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EFFECT OF THE IN-PLAN DISTRIBUTION OF STRENGTH ON THE NON-LINEAR SEISMIC RESPONSE OF TORSIONALLY COUPLED BUILDINGS

Octavio GARCIA[1], Alfonso ISLAS[1] and A. Gustavo AYALA[2]

SUMMARY

Studies based on simplified asymmetric building models have demonstrated that one of the most significant parameters in their seismic torsional response is the in-plan strength distribution. Studies carried out in Mexico show that strength distributions similar to those of stiffness produce the least demanding behaviours. However, given the uncertainties and difficulties to extrapolate the results of simplified single-storey models to 3D multilevel models of asymmetric buildings, in this paper the torsional behaviour of reinforced concrete 3D buildings is evaluated when incursion in the non linear range by effect of strong seismic excitation. The models studied represent real buildings designed with the current Mexico City code considering different in-plan strength distributions. Various degrees of structural asymmetry due to irregular in-plan distributions of masses and stiffness are considered. The obtained results show that providing in-plan strength distributions similar to the corresponding stiffness distributions leads to better behaviours, particularly in stiffness asymmetric models.

INTRODUCTION.

The investigation of the torsional coupling shown when an asymmetric structure incursions in the non-linear range of behaviour when subjected to intense earthquakes is a highly complex problem, in which the response cannot be estimated solely from elastic structural parameters, regardless of having been used in most existent seismic codes. Helped by the availability of efficient computational tools, recent studies aiming to understand this problem have been carried out using models which consider damage or deterioration in structural elements. In this respect, most research coincides in that the torsional inelastic response of an asymmetric building is affected by variables such as the level of structural eccentricity (e_s), the uncoupled periods of lateral vibration (T_X y T_Y), the ratio of uncoupled torsional to lateral frequencies (Ω), the structural overstrength, the design criteria established in the codes and, importantly the in-plan distribution of strengths of their structural elements, Sadek and Tso, [1]. The majority of these studies have been based on simplified one-level models aimed to simulate in an approximate way the behaviour

[1] División de Estudios de Posgrado de la Facultad de Ingeniería, UNAM. Cd. Universitaria, México D.F. 0.4510, MEXICO, Tel. 52-55- 56223029, Fax 52-55-56223287, email: octavio@dali.fi-p.unam.mx
[2] Instituto de Ingeniería, UNAM. APDO 70-642, Cd. Universitaria, México D.F., 0.4510, MEXICO, Tel. 52-55-56233508, Fax 52-55-56161514, email: gayala@dali.fi-p.unam.mx

of real multi-level buildings. However, the results obtained have not been easily extrapolated due to the complexities of some variables which determine the behaviour of real structures.

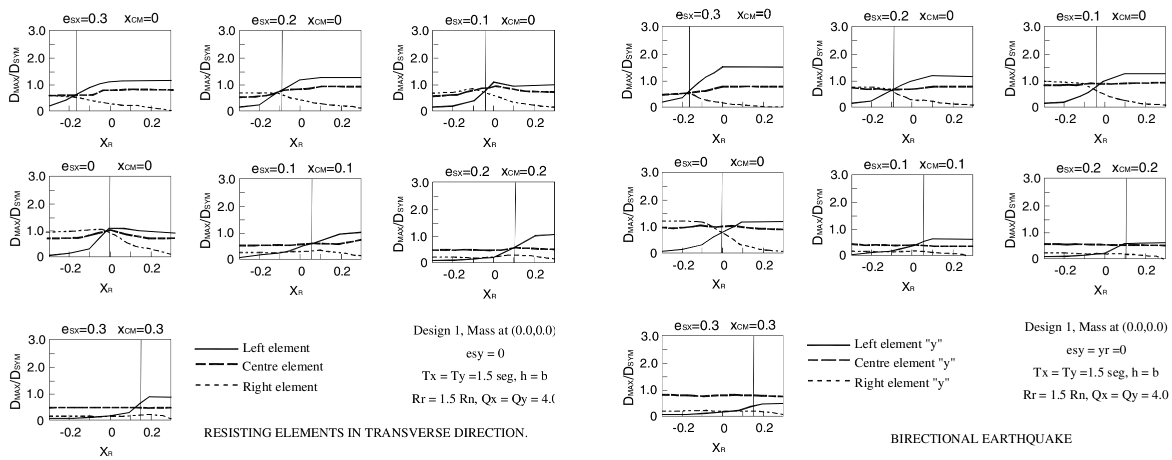
The objective of this work is to present a study which evaluates the influence of the in-plan variation of storey strengths on the torsional behaviour of models of real asymmetric buildings. A very strong seismic excitation was applied to models of buildings of various levels, representative of those built in Mexico City. The groups of structures selected were eight-storey reinforced concrete buildings designed according to the Seismic Code for Mexico City (RCDF-93) with different levels of structural asymmetry provided by an irregular distribution of mass and/or stiffness, Ortega, [2]. To obtain the different levels of strength asymmetry, the value of the design shear force was increased in different structural axes of the storeys.

To evaluate the behaviour of the structural models the demands of the shear force *vs.* the torsional moment produced in the storeys were calculated and superimposed on a capacity envelope analogous to that proposed by De la Llera [3]. To help the understanding of the problem, the variation of the Instantaneous Centre of Stiffness (ICS) and that of seismic shear (ICSS) were defined and evaluated by Chípol [4]. The ICS is equivalent to the centre of torsion (CT) obtained from a conventional static analysis, while the ICSS is analogous to the centroid of design strengths of the structural elements. The non-linear dynamic analyses of the 3D building models were carried out with the programme CANNY-E, Li [5] and for the seismic excitation the records of the horizontal components of the September 19, 1985 Michoacan earthquake registered at the SCT site were used. Finally, the results of this work were compared with those obtained in previous investigations carried out at the Institute of Engineering of the National Autonomous University of Mexico, (UNAM) and which were based on simplified one-storey models.

