EFFECTS OF SEISMIC DIRECTIVITY WITHIN THE FRAMEWORK OF THE LATERAL FORCE PROCEDURE

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ABSTRACT :

In the present paper the influence of the seismic incident angle on the longitudinal steel reinforcement of R/C buildings within the context of the lateral force method of analysis is investigated. According to current seismic codes the horizontal static seismic forces are applied along the structural axes of the building, provided that can be clearly identified. In an extensive parametric study a wide range of buildings (symmetric, asymmetric, with or without orthogonal arrangement of their resisting elements) have been analysed and their response is computed due to the simultaneous action of the two horizontal seismic components for a series of different angles of seismic incidence. It is proved that, in general, different orientations of the seismic action may lead to differences of up to 29% concerning the required longitudinal steel reinforcement. The only case in which the structural response does not depend on the loading direction is that of structures which fulfill the criterion $T_B<T_\alpha<T_C$ for any value of α, where α is the angle of incidence, T_α is the uncoupled fundamental period of the structure along the α-direction and T_B, T_C are the lower and upper limits of the constant spectral acceleration branch.

KEYWORDS: Seismic analysis, Lateral Force Procedure, seismic directivity

1. INTRODUCTION

As far as seismic analysis of regular buildings is concerned, all modern seismic codes (EC8, NEHRP, FEMA 356, UBC) suggest the use of the Lateral Force Procedure (LFP). According to LFP, the time-dependent seismic action is represented by horizontal static forces. As a natural consequence of this loading model the following significant question arises: In what direction should the horizontal seismic forces be applied? According to the aforementioned seismic codes, buildings must be designed in a manner ensuring that they are protected against the most unfavourable combinations of actions. It is generally believed that this is achieved, regardless of the analysis method used (LFP or Response Spectrum Procedure - RSP), if the seismic actions are independently applied along two horizontal orthogonal (i.e. perpendicular to each other) directions and the calculated action effects are combined using an appropriate directional combination rule (SRSS or percentage combination rule). At this point it is worth mentioning that in spite of the fact that the percentage combination rule does not always yield safe results (E. L. Wilson et al., 1995, Lopez et al., 2001, Heredia-Zavoni et Machicao-Barrionuevo, 2004), its use is explicitly stipulated in all current seismic codes.

Within the framework of RSP many researchers (Smeby & Der Kiureghian 1985, Anastassiadis 1993, Lopez & Torres 1997, Avramidis & Anastassiadis 1998, Lopez et al 2000, Anastassiadis et al 2002) have examined the influence of seismic directivity on structural response on the basis of the Penzien-Watabe model (1975). All these investigations have led to the general conclusion that the maximum structural response may be considerably affected by the seismic direction, but it remains constant if the two horizontal seismic components are expressed by the same design spectrum and applied simultaneously, while the SRRS rule is used for the subsequent directional combination of the action effects. No analogous research has been carried out within the context of LFP so far.

When LFP is applied, seismic codes generally recommend the application of the horizontal seismic forces along the principal axes of the building. However, they do not always clearly specify how these axes can be determined (with the exception of the Greek seismic code EAK), maybe implying that they are identical to the structural axes of the building. Thus, in case of buildings with earthquake resistant elements arranged in an orthogonal pattern the principal directions are usually considered to be parallel to the pattern lines (EC8, NEHRP), while in case of buildings lacking an orthogonal configuration the principal axes are generally chosen by the engineer on the basis of his empirical judgement, thus paying no attention to other, potentially more disadvantageous seismic directions.

In the present paper the influence of the seismic excitation's direction on the longitudinal steel reinforcement of R/C buildings within the context of LFP is examined by conducting an extensive parametric study. Symmetric and unsymmetric, regular (i.e. torsionally stiff) buildings with or without orthogonally arranged resisting elements are analysed. Every example building is analysed for 13 values of the seismic incidence angle ranging from 0^o to 180^o (i.e. 0^o, 15^o, 30^o, ... , 180^o). For each incidence angle the required longitudinal reinforcement is calculated. The analyses results demonstrate that, in general, the required longitudinal reinforcement is quite influenced by the direction of the lateral seismic forces. It is also proved that the maximum longitudinal reinforcement generally develops for a seismic direction which does not coincide with any of the structural axes.

