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CONSIDERING THE BI-DIRECTIONAL EFFECTS AND THE SEISMIC ANGLE VARIATIONS IN BUILDING DESIGN

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SUMMARY

Different methodologies to consider the bi-directional seismic effects in the building design process are analyzed in this work. These effects consist in: a) the transverse seismic component, and b) the variation of the incidence angle of the ground motion. Analysis recommendations are studied. A number of five story concrete buildings are analyzed. The materials are considered as elastic. The models of the buildings are three-dimensional, compatibility of vertical deformations is enforced, and the transverse and torsional stiffness of the particular elements is considered. The seismic angle variation is studied, and critical angles for stated maximum responses are determined. The maximum responses and their relations with the maximum responses obtained from uni-directional ground motion input are determined. The observed responses correspond to the maximum element forces. The studied design criteria to define the design strengths are: i) the combination of the force resulting from an uni-directional earthquake applied in the direction of the element added to a 30% of the force resulting from an uni-directional earthquake applied in the orthogonal direction of the element; ii) the combination defined as the square root of the sum of the square of the forces resulting from the use of an uni-directional earthquake applied in both directions; iii) a 20% amplification of the maximum force resulting from an uni-directional earthquake applied in the most unfavorable direction for the element. For the analyzed structures the building analysis by an uni-directional seismic input, amplified by a factor of 1.2 gives similar responses to those coming from bi-directional seismic analysis acting in the most unfavorable incidence angle. From this methodology the responses are overestimated, and the maximum observed error is of 25%. The design criteria defined in points i) and ii) underestimate the responses, and the errors are close to –25%.

INTRODUCTION

The buildings have resistant elements orientated according to two principal directions, in order to resisting the loads due to gravitational actions (self weight, permanent load, overload of use, etc.) and eventual actions due to seismic movement of the ground. Latest east, to the being of hazard nature, it is manifested in magnitude and direction both variables in the time. The instruments that measure such actions only register the seismic acceleration in the direction in that they has been orientated and which not necessarily coincides with the predominant direction of the movement that had the ground. Is as well as, in case to be counted with the information that bringing these instruments, is provided of a total of three records of acceleration: two horizontals orthogonals components and a vertical component. Obviating the effect of the vertical acceleration, not because it worthless, but because it complicate still plus the solution of the problem that is expounded in this study, the following query ¿with the tools appears that they now are provided in an office of projects, how could consider the effects of a bi-direccional seismic for the structure that is analyzed appropriately if not to be acquainted with who is it the most unfavorable direction for the system structure and seismic movement given?. Also, ¿would this unfavorable direction originate the big strain in all the resistant elements that conform the structure? and ¿is it only one?. In the Chilean current practice of design is supposed that the seismic actions does act separately in each one of the two orthogonals directions that possesses the building. This is valid if the seismic has had a predominant direction that coincides with any of these. For the contrary, if the seismic has two horizontal components simultaneous, all the resistant axes will meet committed in

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resistant elements that conform the structure? and ¿is it only one?. In the Chilean current practice of design is supposed that the seismic actions does act separately in each one of the two orthogonals directions that possesses the building. This is valid if the seismic has had a predominant direction that coincides with any of these. For the contrary, if the seismic has two horizontal components simultaneous, all the resistant axes will meet committed in important form. If this last situation is produced, the added difficulty is added of that the seismic movement experiences change in the directions of incidence and in their magnitude during the occurrence of the event. The norm of earthquake resistant design of buildings recommends carry out two analysis, according to the principal addresses of the building, considering the structure like a three-dimensional system and solicited by a uni-directional movement of the ground. The seismic movement, that possesses really one only component in an arbitrary direction and that for practical goods [bi-direccional] is represented for a movement, it could generate different answers of those that result of effecting analysis independent with uni-directional seismic. One could think then that the conclusions to that we are arrived in the analysis that they are carried out considering to uni-directional seismic they could not be the most representative. For this reason, we are interested in determine the effect of the component traverse of the seismic on the resistant lateral elements, enjointmy with the direction of incidence that could result more unfavorable for the structure, with the objective of finding rational solutions that consider these goods during the procedure of analysis and design of a structure in adequate form. At the present time, a series of recommendations is relied on coming national professionals and foreigners, as well as also of some of norms of earthquake resistant design of buildings.