BACKGROUND

After the 1985 Michoacan earthquake in Mexico, the existing recommendations for seismic design were severely questioned. The damaged due to torsional effects served as a wake up call for researchers to acquire a better understanding of the non-linear dynamic behaviour of asymmetric buildings. Since then, particularly at the Institute of Engineering, investigation has been carried out on the seismic torsional behaviour of structures considering the non- linearity of the problems. Before 1985, the recommendations present in the then current construction code were based only on results from studies of models with linear elastic behaviour. However, due to the complexity of the torsional phenomenon, inelastic studies initially used simplified one-level shear models, whose general objectives had been to understand the characteristics of the seismic behaviour of asymmetric structures and to identify the most relevant structural parameters that influenced the seismic response; all this with the aim of improving existing seismic design recommendations for torsion. This topic has been touched on by national researchers from institutions other than the UNAM, which has provided a greater knowledge of the seismic response of asymmetric structures subject to seismic conditions prevalent in Mexico. Current specialized literature on the topic reports numerous studies by national and foreign researchers. Some investigations at the Institute of Engineering and others by foreign researchers, which were taken as a basis for the study presented in this paper, will now be described briefly.

Gómez *et al.* [6] carried out a parametric study in which they evaluated the effect that static eccentricity produces on the seismic behaviour of structures. They found out that as the static eccentricity increased so did the ductility demands. Ayala et.al, [7] studied monosymmetric models with resistant elements only in the direction of analysis. They found that the element which increases its strength causes reductions in ductility; while in the elements with no change in strength, their ductilities increase, up to a certain point beyond which they remain constant. Ayala and García, [8] investigated shear models with resisting elements in two orthogonal directions, designed with the RCDF-87 code and two variations of it. Different aspect ratios of the plan, varying numbers of resisting planes in the direction of analysis and vibration periods of 0.5, 1.0 and 1.5 sec were considered. The seismic behaviour was evaluated with the ratio of maximum demanded ductility in the asymmetric structure to the maximum demanded ductility of the symmetric structure used as reference. The results of this work, figs 1 and 2, corresponding to models with three elements in each principal direction, show that the structural behaviour has a common tendency, namely, the reduction of the ductility ordinates with the increase of strength of the storey elements. It was noticed that this decrease is only up to a certain point, which implies that providing a large strength to the elements does not necessarily result in a better structural behaviour. In all the cases studied, a better behaviour was obtained when the resultant of the resisting forces (*i.e.,* strengths of the elements) was situated near the centre of torsion; this was more obvious when the strength distribution was similar to the stiffness distribution. This study considered mono-symmetric models with seismic excitation in the direction of analysis and in the two principal directions of the plan.



(a) (b)

Figure 1. Relationships of maximum ductility ratios *vs.* Strength distribution, Ayala and García [8]

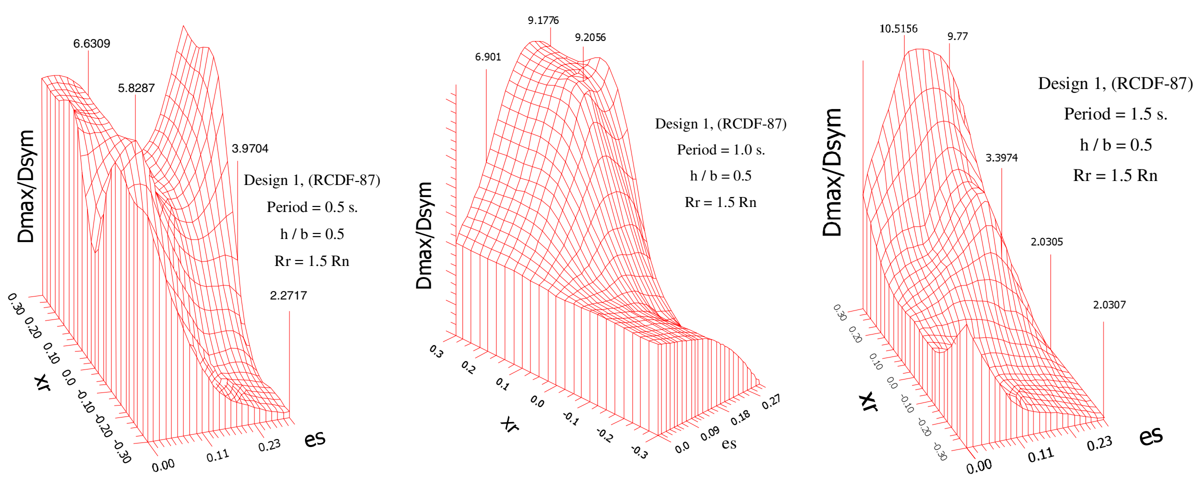


Figure 2. Envelopes of maximum ductility ratios *vs.* strength distribution, Ayala and García [8]

Other studies carried out by researchers such as Tso and Ying [9], based on simplified one-storey models, showed a strong influence of in-plan strength distribution on the response. Wong and Tso [10] investigated the variation in the inelastic seismic response of simplified one-storey structural systems with a strength distribution obtained from modal spectral design. The results of this investigation indicate that the displacements at the extremes of a torsionally coupled system depend on its torsional stiffness and which are highly sensitive to the in-plan distribution of strengths. Recently, Myslimaj and Tso [11] studied simplified one-storey models to evaluate a criterion of balanced in-plan distribution of strengths and stiffnesses. The conclusions of this work indicate that it is not possible to obtain the optimum locations of the centres of strength and stiffness which would minimize the seismic response at all levels of excitation studied.

As it may be seen, the in-plan distribution of strengths is a characteristic which has deserved special attention from researchers who intend to explain the phenomenon of torsional coupling in the non-linear range of behaviour. The results obtained from simplified models of buildings show the close relationship between experimental behaviour and the yielding of the elements in different resistant plans, and have identified some tendencies that may help decrease the seismic torsional response of asymmetric structures.

ADDITIONAL PARAMETERS FOR THE EVALUATION OF THE NON-LINEAR BEHAVIOUR OF MODELS OF ASYMMETRIC MULTILEVEL BUILDINGS

For the aims and purposes of the design codes for torsion, it is essential to use parameters which are easy to evaluate. Unfortunately, the torsional seismic response of structures does not only depend on elastic parameters but also on inelastic parameters which may be difficult to consider. As already mentioned, the results obtained with simplified one-storey models have provided valuable information. However, there exist some limitations related to the simplicity of the assumptions made, the parameters used and the seismic conditions present in a particular region, making extrapolation to multilevel structures uncertain.

Results from elastic analyses of multilevel asymmetric buildings, show the difficult in characterizing the level of asymmetry when this is due irregular distributions of stiffness, as the CT does not maintain the same in-plan location for all the storeys. Under the conditions of a static analysis, the location of this point does not only depend on the geometric and structural characteristics of the building but also on the distribution of applied lateral loads. Thus, it is important to know this location as it allows the calculation of the torsional moments produced by the seismic shear force in any storey. However, in the dynamic analysis, especially when non-linear, the determination of this point is highly complex. Thus, in this paper the ICS is used to show the evolution in time of the CT during dynamic response.