2. STRUCTURES EXAMINED

Due to space limitations, only four of the examined buildings are presented here. These are R/C buildings of C20/25 concrete category ($E=2.9*10^7 kN/m^2$, $\nu=0.2$, weight/unit volume $\gamma=25kN/m^3$), reinforced with S400 steel. The stiffness of the load bearing elements has been evaluated taking into account the effect of cracking.

2.1. Three-Storey Unsymmetrical Building with T_i in the Constant Acceleration Branch (model 3SUNB)

The plan view of the building (model 3SUNB) is given in Figure 1. The first story height is h_1=4m, while the height of the other stories is h_i=3m (i=2, 3). All the beams have a 25/60 cross section. The cross sections of 1st story columns are 50/50, those of the 2nd story are 45/45 and those of the 3rd story are 40/40. The building is located in seismic zone I (i.e. peak ground acceleration is A=0.16g) and the ground type is A (T_B=0.1, T_C=0.4sec are the lower and upper limits of the constant spectral acceleration branch of the design spectrum, Fig. 1).

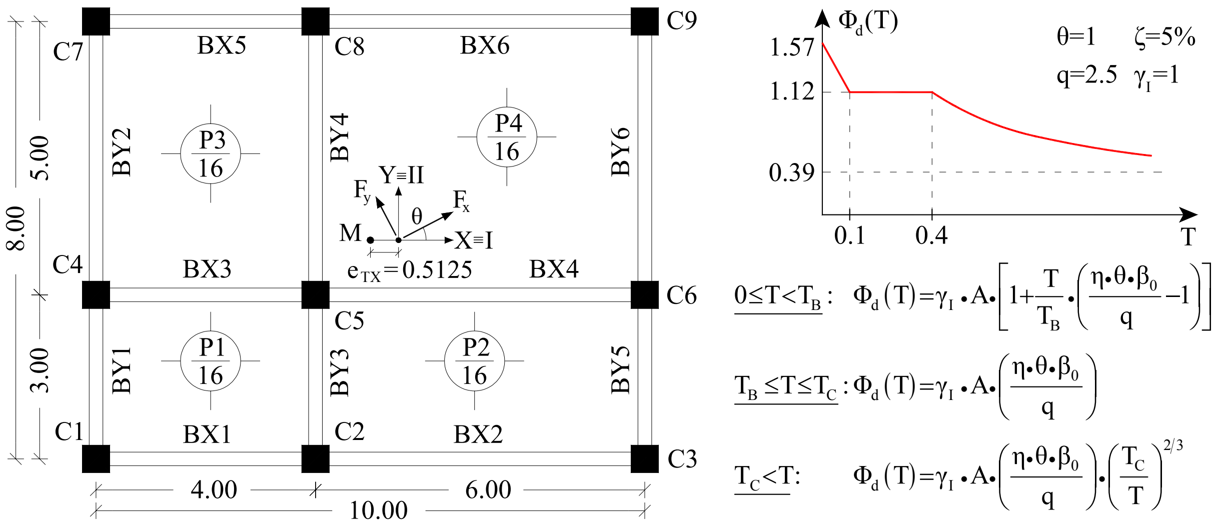

Figure 1 Plan view of a 3-storey unsymmetrical building (3SUNB) with T_i in the constant acceleration branch

2.2. Five-storey Symmetrical Building with $T_i > T_B$ (model 5SST$_L$)

The plan view of the building (model 5SST$_L$) is given in Figure 2. The first storey height is h_1=5m, while the height of the other stories is h_i=3.2m (i=2, 3, 4, 5). Beams oriented along the x-direction have a 25/60 cross section. The columns have a 45/45 cross section, except for C3, C8, C7 and C12, the dimensions of which are given in figure 2). The cross sections of the shear walls along the y-axis are 25/250, while those of the walls along the x-axis are 25/225. The building is situated in seismic zone II (A=0.24) and the ground type is A (T_B=0.1, T_C=0.4sec).

