0136415 m
θ_{z8}	0.0009756 rad

The vertical axis of optimum torsion of the building passes through the pole of twist with coordinates P_o (X_p, Y_p) of the level z_o = 0.80H:

$$X_p = -\frac{u_{y8}}{\theta_{z8}} = -\frac{-0.0136415}{0.0009756} = +13.98267733\text{m}\,, \qquad Y_p = +\frac{u_{x8}}{\theta_{z8}} = +0.0\text{m} \qquad (2)$$

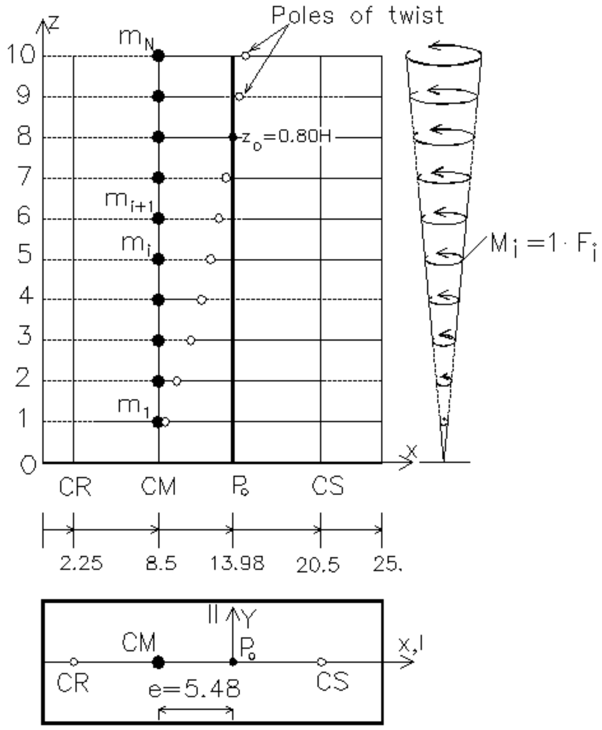


Figure 3: Poles of twist of the stories for the loading vector M

In the figure 3, are shown the poles of twist of the stories for the loading of the system by the vector **M**. We observe that the poles do not lie all on a vertical line, because the system has not a real elastic axis, however they always lie within interval D. If the system has a real elastic axis, then the poles of twist under consideration will all lie upon same axis.

Loading along direction x – x

The forces F_i are imposed on the vertical axis, which passes through the point P_o (X_p, Y_p) with direction x – x. The displacements of point P_o of level $z_o = 0.80H$, because of this loading are:

$$u_{xx} = 0.100371\text{m}, \qquad u_{yx} = 0.0\text{m}$$

Loading along direction y – y

The forces F_i are imposed on the vertical axis passing through point P_o (X_p, Y_p) with direction y – y. The displacements of point P_o at level $z_o = 0.80H$, because of this loading are:

$$u_{yy} = 0.1166308\text{m}, \qquad u_{xy} = 0.0\text{m}$$

Principal directions of the building

The angle a formed by the principal axis I with the axis x – x of reference system Oxyz is given by the formula:

$$\tan 2a = \frac{2 \cdot u_{xy}}{u_{xx} - u_{yy}} = 0 \quad \Rightarrow \quad a = 0° \tag{3}$$

That is, the principal axis I coincides with the axis x and this was expected because the axis x –x is a symmetry axis of the system.

The static eccentricity of the building along the principal direction I results geometrically equal to $e = X_p - X_m = 13.98 - 8.50 = 5.48$ (fig. 1).