If the three-dimensional model of the building is solicited by bi-directional seismic movements, the effect of interaction of responses acquires importance especially in the elements vertical located in the corners; like responses are the follows: a) bending moments M_u and M_v, around to two principal axes of the element; b) shear forces V_u and V_v; c) torsion moment M_z; d) axial force N. Such effects acts on the element in the same instant of time, the one which implicates that the maximum response considerate like "exact" should be evaluated through a history time analysis, not could be esteemed for a spectral modal superposition dynamic analysis.

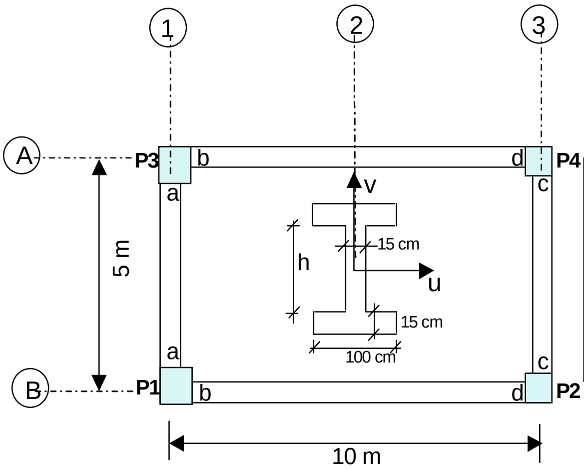
[Hisada et al, 1988] they study the orthogonals effects in structures with concerning the characteristics of the movement of the ground and the structural elastic response. They obtain mean values of the maximums responses that are 1,3 to 1,7 time higher that the of an uni-directional seismic and in the case of the columns of corner the axial forces are substantially higher. The Chilean norm of earthquake resistant design of buildings [INN, 1996], advise to effect independent analysis according to each one of two orthogonal directions or approximately orthogonals, but it doesn't make reference any on the combination of like outputs in order to represent appropriately the effect of the bi-directionality of the seismic movements. [Wilson, 1997] proposes a methodology in order to confront the problem of the bi-directional effects, meeting their application in the work of [Fernández, 1994] who take it upon to incorporate said methodology for the estimate of the responses of one story structure, employing the method of spectral modal superposition. Many studies of simple elastic systems, such as [Riddell, 1992], who demonstrate that the estimate of the response suggested by [Chopra et al, 1980] well-known like the rule of the square root, result adequate for the particular studied case. In this study are observed that if the uni-directional lateral response is considered plus the 30% of the response due to the same solicitation applied in the traverse direction be obtained a value equal to 91% of the maximum response. If on the other hand be evaluated the root of the square of both values is obtain a value equal to 97% of the maximum response. Based on these observations could be concluded that it is necessary amplify the responses coming from uni-directional earthquake applied in the direction of the element in a 40% in order to consider the two effects in study, or that it is more adequate combine the responses in base to the square root of the sum of the square of the resulting values of uni-directional analysis. However in order to effect recommendations of this type for all the structural systems it should investigate more to the respect, enlarging the models of analysis to systems that represent more real structures.

2. METHODOLOGY

2.1 Basic Model

Considering that the axial effect is relevant in column elements under the occurrence of bi-directional seismic movement, three-dimensional models of concrete buildings structured by frames is and with a wall central double "T" representative of the nucleus of elevators is studied. Varying the characteristics of the extreme axes (axis 1: rigid side and axis 3: flexible side) allow to study a range of buildings with different levels of eccentricity; from the same manner, vary the characteristics of the central wall allow to study buildings with several values of lateral stiffness. A building of five story is analyzed, with story height equal to 3m and a plant of 10 x 5 m^2. In the figure 1 is shown six models of analyzed structures and in the table 1 is indicated the dimensions of the elements that conform them.