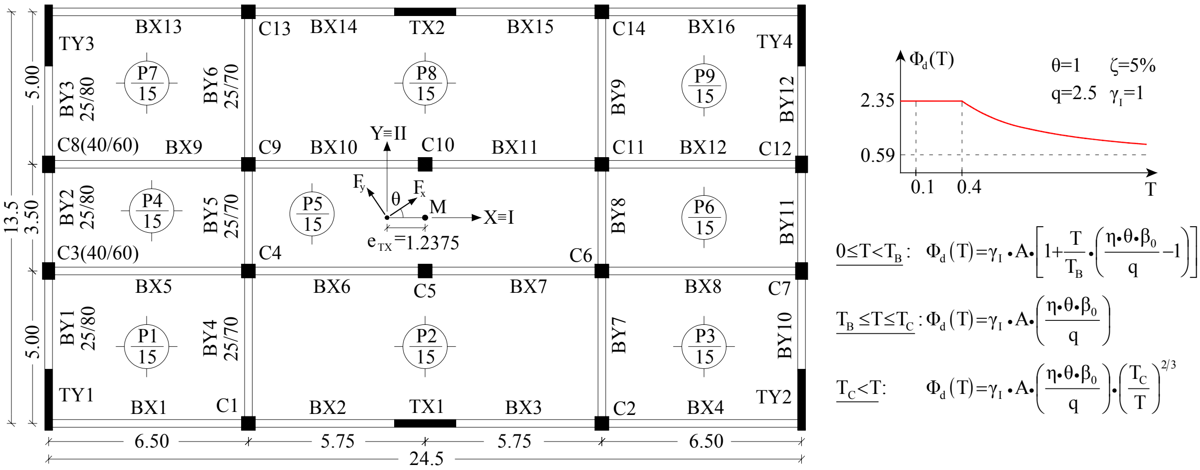

Figure 2 Plan view of a 5-storey symmetrical building ($5SST_L$) with $T_i > T_C$

2.3. Five-storey Symmetrical Building with $T_x>T_C$ and $T_B<T_y<T_C$ (model $5SST_{xL}$)

The plan view of this building (model $5SST_{xL}$**)** is shown in Figure 3. The first storey height is h_1=5m**,** while the height of the other stories is h_i=3.0m (i=2, 3, 4, 5). The cross sections of the beams are identical with those of the previous building ($5SST_L$). The columns have a 45/45 cross section (except for C3, C8, C7 and C12 with a cross section of 40/55). The cross sections of the walls along the y-axis are 25/250, while those of the walls along the x-axis are 25/225. The building is situated in seismic zone II (α=0.24) and the ground type is A (T_B=0.1, T_C=0.4sec).

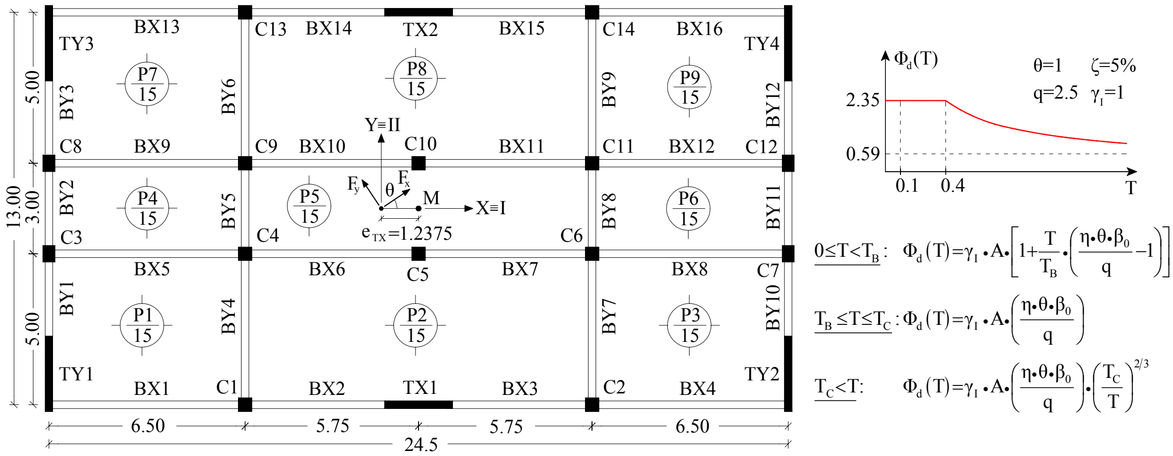

Figure 3 Plan view of a 5-storey symmetrical building ($5SST_{xL}$) with Tx $>T_C$ and T_B<Ty<T_C