An additional behaviour characteristic which has been used in the study of complex models is the variation of the Instantaneous Centre of Seismic Shear (ICSS), Ortega, [2], which indicates the in-plan location of the seismic shear force and may be considered analogous to the Centre of Strengths (CS) of the structural elements.

Another source of information proposed to evaluate the inelastic behaviour of the structural models is the instantaneous location of the seismic responses represented in terms of shear force *vs.* torsional moment superposed within a bounding surface of storey strengths called Surface of Ultimate Storey-Shear and Torque, (SUSST), by De la Llera, [3]. This surface defines the capacity of a storey subjected to earthquake action. For the calculation of the strength of the storey elements it is necessary to carry out several non-linear static analyses under monotonically increasing loading (pushover), considering three degrees of freedom per level, Chípol, [4], until the Centre of Mass of the roof reaches a displacement of 0.012 times the height of the building, Ortíz [12]. The distribution of lateral loads used in the pushover analyses was obtained from a static seismic analysis considering bidirectional effects as recommended in the RCDF-93.

The strength of the planes of a storey is obtained from the envelope of the considered combination of loads. In accordance with the definition of the SUSST, reaching or crossing the bounds of this surface represents the collapse of the storey. However, in this study this condition does not apply, as the maximum allowed displacement used as the basis in the calculation of the strength of the planes, is situated between the limits of the service and collapse prevention displacements of a structure, Reyes and Meli [13].

STRUCTURAL MODELS STUDIED

In the investigation of the torsional behaviour of the groups of buildings considered a distinction was made between the asymmetry produced by irregular in-plan distributions of masses and stiffness. To evaluate the effect of the in-plan distribution of strengths in such a behaviour, the design of the eight-storey reinforced concrete buildings studied were obtained from Ortega [2] and to obtain different levels of strength asymmetry the value of the shear strength given by the design in accordance with the RCDF-93, was incremented in different planes or structural axes of the storeys. In this way the 25 models presented in table 1 were obtained. In this table the level of structural mass and stiffness asymmetry is arranged by columns and the variation of the position of the CS by rows. The word "original" indicates models of buildings designed in accordance with the code.

To identify the models used in table 1, the following codes are used: a) M02b_CS01aY indicates a mass eccentric model in which the Centre of Mass is located at a distance 20% of the dimension 'b' of the plan with respect to the geometric centre (GC) and the strength centre is located at a distance 10% of the dimension 'a' of the plan in the Y axis direction also measured from the GC; and b) M22w_CS02bX indicates a stiffness eccentric model in which the eccentricity is produced by two reinforced concrete walls and their strength centre is located at a distance 20% of the dimension 'b' of the plan in direction X measured from the GC.

Table 1 Nomenclature used to identify the groups of models studied in this paper.

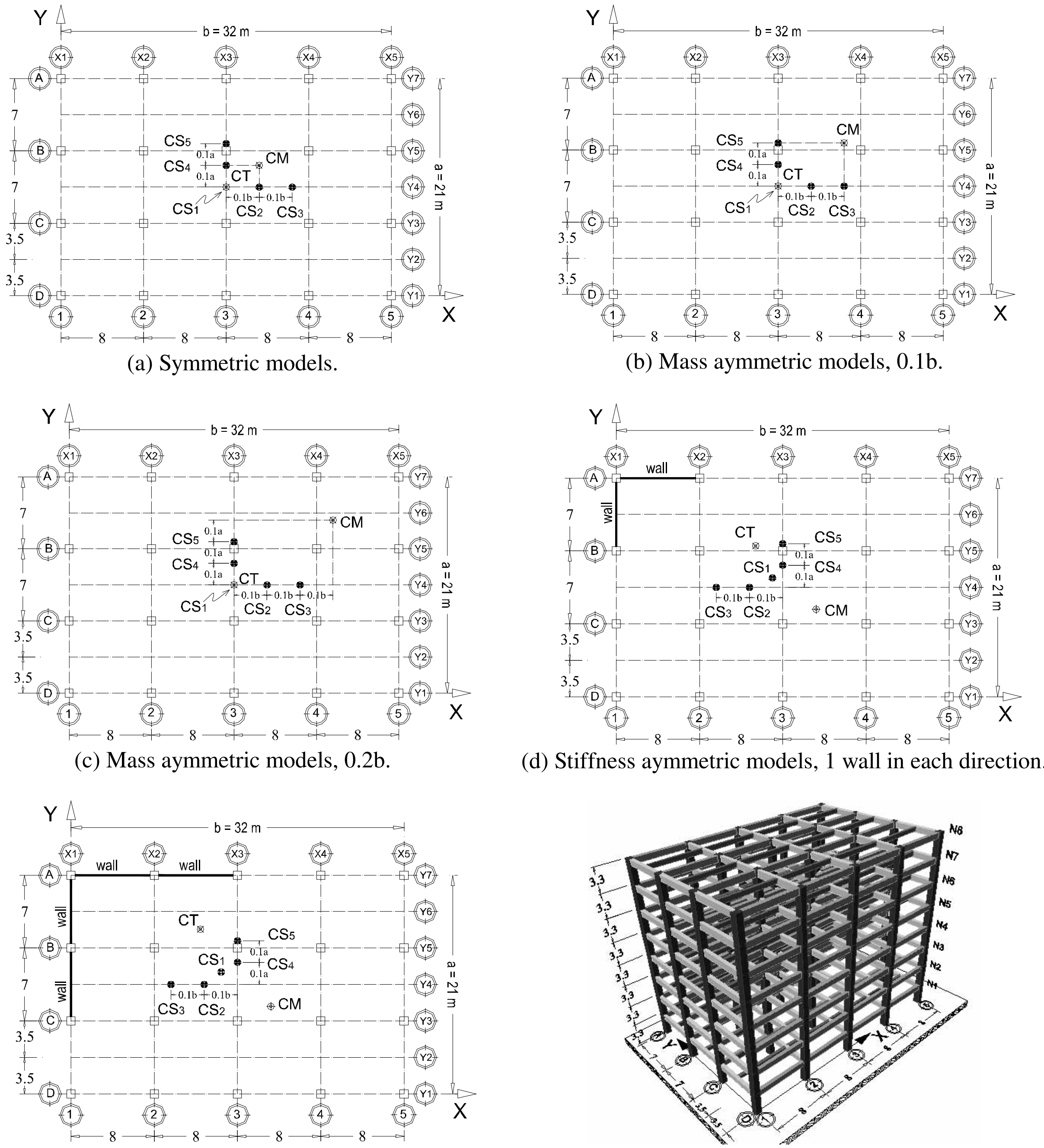
Position of the strength resultant referred to the GC	1.- Symmetric models	2.- Mass asymmetric models (0.1b)	3.- Mass asymmetric models (0.1b)	4.- Stiffness asymmetric models with 1 wall in each direction	5.- Stiffness asymmetric models with 2 walls in each direction
RCDF-93	Msym_original	M01b_original	M02b_original	M11w_original	M22w_original
0.1 b_x	Msym_CS01bX	M01b_CS01bX	M02b_CS01bX	M11w_CS01bX	M22w_CS01bX
0.2 b_x	Msym_CS02bX	M01b_CS02bX	M02b_CS02bX	M11w_CS02bX	M22w_CS02bX
0.1 a_y	Msym_CS01aY	M01b_CS01aY	M02b_CS01aY	M11w_CS01aY	M22w_CS01aY
0.2 a_y	Msym_CS02aY	M01b_CS02aY	M02b_CS02aY	M11w_CS02aY	M22w_CS02aY