Table 1: Dimensions of the individual elements of the analyzed models



Model	h [cm]	a [cm]	b [cm]	c [cm]	d [cm]
1	300	30	30	30	30
2	100	30	30	30	30
3	300	65	65	30	30
4	100	65	65	30	30
5	100	600	30	30	30
6	100	15	100	30	30

2.2 External Loads

For the determination of the seismic mass is considered gravitational loads coming from of the self weight of the structure and of the overload of normal use for buildings, and they are considered as an uniformly distributed load of $w_g = 1.0$ T/ m^2. As seismic loads is utilized the two horizontal components of acceleration of the ground recorded in Llo-Lleo during the earthquake occurred the March 3 of 1985 in the central region of Chile. The components principal, LLN10E, and secondary, LLS80E, reached maximums acceleration peaks same to 0.668g 0.4243g respectively. In a first analysis both components are applied simultaneously in two orthogonals directions, making vary the angle of incidence, such is indicated in the figure 2, in that is shown the three-dimensional model utilized also. In a second analysis the higher component is applied for separating in the two orthogonals directions.

2.3 Combination of the responses due to lateral seismic and due traverse seismic

In order to proposing combinations that represent the maximums seismic responses due to the application of uni-directional seismic, it is necessary to obtain the maximums seismic responses resulting of analyzing in the time each three-dimensional model of the building, according to the follows considerations:

a) Response that results of applying the two horizontal components of the earthquake with several angles of incidence simultaneously. The calculated response in this way is called "exact", R_{ex}.

b) Response that results of applying the higher component of the earthquake in each direction of the building independently.

c) Response that results of the combination:

$$R_{30\%} = R^{0^\circ} + 0.3R^{90^\circ} \tag{1}$$

In that the superscript indicates the inclination of the earthquake concerning the direction of the element in that is evaluating the combination.

d) Response that results of the combination:

$$R_{\sqrt{\ }} = \sqrt{(R^{0^\circ})^2 + (R^{90^\circ})^2} \tag{2}$$

with equal meaning of the superscript that in the previous combination.

e) Response that results of amplifying in 20% the maximum response obtained of the application of the higher component in the two principal directions of the building in independent form, that is:

$$R_{20\%} = 1.2 \cdot max\{R^{0^\circ}; R^{90^\circ}\} \tag{3}$$

3. ANALYSIS OF THE RESULTS

In the figures 3 and 4 is shown the curves of the responses of some structural elements (column P1 of the axis 1, column P2 of the axis 3 and central wall of the axis 2) corresponding to the model 6, which have been subjected to the bi-directional seismic movement and to the uni-directional seismic movement, with angles of incidence variables each 15º. It are observed in these figures that the maximum response that is obtained in the majority of the elements, due to the application of a bi-directional earthquake, not necessarily coincides with the principal directions that possesses the building. The same occur when on the same structure is applying uni-directional earthquakes, in where one could appreciate that the maximum response are not obtained when the angle of seismic incidence coincides with any of the principal directions of the building. Precisely the response belonging to the axial force of the columns of corner P1 and P2, possess the observed characteristics previously, with which is manifested the necessity of knowing the most adequate criterion that allows to esteem this response. Is also observed that the angle of incidence that produces the maximum responses is different and is not only.