2.4. Five-storey Unymmetrical Building with T_i longer than T_C (model $5SUNT_L$)

The plan view of the building (model $5SUNT_L$) is presented in Figure 4. The first storey height is h_1=5m, while the height of the other stories is h_i=3.2 m (i=2, 3, 4, 5). All the beams have a 25/60 cross section. The cross section of columns C5 and C6 is 50/50, that of column C4 is 50/60 and that of all other columns is 45/45. The cross section of walls T1 and T4 is 25/200 and that of walls T2 and T3 is 25/250. The building is located in seismic zone I (A=0.16g) and the ground type is B (T_B=0.15, T_C=0.6sec).

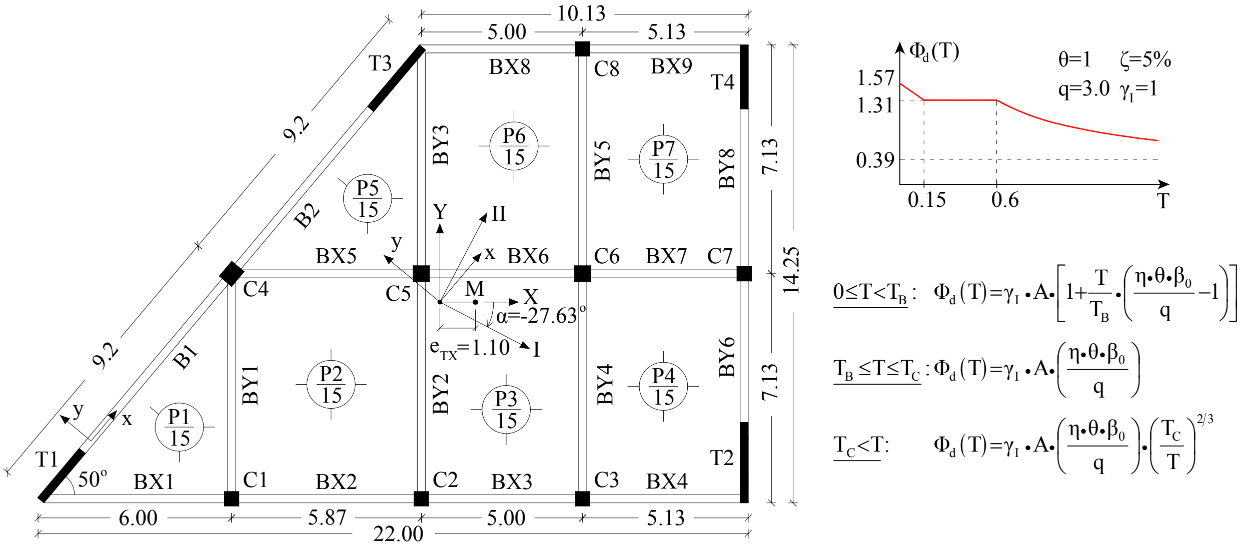

Figure 4 Plan view of a 5-storey non-symmetrical building (5SUNT$_L$) with T_i larger than T_C