Radii of torsional stiffness ρ_I, ρ_{II}

The two torsional stiffness radii of the ten-story system are determined along the principal directions I and Y ($Y \cong II$). From the loading by forces F_i along direction I, level $z_o = 0.80H$ is subjected to a clear translation equal to u_I ($\xi = 0.8$) = 0.100371m along direction I. From loading by forces F_i along direction II, level $z_o = 0.80H$ is subjected to a clear translation equal to u_{II} ($\xi = 0.8$) = 0.1166308m along direction II. Also, from the initial loading of the system by the vector **M**, level $z_o = 0.80H$

rotates by θ_z (ξ = 0.8) = 0.0009756 rad. Consequently, the two torsional stiffness radii ρ_I , ρ_{II} of the building along the principal directions I and II are:

$$\rho_I = \sqrt{\frac{u_{II}(\xi=0.8)}{\theta_z(\xi=0.8)}} = \sqrt{\frac{0.1166308}{0.0009756}} = 10.93\text{m} \quad (4a)$$

$$\rho_{II} = \sqrt{\frac{u_I(\xi=0.8)}{\theta_z(\xi=0.8)}} = \sqrt{\frac{0.100371}{0.0009756}} = 10.14\text{m} \quad (4b)$$

In order to investigate the torsional sensibility of the building, we express the torsional stiffness radii with respect to mass center CM of the building and compare them with the inertia radius r of the diaphragm (Anastassiadis et al. 1998) [5]:

$$\rho_{I,m} = \sqrt{\rho_I^2 + e_x^2} = \sqrt{10.93^2 + 5.48^2} = 12.23 > r = 9.32 \quad (5a)$$

$$\rho_{II,m} = \sqrt{\rho_{II}^2 + e_y^2} = \sqrt{10.14^2 + 0.0^2} = 10.14 > r = 9.32 \quad (5b)$$

where $r = \sqrt{J_m / m} = \sqrt{32562.5/375} = 9.32\text{m}$.

Because the two torsional stiffness radii, expressed with respect to mass center are larger than the inertia radius r of the diaphragm, it results that the building is stiff in torsion.

Uncoupled Periods

Generally, in order to determine the base shear for every principal direction it is required to find the corresponding uncoupled fundamental periods of the system. For this reason, all the degrees of freedom of all the stories are fixed, except for the translational one along the direction under consideration. So, the eigenperiods result respectively T_I = 0.998sec and T_{II} = 1.010sec. In the example under consideration, we assume a spectral seismic acceleration $R_d(T)$ = 0.171·g for every period (plateau spectrum) and consequently the base shears along the principal directions are:

$$V_{o,I} = m_{tot} \cdot R_d(T) = (10 \cdot 375) \cdot (0.171 \cdot 9.81) = 6290.66\text{kN} \quad (6a)$$

$$V_{o,II} = m_{tot} \cdot R_d(T) = (10 \cdot 375) \cdot (0.171 \cdot 9.81) = 6290.66\text{kN} \quad (6b)$$

By triangularly distributing the base shears (eq. 7) we obtain the components F_i of the vector **F** of the static seismic forces, which are the same in both principal directions:

$$F_i = V_o \cdot \frac{z_i}{\sum_{1}^{i=N} z_i} \quad (7)$$

where z_i is the distance of story i from the ground, that is:

F_{10}=	1143.76 kN·m	F_5 =	571.88 kN·m
F_9 =	1029.38 kN·m	F_4 =	457.50 kN·m
F_8 =	915.01 kN·m	F_3 =	343.12 kN·m
F_7 =	800.63 kN·m	F_2 =	228.75 kN·m
F_6 =	686.25 kN·m	F_1 =	114.38 kN·m

Verification of the optimum torsion

When the lateral static seismic forces which lie all on the same loading plane pass through the point P_o, then the state of optimum torsion of the N-story building is realized because the quantity $\overline{\theta}^2$ is minimized according to eq. 1. For various positions of vertical loading planes of vector **F** perpendicular to axis x, the rotations θ_i of the stories excessively increase, having as consequence the increase of the quantity $\overline{\theta}_x^2$ (eq. 1). In figure 4, the variation of quantity $\overline{\theta}_x^2$ is shown for the specific building.