Figs 3(a) to 3(e) show the positions of the CS in these models, using a sub-index *i* to indicate the type of model, in accordance with the columns in table 1. Fig. 3(f) illustrates an isometric view of the buildings investigated.

To obtain the different positions of the CS indicated in the first column of table 1 and considering that there are two types of asymmetry, the following criteria were defined (see figs. 3(a) to 3(e)):

a. For symmetric and mass asymmetric models. To move the CS in the X axis direction (CS_2 and CS_3 in figs. 3(a) to 3(c)) the shear strengths of the columns of axis 5 were increased in each of the storeys. Similarly to move the CS along the Y axis (CS_4 and CS_5 in figs. 3(a) to 3(c)) the strengths of the columns of axis A were increased in each storey.

b. For stiffness asymmetric models (with one and two walls in each direction). To obtain the variation of the CS in the direction of the X axis (CS_2 and CS_3 in figs. 3(d) and 3(e)) the strengths of the walls at axis 1 were increased at each storey. While, in the Y axis (CS_4 and CS_5 in figs. 3(d) and 3(e)), the strength of the walls at axis A were increased in each storey.



(a) Symmetric models.

(b) Mass aymmetric models, 0.1b.

(c) Mass aymmetric models, 0.2b.

(d) Stiffness aymmetric models, 1 wall in each direction.

(e) Stiffness aymmetric models, 2 walls in each direction.

(f) Isometric view of the buildings studied.

Figure 3. Typical plans of the five groups of models investigated.

Considering that only the shear strengths were modified keeping the stiffness of the elements constant, table 2 shows the modal vibration periods of the five groups of building models investigated and their respective uncoupled frequency ratios (Ω). Referring back to figs. 3(a) to 3(c) the CT is located in the GC of the plan, whereas in figs. 3(d) and 3(e) the location of the CT as obtained using the layout of the reinforced concrete walls is shown only for the first storey. It is important to mention that for that in all investigated cases only one criterion in the application of the accidental eccentricity was considered, *i.e.*, the CM was moved a distance of 0.1b to its right.

Table 2. Vibration periods and uncoupled frequency ratios, Ortega, [2]

Groups of models	Period, T(s)					$\Omega = T_t / T_\theta$
	Mode					
	1	2	3	4	5	
Symmetric	1.0106 ^{t}	0.9304	0.7173 $^{\theta}$	0.3183	0.2928	1.4160
Mass Asymmetric (0.1b)	1.2001 ^{t}	0.9304	0.6908 $^{\theta}$	0.3784	0.2928	1.7372
Mass Asymmetric (0.2b)	1.4456 ^{t}	0.9277	0.6758 $^{\theta}$	0.4564	0.2921	2.1391
Stiffness Asym. (1 wall)	1.0164 ^{t}	0.6692	0.3208	0.3098 $^{\theta}$	0.1917	3.2803
Stiffness Asym. (2 walls)	1.0245 ^{t}	0.4688	0.3230	0.1929 $^{\theta}$	0.1764	5.3105

NON-LINEAR ANALYSES

To evaluate the response of the structural models considered in this paper several non-linear dynamic analyses were carried out with CANNY-E program, Li [5]. For the seismic excitation the horizontal components of the September 19, 1985 Michoacan earthquake registered at the SCT station were used. For practical purposes, the following assumptions and considerations regarding the non-linear dynamic analysis of the models were made:

- Building models were idealized as assemblages of discrete elements such as beams, columns and walls with particular non-linear behaviour and all connected to rigid nodes.
- For beam and column elements, plastic hinges could only occur at the ends, ignoring all other variations in properties along the length.

To optimize the computational effort involved in the non-linear step by step dynamic analysis of the models, the duration of the intense part of the records (Td) was limited using a criterion based on the elimination of the initial and final segments of the original record each corresponding to 5% of the total Arias intensity (Ia). The procedure used is illustrated in figs 4 and 5.

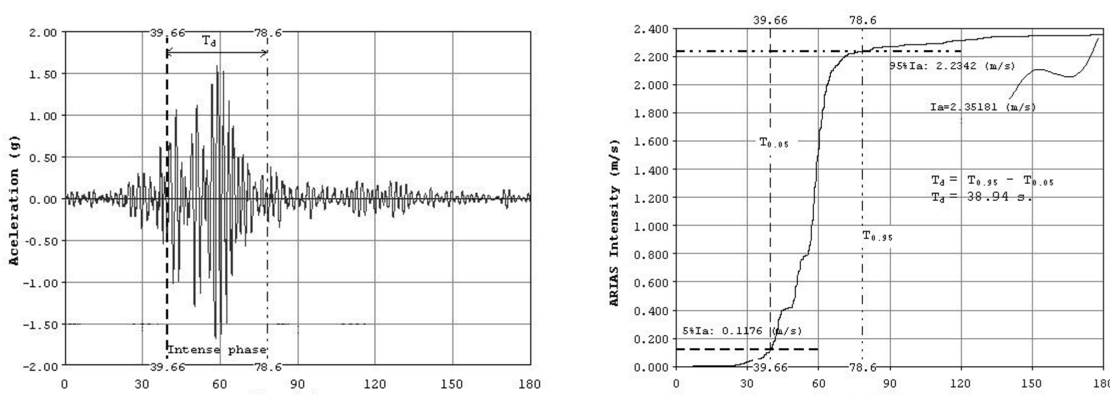


Figure 4. Time history of SCT-EW seismic record and definition of its intense phase.