In the tables 2 and 3 is shown the estimates for each one of the several rulers of combination of the responses, obtained of applying the higher horizontal component of the seismic in each principal direction of the building. Is appreciated that so much the rule of the 30% (item 2.3.c) as well as the rule of the square root (item 2.3.d), in general underestimate the seismic response in almost 25% if they are compared with the 'exact' response. The bi-directional effect sometimes produces minors responses to those that would be obtain of applying uni-directional earthquake, for example, the axial forces of compression and of traction due to both effects. It is for this that sometimes this combination comes to produce larger errors at 20% and could come to be of until a 25%. On the other hand, a better estimate is obtained upon amplifying in 20% the response that results higher upon applying the higher horizontal component of the seismic in each one of the two principal directions of the building. From this manner, is underestimated the response in quantities that like maximum arrive at 25% respect of the value considerate like exact, which from the engineering point of view results acceptable.

4. CONCLUSIONS

The maximum response that is obtained in any structural element due to the application of a bi-directional seismic movement with angle of variable incidence, not necessarily coincides with any of the two principal directions of the buildings.

The rules of combination of the 30% and of the square root, underestimate the seismic responses in 25% respect of the 'exact' response.

It proposes a rule that consists of amplifying in 20% the response that results higher upon only applying the higher horizontal component of the seismic in each one of the two principal directions of the building, with which it is possible get errors that don't overcome the 25%.

A valid correspondence between the structural configuration of the building could not have been found (so much in plant like in elevation) and the response that is obtained of applying a bi-directional seismic movement

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Chopra, A.K. and Newmark, N.M., E. Rosenblueth (ed.) (1980), "Design of Earthquake Resistant Structures”, *Pentech Press, London*, 27-53.

Fernández, L., (1994), "Determinación de la Significación de la Direccionalidad del Sismo en el Diseño", *Memoria para optar al Título de Ingeniero Civil.* Universidad de Chile.
Hisada, T., Miyamura, M., Kan, S. and Hirao, Y., (1988), "Studies on the Orthogonal Effects in Seismic Analyses" *Proceedings of Ninth World Conference on Earthquake Engineering*. August 2-9, Tokyo-Kyoto, Japan, Vol. V, pp191-196.
INN, (1996), "Norma Chilena Oficial NCh433.Of96 Diseño Sísmico de Edificios", *Instituto Nacional de Normalización.*
Riddell, R., (1992), *Personal Communication.*
Wilson, E.L., (1997), "Three Dimensional Dynamic Analysis of Structures with Emphasis on Earthquake Engineering", *Computers and Structures, Inc*. February.