3. DESCRIPTION OF THE ANALYSES

First, each building is analyzed for the vertical gravitational loads that correspond to the seismic combination of actions. Then the seismic action effects are computed using the LFP. The seismic analysis is performed for 13 different angles θ of seismic incidence (θ=0°, 15°, 30°, 45°, …, 180°). The principal axes I and II (see Figs 1, 2, 3 and 4) are determined according to EAK. The seismic forces are applied to the centre of mass M, which is considered to be displaced from its nominal location by the accidental eccentricity (e_{ai}=0.05L_i). The accidental eccentricity has been considered constant, i.e. independent of the seismic direction. The seismic design of a column is controlled by the simultaneous action of 3 response parameters: axial force N and bending moments M_x and M_y (x, y are the principal axes of the element cross section). Using N, M_x and M_y the longitudinal reinforcement of the structural elements is calculated for all 13 incident angles θ considered here. In addition, every building is also analysed using RSP and the longitudinal reinforcement of the structural elements is derived based on the results of this method. The longitudinal reinforcement is calculated using both options stipulated in EAK: (a) taking into account the extreme value of each of the 3 response parameters and the probable simultaneous values of the other two (6 combinations for each cross section) and (b) taking into account the extreme values of all 3 response parameters in all possible combinations of their algebraic signs (8 combinations for each cross section) (see EAK, paragr. 3.4.4, and EC8 paragr. 4.3.3.5.1).

4. ANALYSES RESULTS

The fundamental uncoupled natural periods of models 3SUNB, 5SST$_L$, 5SST$_{xL}$ and 5SUNT$_L$ for every direction considered, as well as the respective base shears are presented in Tables 4.1 and 4.2, respectively.

Table 4.1 Fundamental uncoupled natural periods and base shears per direction θ_i°
(The principal axes I and II coincide with the structural axes X and Y, Figs 1, 2, 3)

	θ_i	0	15	30	45	60	75	90	105	120	135
3SUNB	T_i	0.34	0.339	0.335	0.33	0.326	0.323	0.32	0.32	0.326	0.33
	V_{0i}	737	737	737	737	737	737	737	737	737	737
5SST$_L$	T_i	.679	.657	.608	.555	.514	.489	.481	.489	.514	.555
	V_{0i}	2820.6	2881.7	3036.7	3225.6	3394.4	3508	3547.8	3508	3394.4	3225.6
5SST$_{xL}$	T_i	.604	.579	.525	.47	.43	.407	.398	.407	.43	.47
	V_{0i}	2923.5	3006	3210.3	3452.8	3664.6	3805.7	3847.4	3805.7	3664.6	3452.8

It can be observed (Tables 4.1 and 4.2) that the fundamental uncoupled natural periods change in dependence of the excitation angle, with a maximum value that corresponds to the direction of principal axis I and a minimum value that corresponds to the direction of principal axis II (Makarios and Anastassiadis, 1998a,b, Marino, E.M. and Rossi, P.P., 2004, Athanatopoulou and Doudoumis, 2007). The values of the fundamental uncoupled natural periods for any other direction range between the above max/min values. If the two periods corresponding to the principal directions belong to the constant acceleration branch of the design spectrum, then the calculated base shear V_0 remains constant for all seismic directions and, consequently, the produced action effects do not depend on the direction of seismic excitation (For a proof see Appendix). If the above condition is not fulfilled, a different base shear V_{0i} is derived for every direction in the range [0^o, 90^o]. The base shear reaches its maximum value when the excitation angle is $\theta=90^o$ (with respect to the principal axis I).

Table 4.2 Fundamental uncoupled natural periods and base shears per direction θ_i^o of model 5SUNT$_L$ (angles θ_i with regard to principal axes I and II, Figure 4)

θ_i	0	15	27.634	30	45	60	75	77.634	90
T_i	.805	.786	.736	.726	.666	.625	.603	.601	.598
V_{0i}	1445.2	1468.3	1533.7	1548.2	1638.4	1710.1	1751.6	1755.5	1757.5
θ_i	105	117.634	120	135	150	165	167.63	180	
T_i	.61	.631	.637	.676	.724	.773	.781	.805	
V_{0i}	1738	1698.5	1689.4	1623.6	1551.2	1484.3	1474.6	1445.2	

The required longitudinal reinforcement for column C1, C3 and C5 bottoms (Figure 2) of model 5SST$_L$ vs the incident angle θ, using the probable simultaneous values ($A_{s,simult}$) as well as the extreme values ($A_{s,extr}$), is depicted in Figure 5. For the sake of comparison, the maximum (maxA_s) and the minimum (minA_s) allowed reinforcement according to EKOS as well as the reinforcement derived using RSP ($A_{s,simult}$(RSP) and $A_{s,extr}$(RSP) for a design based on the probable simultaneous values and the probable extreme values respectively), are also given in Figure 5. The values for every column are normalized with regard to the reinforcement derived using the LFP for a direction of excitation along the X and Y axes of the building and using the probable simultaneous values of internal forces for design purposes.