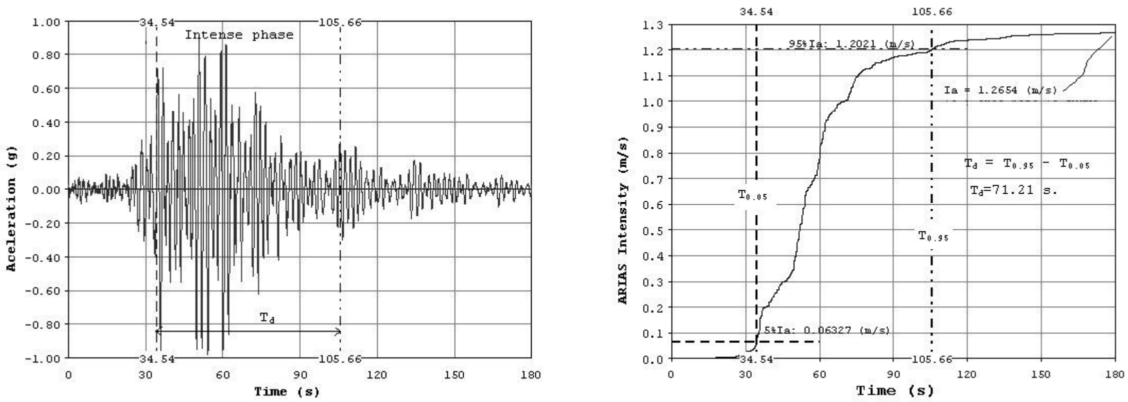


Figure 5. Time history of SCT-NS seismic record and definition of its intense phase.

ANALYSIS AND PRESENTATION OF RESULTS

Due to the large volume of information obtained in this study, a selection of the most important results was carried out with the aim of illustrating the global behaviour of the buildings studied. The figures that follow show exclusively the response of the models in the first storey. For all the models studied storey demands, function of shear force and torsional moment, found from the inelastic analyses in the principal direction of the seismic demand (Y direction), were obtained. These demands were superimposed on the surface of the corresponding SUSST. Also superimposed were the variations of the positions of ICS and the ICSS which, as mentioned before, provided additional information for the interpretation of the seismic response of the buildings investigated. To understand the variation of the ICS and the ICSS it was necessary to study the evolution of their location, identified with different colour dots; before, during and after the intense phase of the earthquake.

Considering that these results were assumed representative of the global behaviour of the buildings studied, figs. 6 to 10 present the histories of the ICSS, ICS and the seismic response, given by the seismic shear force *vs.* torsional moment, of the models M02b_CS02bX, Msim_CS02bX, M01b_original, M22m_CS02aY and M11m_CS01aY, respectively. Fig. 11 shows the layout of the frame with the nomenclature of the structural elements used to identify the local ductility demands produced in the beams of the frame shown in figs. 12 and 13 for all the models studied.

In figs. 6a, 7a, 8a, 9a, and 10a it may be observed that, in general terms, the location of the ICSS presents the largest dispersions when the structural eccentricity is increased in the mass asymmetric models. The stiffness asymmetric models do not show much variation in the location of the ICSS being concentrated around the Shear Centre (SC) in the final phase of the earthquake.

In figs 6b, 7b and 8b it may observed that, for the symmetric and mass asymmetric models, the ICS is concentrated between the CT and the SC. For this type of model the tendencies presented are less disperse than for the stiffness asymmetric models, figs. 9b and 10b; the M11m_CS01aY model presenting the largest dispersions. In this model, it may also be observed that during the initial phase of the earthquake, the ICS tends to be located between the CT and the CS, and then, during the intense phase of the earthquake, the ICS moves towards the GC and finally it is moved to a zone opposite to that corresponding to the maximum design stiffness.

In figs 6c, 7c and 8c the demands of shear force *vs.* torsional moment are superimposed of the SUSSTs of the symmetric and mass asymmetric models. It may be observed that some of the demands lightly fall outside the bounds of the SUSST and present torsional effects, even in the case of the symmetric model, which is a likely condition considering the uncertainty in the position of the CM. However, in the three presented cases it is observed that the non-linear behaviour tends to be localized towards the parallel branches of the corresponding SUSST which have negative slopes, which correspond to the elements located to the left of the GC (structural axis #1). The above observation implies that this axis is maintained elastic while the rest experiment inelastic displacements due to the rotation of the levels and, as a consequence, it would be expected that axis 5 presents larger ductility demands. Another important aspect, identified in the distributions of the seismic demands, is that this becomes larger as structural eccentricity is increased.

In the case of the stiffness eccentric model with one wall (fig. 9c) it may be observed that the demand produces predominant translation mechanisms which do not exceed the SUSST which affect, as in the previous models, the parallel branches with negative slope (structural axis #1).

Fig 10c presents the seismic response of the stiffness eccentric model with two walls. It may be observed that the demand produces torsional effects within the SUSST which increased its dimensions due to the modification of the strength of the structural axis #1. To compare the seismic demand in the elastic range of behaviour with the elastic capacity, a new inner capacity surface was calculated as a function of the elastic strengths of the structural elements. This surface is named the Surface of Elastic Storey Shear and Torque (SECT), which in this case was exceeded by the seismic response. Hence, the zone between the SECT and the SUSST corresponds to the inelastic capacity of the structure. In this model, it is evident that such a capacity was small enough for the structure to develop the plastic hinges presented in fig 13.

As it may be seen, for the two stiffness eccentric models, the non-linear behaviour of the structures was also concentrated towards the parallel branches with negative slopes, that is, the strength corresponding to axis # 1, which explains why axis # 5 was the most demanded.

As the frame along axis # 5 presented the largest displacement demands, it is important to observe the damage distribution experimented by its structural elements. In figs. 12 and 13 it may be observed that the mass asymmetric models with eccentricity equal to 0.2b present the best behaviour while the stiffness eccentric models with one wall present the worst behaviour. It is evident that the mass eccentric models present smaller ductility demands when compared with those of the stiffness eccentric models. Regarding the latter it may be observed that those with two walls with the CS close to the elastic CT had a better behaviour than those with one wall.