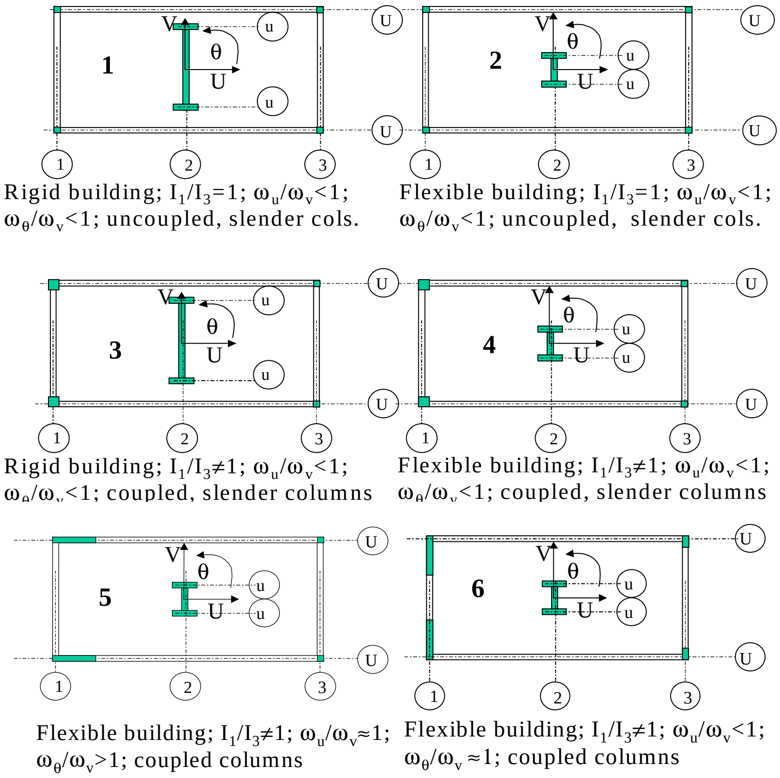

Figure 1: Models of the analyzed buildings

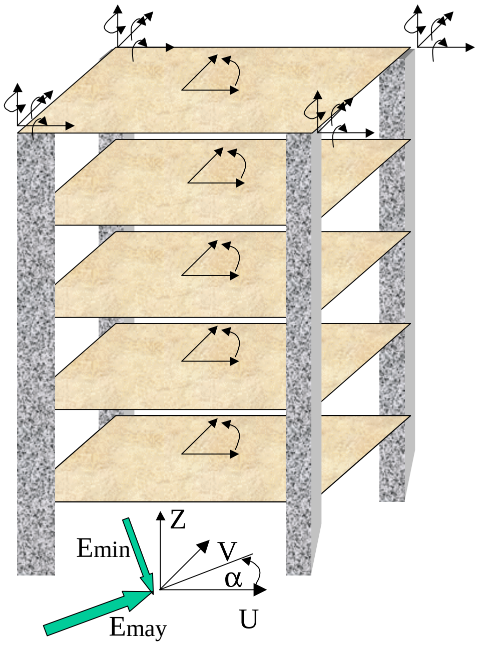

Figure 2: Three-dimensional model and seismic excitation utilized

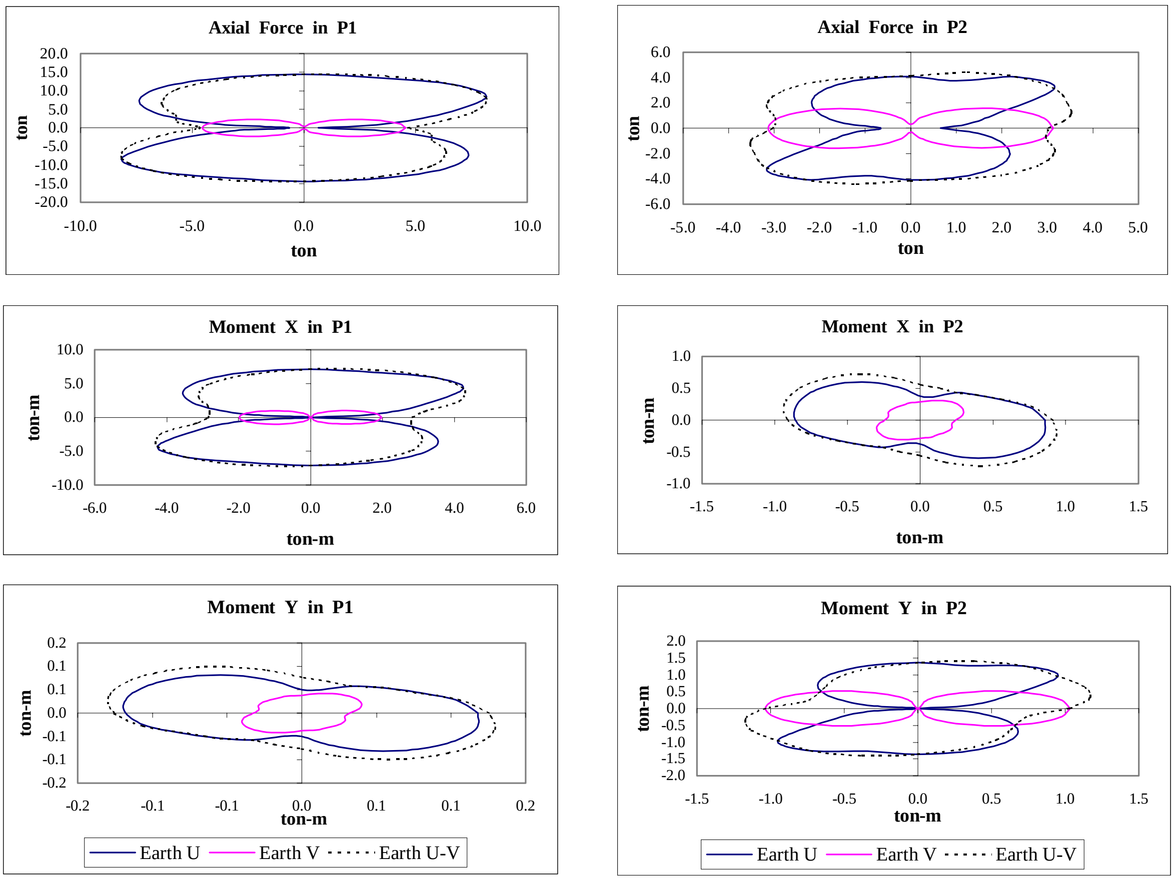

Figure 3: Seismic responses in columns of model 6

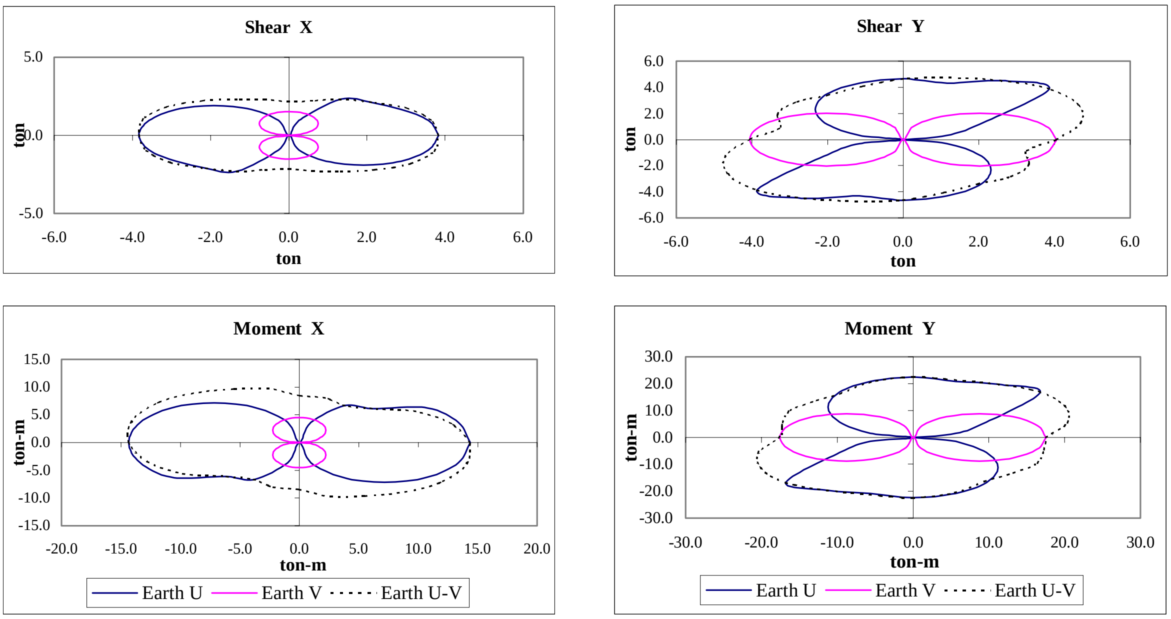

Figure 4: Seismic responses in the central wall of model 6

Tabla 2: Combined responses in the columns of first story

P1

Model	N^{ex}	$N^{0°}$	$N^{90°}$	$N_{30\%}$	error (%)	$N_{\sqrt{}}$	error (%)	$N_{20\%}$	error (%)
1	2.65	1.18	2.43	2.78	5.1	2.7	2.0	2.91	10.2
2	3.15	1.18	2.85	3.20	1.6	3.1	-2.2	3.42	8.5
3	10.26	1.72	10.65	11.17	8.9	10.8	5.2	12.78	24.6
4	6.31	1.72	6.48	6.99	10.8	6.7	6.2	7.77	23.1
5	3.87	1.24	3.39	3.76	-2.7	3.6	-6.6	4.07	5.2
6	14.44	0.65	14.39	14.59	1.0	14.4	-0.2	17.27	19.6