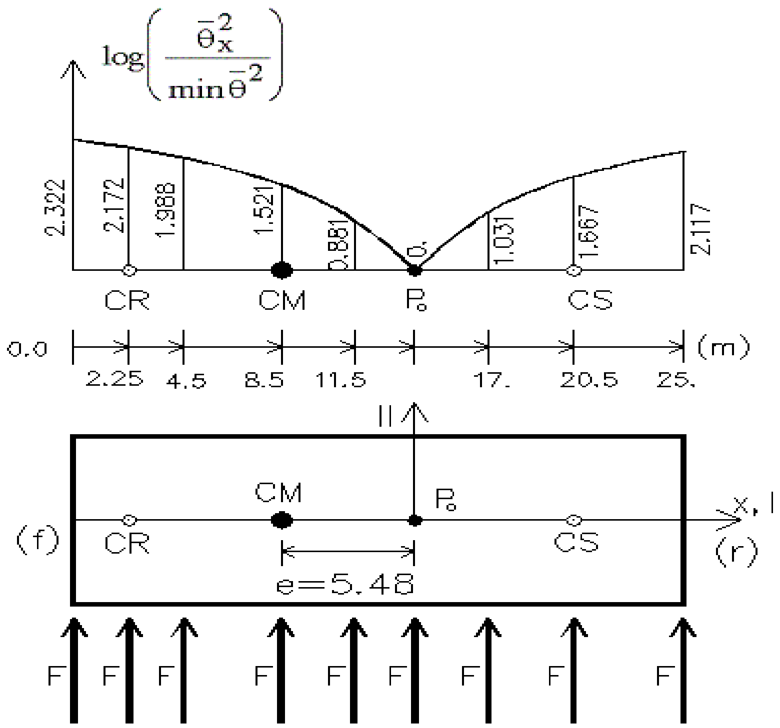


Figure 4: Distribution of the quantity $\overline{\theta}_x^2$

The minimization of the quantity $\overline{\theta}_x^2$ indeed occurs in a near region close the point P_o. So, when the loading plane of vector **F** is imposed on the mass center CM then the magnitude $\overline{\theta}_x^2$ grows 33 times, because it holds (fig. 4):

$$\log\left(\frac{\overline{\theta}_x^2}{\min\overline{\theta}^2}\right)=1.521 \Rightarrow \overline{\theta}_x^2=33.2\cdot\left(\min\overline{\theta}^2\right)$$

The maximum deviation of the quantity $\overline{\theta}_x^2$ appears by imposing the loading plane of vector **F** on the perimeter of the flexible side of the building in which case it takes a value about 210 times larger than the minimum one, because it holds (fig. 4):

$$\log\left(\frac{\overline{\theta}_x^2}{\min\overline{\theta}^2}\right)=2.322 \Rightarrow \overline{\theta}_x^2=209.89\cdot\left(\min\overline{\theta}^2\right)$$

Optimum translational vibration

The weakest coupling of translational vibrations with torsional vibrations of the floors is realized when the magnitude $\overline{\varphi}_{z,x}^2$ is minimized:

$$\overline{\varphi}_{z,x}^2=\frac{\varphi_{z1}^2+\varphi_{z2}^2+\ldots+\varphi_{zN}^2}{N} \tag{8}$$

where φ_{zi} is the torsional component of the fundamental mode shape of story (i) and N the stories number of the building. In figure 5, the variation of magnitude $\overline{\varphi}_{z,x}^2$ for various positions x of the vertical mass axis is shown. The magnitude $\overline{\varphi}^2_{z,x}$ is minimized when the vertical mass axis of the building coincides with the optimum torsion axis P_o,z. In this case, the state of optimum translational vibration appears and the results are in a complete analogy with those holding for the single-story building (when the center of stiffness coincides with the mass center CM, then we have uncoupling of the translational vibrations from the torsional ones). The appearance of optimum translational vibration in this case completely justifies the definition of static eccentricity in the multi-story system, which is defined as the horizontal distance of the vertical mass axis from the optimum torsion axis.