Based on the results obtained from the models of the 25 buildings investigated in this work, table 3 presents an ordered list of the models which presented the best and the worst behaviours as a function of the local ductility demands. The first model indicated in table 3 corresponds to the case in which the smallest local ductility demands occurred, and the last model, the largest ductility demands. Models 1 to 5 correspond to mass asymmetric buildings, the remaining to stiffness asymmetric buildings.

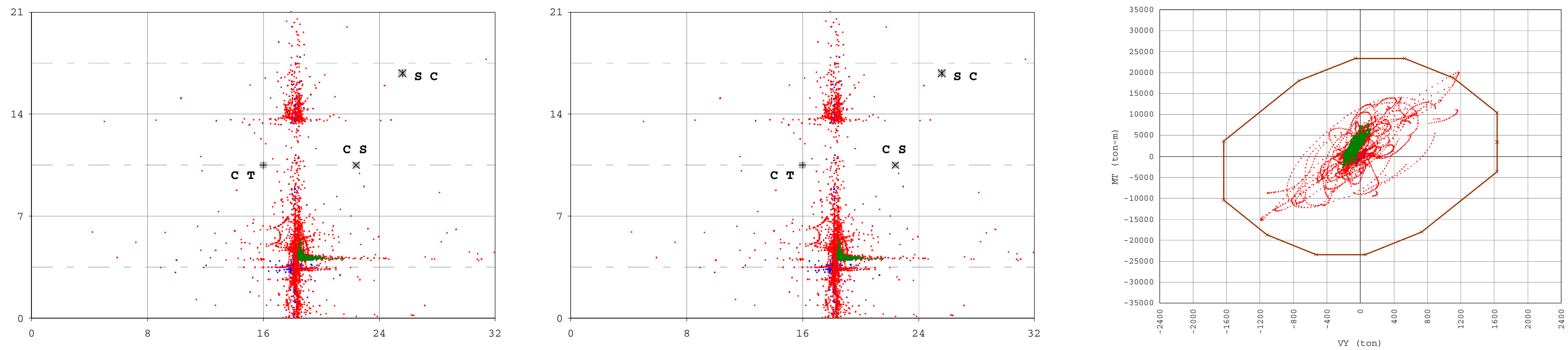


Figure 6. Model M02b_CS02bX. a) Variations of the ICSS. b) Variations of the ICS. c) Shear Force vs Torsional Moment.

- Initial Phase
- Intense Phase
- Final Phase

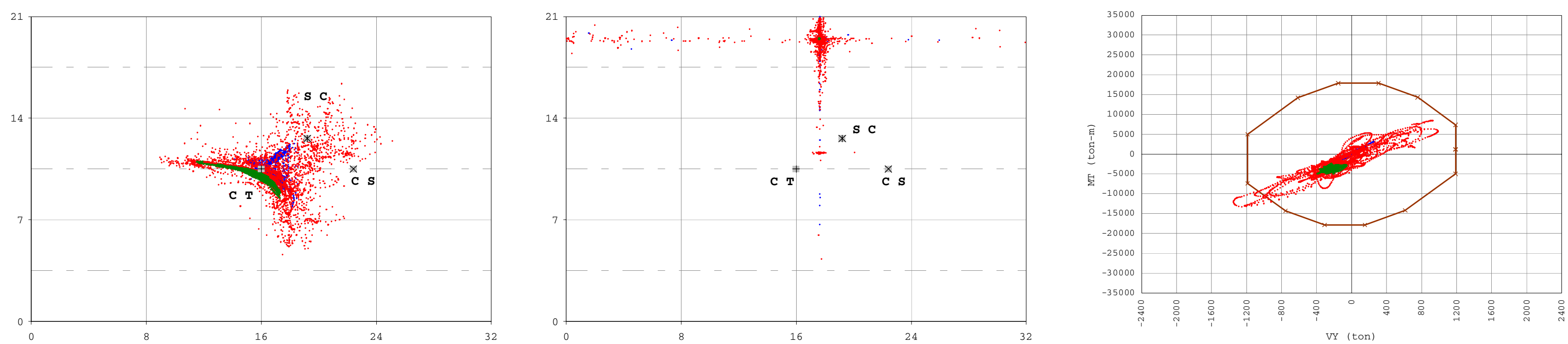


Figure 7. Model Msim_CS02bX. a) Variations of the ICSS. b) Variations of the ICS. c) Shear Force vs Torsional Moment.

- Initial Phase
- Intense Phase
- Final Phase

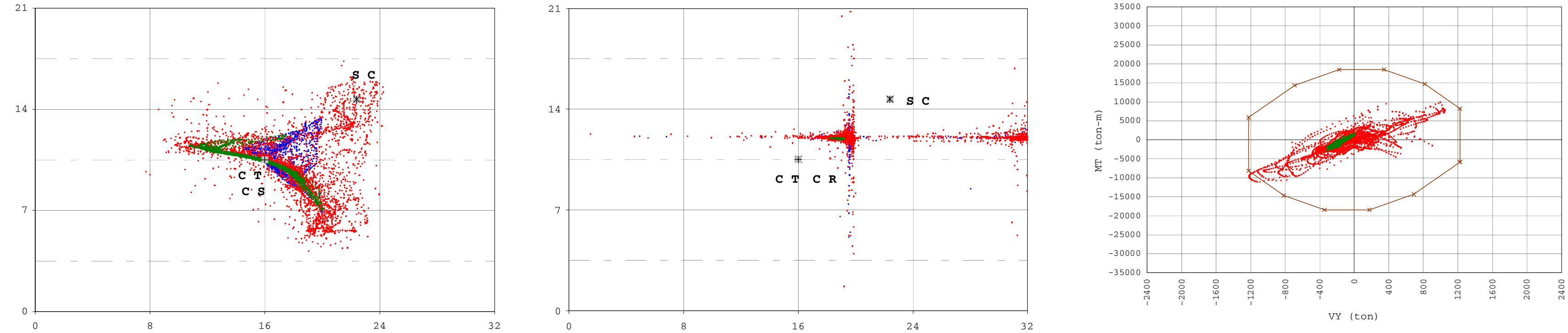


Figure 8. Model M01b_original. a) Variations of the ICSS. b) Variations of the ICS. c) Shear Force vs Torsional Moment.