Model	M_x^{ex}	$M_x^{90°}$	$M_x^{0°}$	$M_{x\,30\%}$	error (%)	$M_{x\sqrt{}}$	error (%)	$M_{x\,20\%}$	error (%)
1	0.65	0.52	0.00	0.52	-19.3	0.52	-19.3	0.63	-3.2
2	0.65	0.52	0.00	0.52	-19.3	0.52	-19.3	0.63	-3.2
3	9.15	6.70	3.94	7.88	-13.9	7.77	-15.1	8.04	-12.1
4	8.24	6.70	3.70	7.81	-5.3	7.65	-7.2	8.04	-2.4
5	115.04	118.74	6.49	120.69	4.9	118.91	3.4	142.48	23.9
6	0.13	0.12	0.05	0.13	-1.2	0.13	-4.8	0.14	5.1

Model	M_y^{ex}	$M_y^{0°}$	$M_y^{90°}$	$M_{y\,30\%}$	error (%)	$M_{y\sqrt{}}$	error (%)	$M_{y\,20\%}$	error (%)
1	0.31	0.00	0.31	0.31	0.0	0.3	0.0	0.38	20.0
2	0.72	0.00	0.69	0.69	-3.7	0.7	-3.7	0.83	15.5
3	9.44	0.00	9.31	9.31	-1.4	9.3	-1.4	11.18	18.4
4	4.50	0.00	4.50	4.50	0.0	4.5	0.0	5.40	20.0
5	3.35	0.00	2.78	2.78	-17.0	2.8	-17.0	3.34	-0.4
6	7.22	0.01	7.10	7.10	-1.6	7.1	-1.6	8.52	18.0

P2

Model	N^{ex}	$N^{0°}$	$N^{90°}$	$N_{30\%}$	error (%)	$N_{\sqrt{}}$	error (%)	$N_{20\%}$	error (%)
1	2.91	1.18	2.43	2.78	-4.4	2.7	-7.3	2.91	0.1
2	3.52	1.18	2.85	3.20	-9.0	3.1	-12.4	3.42	-2.8
3	3.91	1.72	3.10	3.62	-7.5	3.5	-9.3	3.72	-4.8
4	5.02	1.72	3.78	4.30	-14.5	4.2	-17.3	4.54	-9.7
5	3.04	1.24	2.48	2.86	-6.2	2.8	-8.8	2.98	-2.1
6	4.66	0.65	4.09	4.29	-8.1	4.1	-11.2	4.91	5.2

Model	M_x^{ex}	$M_x^{90°}$	$M_x^{0°}$	$M_{x\,30\%}$	error (%)	$M_{x\sqrt{}}$	error (%)	$M_{x\,20\%}$	error (%)
1	0.65	0.52	0.00	0.52	-19.3	0.52	-19.3	0.63	-3.2
2	0.65	0.52	0.00	0.52	-19.3	0.52	-19.3	0.63	-3.2
3	0.76	0.55	0.32	0.65	-15.2	0.64	-16.5	0.66	-13.4
4	0.67	0.55	0.29	0.64	-5.7	0.62	-7.9	0.66	-2.2
5	0.07	0.08	0.01	0.08	15.2	0.08	11.6	0.09	32.6
6	0.97	0.86	0.37	0.97	-0.1	0.94	-3.7	1.03	6.0