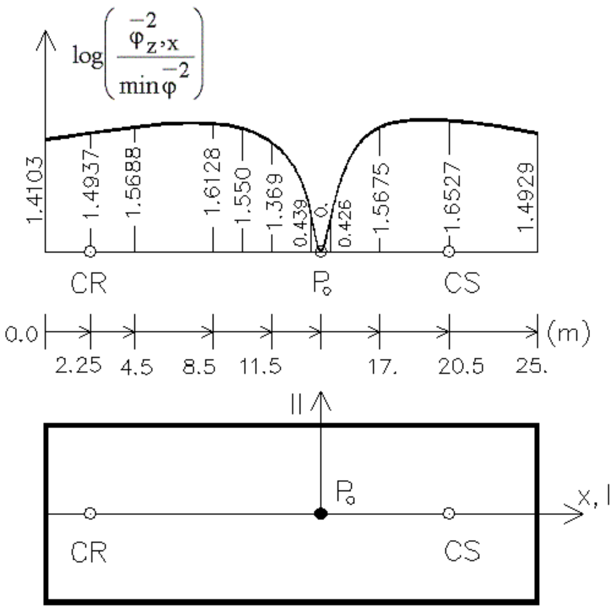


Figure 5: Variation of the magnitude $\overline{\varphi}^2_{z,x}$

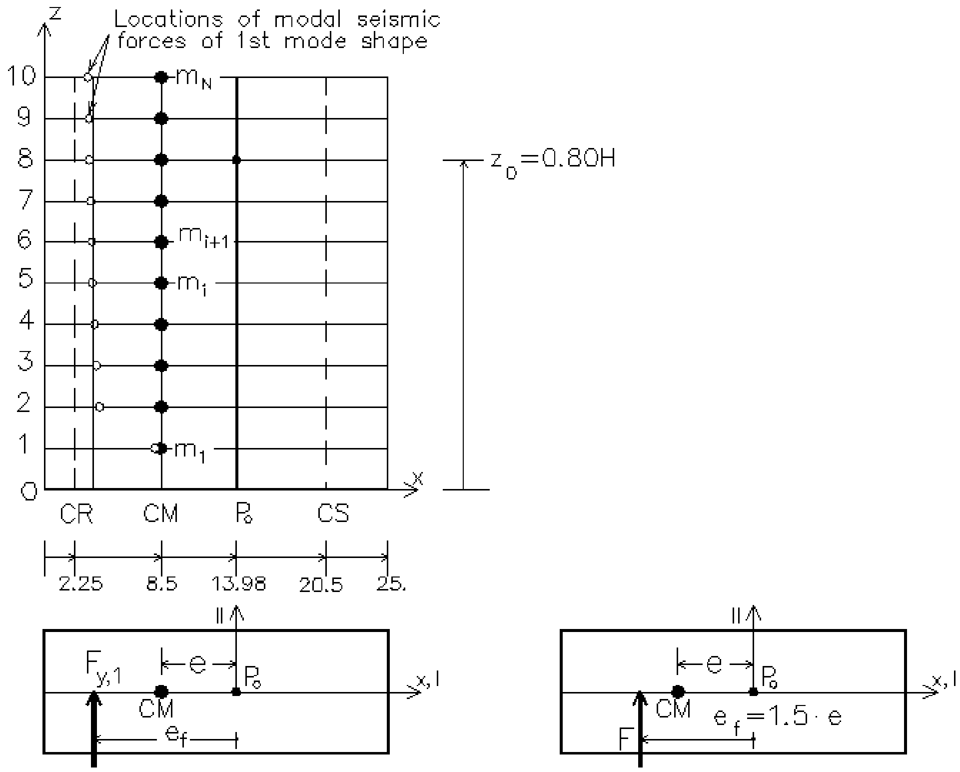
Application points of the modal seismic forces