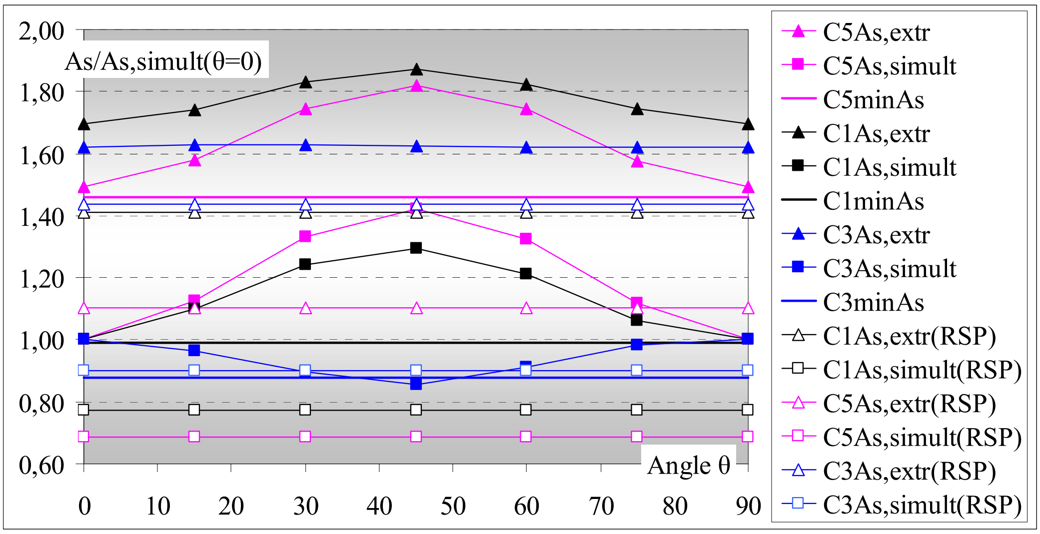

Figure 5 Longitudinal reinforcement of model 5SST$_L$ normalized with regard to the reinforcement derived using the probable simultaneous values of the sectional forces for excitation angle $\theta=0^o$

The required longitudinal reinforcement for column C1 and C4 bottoms of model 5SST$_{xL}$ (Figure 3) vs the incident angle θ (direction of excitation) is shown in Figure 6. In addition, the reinforcement required for columns C1, C4 and C7 bottoms as well as for wall T4 of model 5SUNT$_L$ (Figure 4) are given in Figures 7 and 8, respectively.

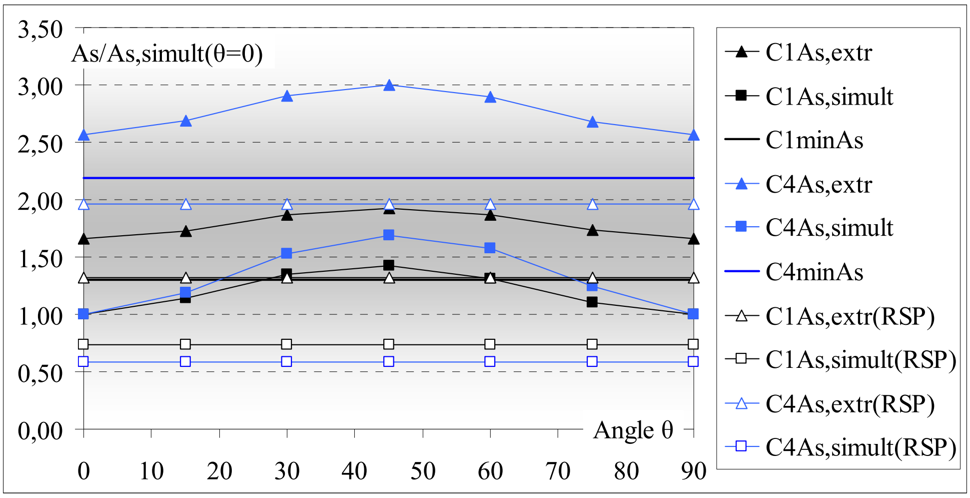

Figure 6 Longitudinal reinforcement of model 5SST$_{xL}$ normalized with regard to the reinforcement derived using the probable simultaneous values of the sectional forces for excitation angle θ=0^o