Model	M_y^{ex}	$M_y^{0°}$	$M_y^{90°}$	$M_{y\,30\%}$	error (%)	$M_{y\sqrt{}}$	error (%)	$M_{y\,20\%}$	error (%)
1	0.31	0.00	0.31	0.31	0.0	0.3	0.0	0.38	20.0
2	0.72	0.00	0.69	0.69	-3.7	0.7	-3.7	0.83	15.5
3	0.68	0.00	0.68	0.68	0.0	0.7	0.0	0.82	20.0
4	1.19	0.00	0.98	0.98	-17.9	1.0	-17.9	1.18	-1.4
5	0.65	0.00	0.55	0.55	-15.4	0.6	-15.4	0.67	1.6
6	1.45	0.00	1.36	1.36	-6.3	1.4	-6.3	1.64	12.5

Tabla 3: Combined responses in the central wall of first story

Model	V_x^{ex}	$V_x^{90º}$	$V_x^{0º}$	$V_{x\,30\%}$	error (%)	$V_{x\sqrt{}}$	error (%)	$V_{x\,20\%}$	error (%)
1	3.19	3.12	0.00	3.12	-2.5	3.1	-2.5	3.74	17.1
2	3.19	3.12	0.00	3.12	-2.5	3.1	-2.5	3.74	17.1
3	1.93	1.58	0.00	1.58	-18.1	1.6	-18.1	1.90	-1.7
4	1.93	1.58	0.00	1.58	-18.1	1.6	-18.1	1.90	-1.7
5	0.17	0.17	0.00	0.17	0.0	0.2	0.0	0.21	20.0
6	3.85	3.83	0.00	3.83	-0.6	3.8	-0.6	4.59	19.2

Model	V_y^{ex}	$V_y^{0º}$	$V_y^{90º}$	$V_{y\,30\%}$	error (%)	$V_{y\sqrt{}}$	error (%)	$V_{y\,20\%}$	error (%)
1	15.92	0.00	15.92	15.92	0.0	15.9	0.0	19.10	20.0
2	5.60	0.00	5.36	5.36	-4.2	5.4	-4.2	6.43	15.0
3	15.03	0.00	14.82	14.82	-1.4	14.8	-1.4	17.78	18.3
4	4.57	0.00	3.65	3.65	-20.0	3.7	-20.0	4.38	-4.0
5	4.85	0.00	3.77	3.77	-22.3	3.8	-22.3	4.53	-6.7
6	5.46	0.00	4.64	4.64	-15.0	4.6	-15.0	5.57	2.0

Model	M_x^{ex}	$M_x^{90º}$	$M_x^{0º}$	$M_{x\,30\%}$	error (%)	$M_{x\sqrt{}}$	error (%)	$M_{x\,20\%}$	error (%)
1	9.98	7.51	0.00	7.51	-24.7	7.5	-24.7	9.01	-9.7
2	9.98	7.51	0.00	7.51	-24.7	7.5	-24.7	9.01	-9.7
3	9.21	8.16	0.00	8.16	-11.4	8.2	-11.4	9.79	6.4
4	9.21	8.16	0.00	8.16	-11.4	8.2	-11.4	9.79	6.3
5	0.89	0.89	0.00	0.89	0.0	0.9	0.0	1.07	20.0
6	14.59	14.36	0.00	14.36	-1.6	14.4	-1.6	17.23	18.0

Model	M_y^{ex}	$M_y^{0º}$	$M_y^{90º}$	$M_{y\,30\%}$	error (%)	$M_{y\sqrt{}}$	error (%)	$M_{y\,20\%}$	error (%)
1	152.65	0.00	152.65	152.65	0.0	152.7	0.0	183.18	20.0
2	26.65	0.00	26.05	26.05	-2.2	26.1	-2.2	31.26	17.3
3	160.65	0.00	158.71	158.71	-1.2	158.7	-1.2	190.45	18.5
4	23.86	0.00	19.96	19.96	-16.3	20.0	-16.3	23.95	0.4
5	25.14	0.00	22.09	22.09	-12.1	22.1	-12.1	26.51	5.4
6	23.73	0.00	22.39	22.39	-5.6	22.4	-5.6	26.87	13.3