The modal seismic forces are given by the following formula for any mode shape i :

$$\mathbf{P}_i = \nu_i \cdot (\mathbf{M}\boldsymbol{\varphi}) \cdot S_{ai} = \begin{bmatrix} F_{xN} \\ F_{yN} \\ M_{zN} \\ \cdots \\ F_{y1} \\ M_{z1} \end{bmatrix} = \nu_i \cdot \begin{bmatrix} m \cdot \varphi_{xN} \\ m \cdot \varphi_{yN} \\ J_m \cdot \varphi_{zN} \\ \cdots \\ m \cdot \varphi_{y1} \\ J_m \cdot \varphi_{z1} \end{bmatrix} \cdot S_{ai}, \qquad i = 1, 2, \dots 3N \tag{9}$$

Consequently, the ratio $e_{ik} = \frac{M_{zk}}{F_{yk}} = \frac{\varphi_{zk}}{\varphi_{yk}} \cdot r^2$ gives the position of the modal seismic forces on the k-th story of the system (1, 2, … k, … N).

In figure 6, the positions of modal seismic forces of the fundamental (1^{st}) coupled mode shape are shown, which lie at left of mass center CM and approximately on a vertical line (fig. 6a). This fact justifies the imposing of static seismic forces at a distance $e_f = 1.50 \cdot e$ from the elastic center (fig. 6b) according to the simplified modal analysis (NBCC-95, EAK-2003, Anastassiadis et al. 1998) [5]. Also, it results that, for all the stories, the flexible part of the building is the left one, in spite of the fact that at this side all the structural walls are concentrated. This fact is due to the relative stiffness of the bending subsystem of the building with respect to the shear one.



a. b.

Figure 6a: Positions of the modal seismic forces in the fundamental (1st) coupled mode shape. 6b: Position of static seismic forces according to NBCC-95 and EAK-2003

Response spectrum analysis

In the building of figure 1 a response spectrum analysis was performed for translational excitation of the base perpendicularly to the symmetry axis of the system and the probable largest elastic displacements of the stories (CQC) were computed, by use of a plateau design acceleration spectrum obtained from EAK-2003. In figure 7, the diagrams of maximum (non-simultaneously) displacements u_y at every point of the plan for two different positions of the mass centers CM of stories are given.