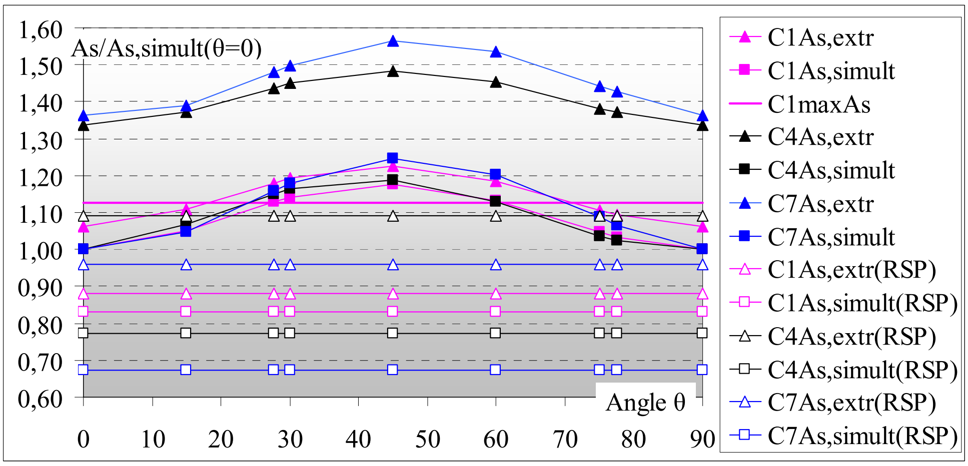

Figure 7 Longitudinal reinforcement for columns C1, C4 and C7 of model 5SUNT$_L$ normalized with regard to the reinforcement derived using the probable simultaneous values of the sectional forces for excitation angle θ=0^o with regard to principal axis I

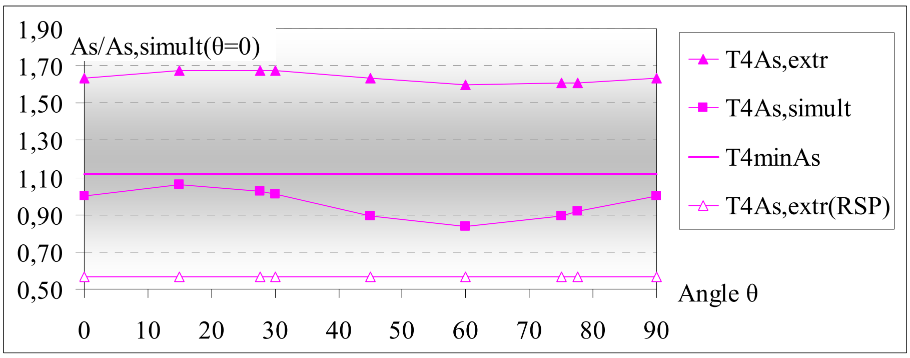

Figure 8 Longitudinal reinforcement for wall T4 of model 5SUNT$_L$ normalized with regard to the reinforcement derived using the probable simultaneous values of the sectional forces for excitation angle θ=0^o with regard to principal axis I

It can be seen (Figs 5 to 8) that the orientation of the excitation influences the required reinforcement. The percentage differences may take values up to 29% and are greater for the design based on the probable simultaneous values than for the design based on the extreme values. In buildings which are symmetrical and have their resisting elements arranged along an orthogonal pattern, the maximum longitudinal reinforcement emerges for excitation angle $\theta=0^o$ or 45^o (Figs 5 to 7). However, for buildings with non-orthogonal arrangement of their resisting elements the angle which produces the most conservative design is for some elements $\theta=0^o$ or 45^o (Fig. 7) and for some others $\theta=15^o$ or 60^o (Fig. 8). For the majority of the structural elements the LFP produces conservative results with respect to RSP. There are some elements for which the LFP underestimates the longitudinal reinforcement but the underestimation is less than 5%.