- Initial Phase
- Intense Phase
- Final Phase

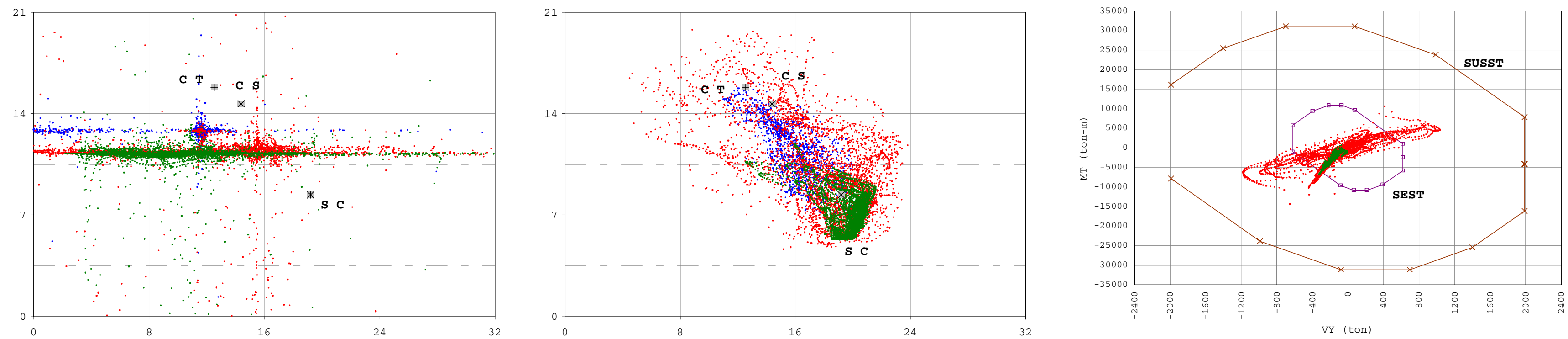


Figure 9. Model M22m_CS02aY. a) Variations of the ICSS. b) Variations of the ICS. c) Shear Force vs Torsional Moment.

- Initial Phase
- Intense Phase
- Final Phase

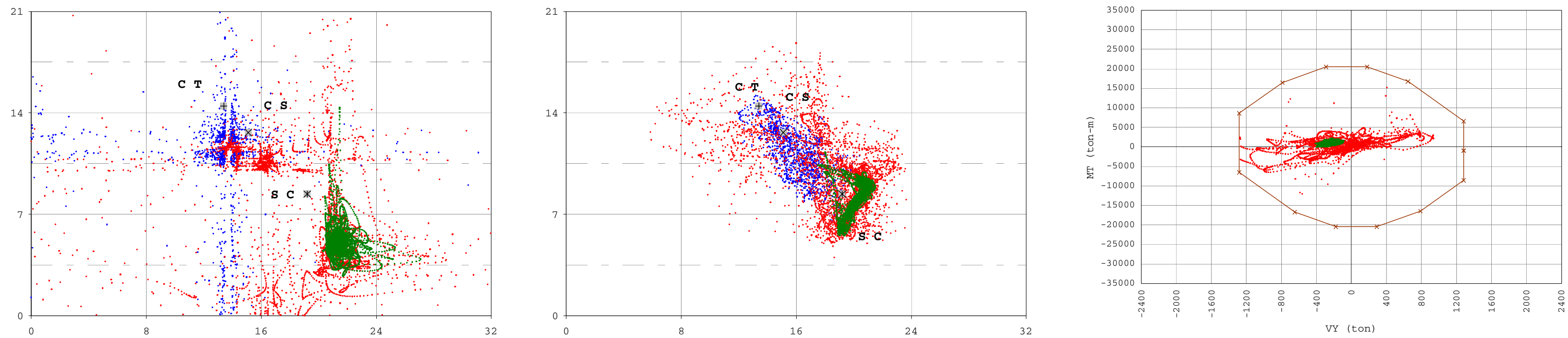


Figure 10. Model M11m_CS01aY. a) Variations of the ICSS. b) Variations of the ICS. c) Shear Force vs Torsional Moment.

- Initial Phase
- Intense Phase
- Final Phase

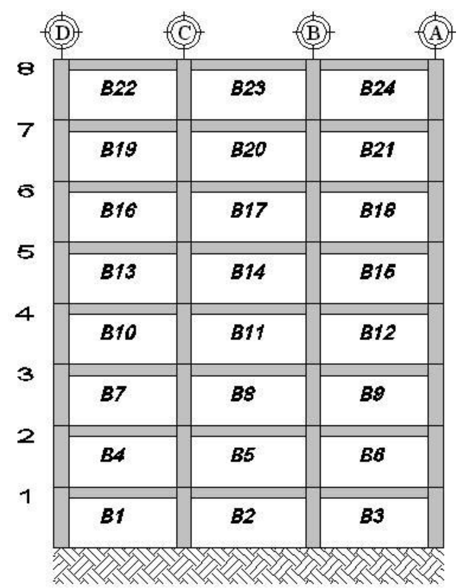


Figure 11. Reference of the numeration of beams in axis 5

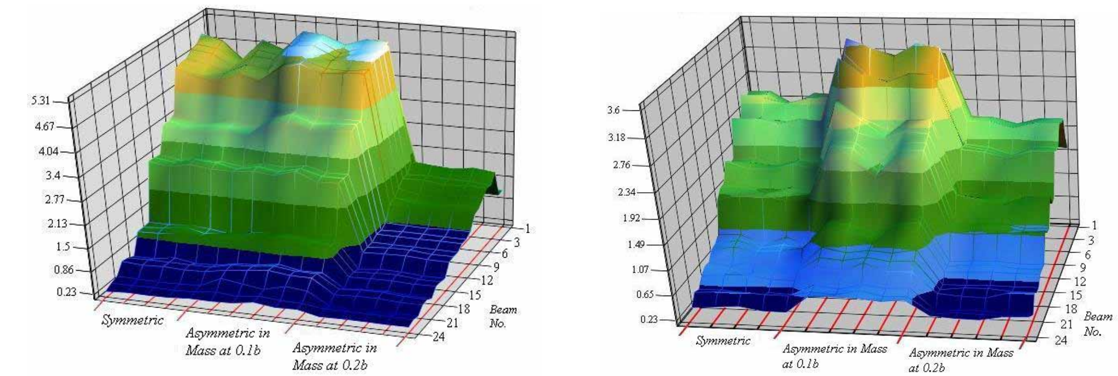


Figure 12. Local ductility demands at the initial and final ends of the beams of axis 5 of the mass asymmetric models.