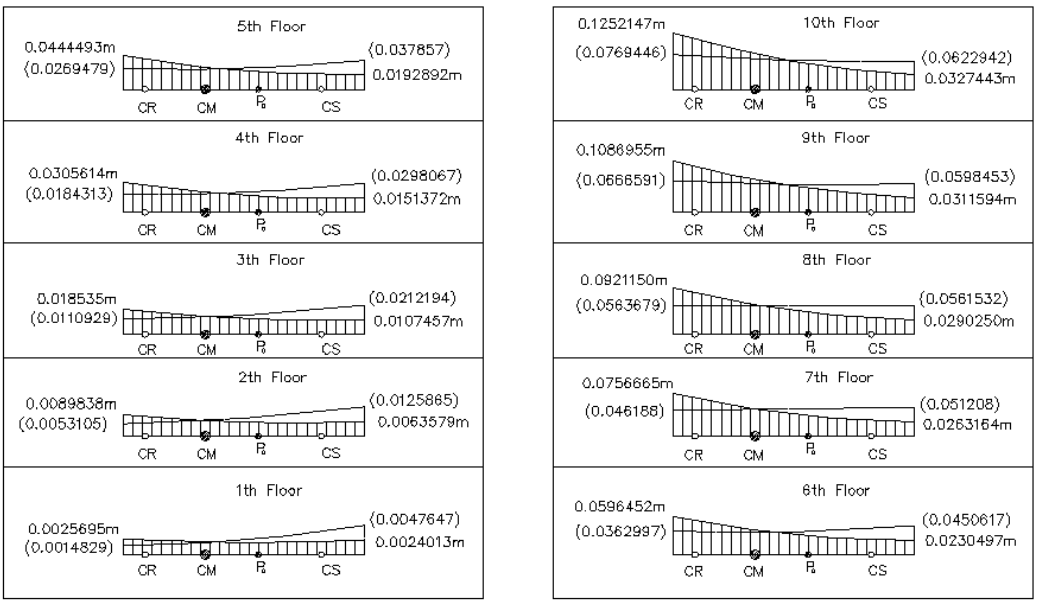


Figure 7: Diagrams of largest probable non-simultaneous displacements (in m) of the stories derived from a response spectrum analysis

1st case: The mass centers of the floors lie at position (8.5, 0.0) (shadowed area in figure 7). The translational mass of the stories is M = 375.0 t (SI), whereas the mass inertia moment around the vertical axis passing through the mass center CM is J_m = 32562.5 tm^2. We observe that the left side of all the stories exhibits a larger displacement than the right one and, for this reason, it is characterized as flexible, whereas the right one as stiff. This conclusion is fully compatible with the location of the optimum torsion axis.

2nd case: The mass centers CM of the floors coincide with the optimum torsion axis at point P_o (values within parentheses in figure 7). The translational mass of the stories is M = 375.0 t, whereas the center CM is now J_m = 27386.88 tm^2. We observe that, in this case, there is mainly a translational vibration without significant rotations in the floors. This conclusion proves the correspondence of the location P_o of the optimum torsion axis with the center of stiffness of the single-story building and thus, we conclude that the axis of optimum torsion can be used for the definition of static eccentricity in multi-story buildings by playing the same role as a real elastic axis in the application of the simplified spectrum method of seismic design.

Linear dynamic time-history analysis

For the needs of present study, a linear dynamic time-history analysis was also performed using three different accelerograms, of different frequency content, which are shown in Table 1. The results for displacements presented in figure 8 refer to the maximum appearing values from the three linear dynamic time-history analyses according to the section 1631.6.1 of UBC-1997. All three accelerograms were assumed to act along the y-horizontal direction and time-history analyses were performed, whereas, for comparison reasons, no second seismic component was used simultaneously along the other direction of the building. The floor displacements resulting from each time-history analysis were normalized with respect to the maximum displacement of the optimum torsion axis P_o at the top of the building. In figure 8, the maximum horizontal normalized displacement of the floors is presented, for the two different cases of the position of vertical mass axis (as already shown in the previous section of "response spectrum analysis"). Within a parenthesis, the normalized maximum displacements of the floors in the case that the vertical mass axis coincides with the optimum torsion axis are shown, whereas by shadowing and values without parenthesis, the respective normalized maximum displacements in the case that the vertical mass axis lies at the position (8.50, 0.00) are shown.

1st case: The vertical mass axis is located at the position (8.50, 0.00), (displacement envelope by shadowing in fig. 8 and values without parenthesis). We observe that the left side of the stories lying above the level z_o = 0.8H exhibits a larger displacement than the right side.

2nd case: The vertical mass axis coincides with the optimum torsion z-axis P_o (values in parenthesis of fig. 8). From the picture of displacements, we observe that, in this case, the building is mainly subjected to translation, with no intensive torsional vibrations. In other words, in the case that the vertical mass axis coincides with the optimum torsion axis, we approach the optimum global translational vibration of the building.