5. CONCLUSIONS

The conducted parametric study concerning the influence of the horizontal seismic forces' orientation on the required longitudinal reinforcement within the context of LFP leads to the following conclusions:

- If the uncoupled fundamental periods along the two horizontal principal directions of the building fall into the constant acceleration branch of the design spectrum, the required longitudinal reinforcement does not depend on the direction of the seismic forces (assuming constant accidental eccentricity and directional combination according to the SRSS rule).
- On the contrary, if one (or both) uncoupled fundamental period(s) along the two horizontal principal directions of the building is (are) longer than the upper limit of the constant acceleration branch of the design spectrum, then the required reinforcement is clearly influenced by the direction of the seismic excitation, even if the resisting structural elements are arranged along an orthogonal pattern. For the buildings studied in the present investigation the required steel reinforcement can be up to 29% larger than in case of an analysis along the building's structural axes.
- There is no specific direction of seismic excitation along which the required reinforcement is maximized simultaneously in all structural elements of a building.
- On the other hand, in all examples studied here the LFP produced for the majority of structural elements slightly conservative results as compared to the RSP (there have been only few structural elements for which the LFP slightly underestimates (< 5%) the required reinforcement). This fact is in accordance to what is generally considered as true.

In general, buildings should be designed to withstand seismic excitation along any direction. This means that within the context of LFP the direction of the seismic forces which yields the maximum reinforcement must be specified for every single structural element. In most cases this direction does not coincide with the structural axes of the building (provided such axes can be identified) or with its principal axes (which can be defined approximately). Thus, LFP analysis for seismic action only along the building's structural axes may produce non-conservative design forces at some structural elements. From what have been said becomes clear that the provisions of certain seismic codes concerning the directions of seismic excitation within the context of the LFP should be more clearly defined or even further completed.

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APPENDIX

Consider an N-story building loaded by horizontal static seismic forces $\mathbf{F}^T=[F_1\ F_2\ \ldots F_N]$ on the storey levels. The forces are applied along the axis x and produce the response $R,_x$, and then the same forces **F** are applied along the axis y and produce the response $R,_y$ (Figure 9). The response due to the simultaneous seismic action along axes x and y using the SRSS rule is: $exR = \sqrt{R,_x{}^2 + R,_y{}^2}$

Consider a coordinate system Οξη forming an angle a with the axis x of the system Oxy. The seismic forces **F** are first applied along the axis ξ and produce the response $R,_\xi$, and then they are applied along the axis η and produce the response $R,_\eta$ (Figure 9). The response due to the simultaneous seismic action along axes ξ and η using the SRSS rule is:

$$exR' = \sqrt{R,_\xi{}^2 + R,_\eta{}^2} = \left[(R,_x \cdot \cos a + R,_y \cdot \sin a)^2 + (-R,_x \cdot \sin a + R,_y \cdot \cos a)^2\right]^{1/2}$$

$$exR' = \sqrt{R,_x{}^2 + R,_y{}^2} = exR$$

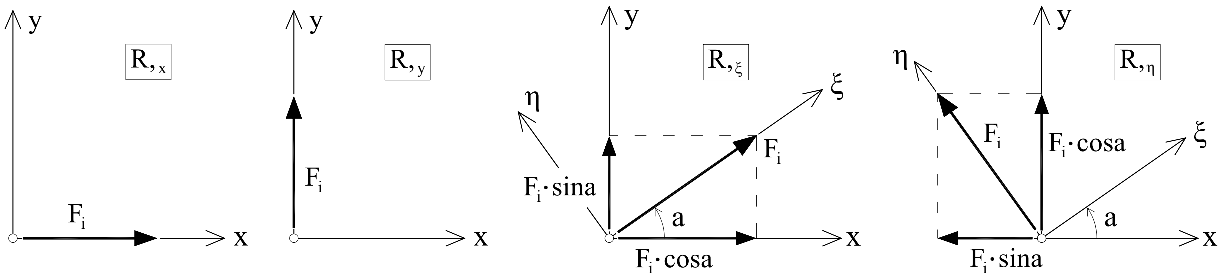

Figure 9 Seismic forces and the respective responses.