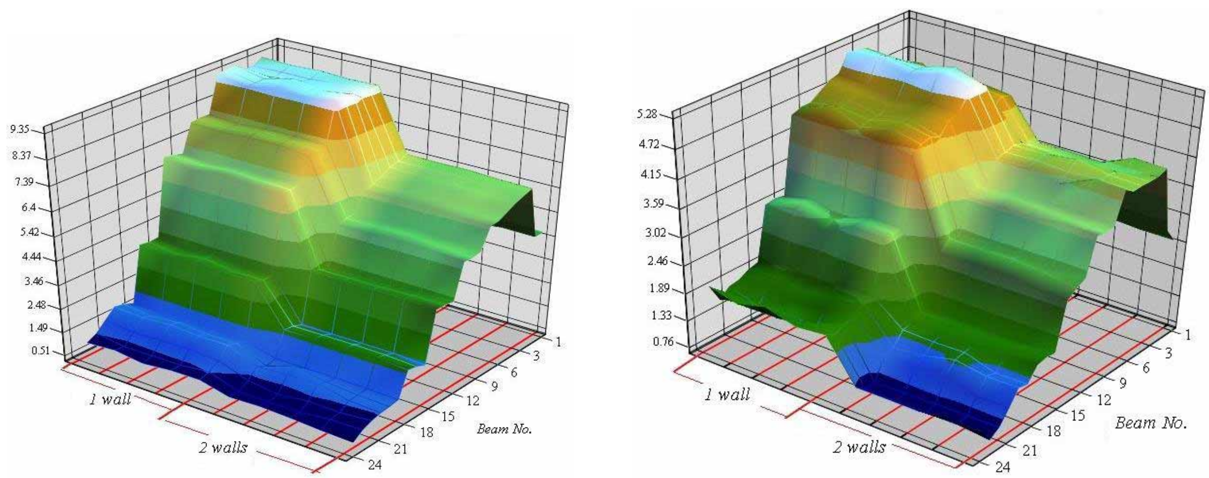


Figure 13. Local ductility demands at the initial and final ends of the beams of axis 5 of the stiffness asymmetric models.

Table 3. Ordered list of the investigated models from best to worst behaviour function of the local ductility demands.

1 M02b_CS02bX	6 Msym_CS02bX	11 M01b_CS02bX	16 M22m_CS02aY	21 M11m_CS02aY
2 M02b_CS02aY	7 Msym_CS02aY	12 M01b_CS02aY	17 M22m_CS01aY	22 M11m_CS01bX
3 M02b_CS01bX	8 Msym_CS01bX	13 M01b_CS01bX	18 M22m_CS01bX	23 M11m_CS01aY
4 M02b_CS02aY	9 Msym_CS01aY	14 M01b_CS01aY	19 M22m_Original	24 M11m_Original
5 M02b_Original	10 Msym_Original	15 M01b_Original	20 M22m_CS02bX	25 M11m_CS02bX

CONCLUSIONS

From the analysis of the results presented in this paper the following conclusions may be drawn:

It is observed that when the shear strength of selected structural axes is increased the response of the different variables involved in the non-linear analysis is modified (ICS, ICSS and the seismic response given by the shear force *vs.* torsional moments). This modification is more noticeable than, for instance, that produced by an increase of the fundamental period of the structure Ortega, [2]. It may be concluded that the torsional seismic behaviour of asymmetric structures, is definitively influenced by the in-plan distribution of strengths, and therefore it may be concluded as one of the most important variables to be considered in future research.

From the variation of the ICS in the different models investigated, it is observed that the uniformity in the location of this point is reflected in a better behaviour than that observed in the models where a large dispersion in location occurred. It is found that structural eccentricity influences the way in which the location of the ICS is distributed in the floor plans of the building. The variation of the ICSS in mass asymmetric buildings is different to that found in the corresponding stiffness asymmetric buildings, being the former those that in general have a better behaviour represented with smaller local ductility demands. It is found that the location of the ICSS presents a larger dispersion with increasing strength eccentricity.

The irregular shape of some of the storey capacity surfaces is due to the asymmetric distribution of strengths, obtained from the static pushover analysis of the models. All seismic responses of shear force vs. torsional moments indicate that axis 5 (the most flexible for the stiffness asymmetric models and the nearest to the SC in the mass asymmetric models) presents the largest inelastic displacements.

When the CS was localized near the SC in the mass asymmetric models the best behaviour was obtained. While in the stiffness asymmetric models the best behaviour occurred when the CS was near the CT. It is important to clarify that the behaviour of the models was evaluated not only as function of their local ductility demands but also by the checking of the tendencies shown by the ICS and the ICSS and in a very important way as a function of the capacity of the structure compared with the seismic demand of shear force *vs*. torsional moment.

The results obtained are congruent with those previously obtained from investigations at the Institute of Engineering and elsewhere based on simplified one-storey models, in which the best behaviour was found in those cases in which, regardless of the type of asymmetry, the distributions of strengths and stiffnesses followed the same pattern*, i.e.,* when the CT and the CS are very close. However, the results presented in this paper indicate that the above conclusion is strictly valid only for the models of stiffness asymmetric buildings, as for the cases of mass asymmetric buildings; the best behaviours were found when the CS is closer to the SC.

In this work it has been observed that increasing the strength of certain structural planes does not necessarily produce smaller local ductility demands, *i.e.,* a stronger structure does not guarantee a better behaviour. This observation is also valid for simplified one-storey models.

FINAL COMMENTS AND RECOMMENDATIONS

Hopefully, the future development of computer equipment and computational tools, as well as the availability of experimental results of the behaviour of structural elements and systems which allow the correct modelling of the non-linear hysteretic behaviour of the resisting structural elements will make possible in the near future to count on a larger number of studies based on more realistic and complex models than those used in this work.

This paper shows that the investigation of torsion in buildings is a complex problem that requires further research efforts using sets of torsionally coupled buildings representative of those in Mexico City and subjecting them to more general seismic demands.

It is imperative that future investigations consider the most adequate way to determine the seismic capacity of the resisting planes in the evaluation of the torsional seismic response of buildings as this has a significant influence in the calculation of the storey capacity surface as well as its geometry.

Recent investigations in progress have shown the importance of soil–structure interaction on the torsional response of asymmetric structures and it is highly recommended that this issue be considered in future studies.

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