Table 1: Accelerograms

	Earthquake, Location, Date, Magnitude	Recording Station of Main Earthquake	Peak Ground Acceleration	Orientation of Horizontal Seismic Component
1	Lefkada, Greece, 14.08.2003, M = 6.4	Hospital of Lefkada	PGA = 0.416 g	N335E
2	Kobe, Japan, 16.01.1995, M = 6.9	OKJMA	PGA = 0.821 g	h0
3	Northridge, USA, 17.01.1994, M = 6.7	24278 Castaic-Old Ridge Route	PGA = 0.514 g	h360

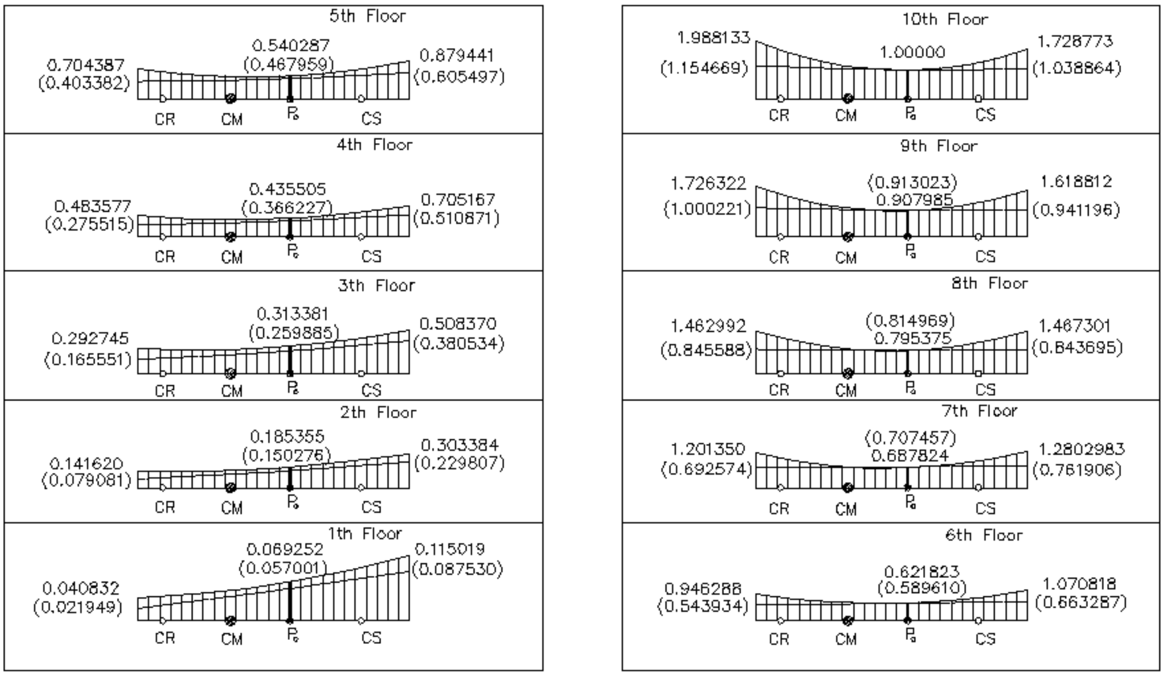


Figure 8: Diagrams of the maximum floor displacements (in m) from linear dynamic time-history analyses by three different accelerograms

CONCLUSIONS

In this article, the verification of the properties of the optimum torsion axis and the principal directions of the multi-story system was made, by use of static, modal, response spectrum, and linear dynamic time-history analyses. An example was presented, among a large number of examined buildings, in which the location of the optimum torsion axis as well as the torsional stiffness radii of the multi-story system were determined. Then the verification of the state of optimum torsion was made, by performing a lot of static analyses for various positions of the loading plane of vector **F**. It was certified that, in the case of coincidence of the mass centers CM with the optimum torsion z-axis P_o, the optimum translational vibration of the system appears, either by the response spectrum analysis or by the linear dynamic time-history analysis. The position of the modal seismic forces in the fundamental (1^{st}) coupled mode shape justifies the equivalent static eccentricities, which are used in the simplified modal analysis of seismic design. Therefore, within the frame of usual approximations accepted by the simplified methods of seismic analysis, we can define the static eccentricity of the building as the horizontal distance of the vertical mass axis from the vertical axis of optimum torsion for all the multi-story asymmetric buildings, which have the required by the Codes regularity along their height.

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