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ESTIMATION OF RELATIVE DISPLACEMENTS ON EQUIPMENT OR SECONDARY STRUCTURES UNDER SEVERE EARTHQUAKE EXCITATION

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Abstract

The design of equipment or substructures mounted on industrial structures is commonly addressed from the perspective of the adequacy of the anchoring system. The results for the design of the supports and anchoring devices in terms of forces, accelerations, and displacements and also for the study of the behavior of the equipment are obtained from the same analysis carried out for the primary structure, which is usually a response spectrum analysis (RSA) that considers a response modification factor to take into account in a very approximate manner the energy dissipation behavior of the primary structure.

The codes allow estimating the “expected displacement” of the structures through the amplification of the displacements obtained from the RSA (for reduced earthquake action) by a factor similar or equal to the response modification factor, based mainly on the “equal displacement rule”. However, the nonlinear behavior inherent to the equipment or substructure, if it exists, is completely independent from the nonlinear behavior of the primary structure. Furthermore, in many cases the configurations of the equipment or substructure are not comparable to the configurations of the primary structures and therefore the applicability of the provisions of the codes is at best uncertain.

A parametric evaluation of the displacements of a range of secondary structures has been carried out using time-history analysis considering different levels of nonlinear behavior in the primary structure while the secondary structure has been made to remain elastic. Average results over a set of 10 ground motions have been compared with the estimations obtained from the RSA results considering the average spectrum of the ground motions, for a range of period of the primary structure and a range of ratios between the secondary and the primary structures.

The results from linear and nonlinear analyses are compared first in terms of the story shears and interstory drifts of the primary structure and also in terms of the drifts in the secondary structure. The primary structure results confirm the trends in the behavior already observed by many researchers, while the set of results for the secondary structure drifts show that using the same approach for the estimation of "inelastic" values is always a "safe side assumption" but in some cases can grossly overestimate the results.

Keywords: Secondary systems; Industrial structures; Expected seismic demand; Relative displacements

1. Introduction

In normal engineering practice the design of equipment or substructures mounted on industrial structures is usually addressed from the perspective of the checking the adequacy of the anchoring system. The results for the design of the supports and of the anchoring devices in terms of forces, accelerations, and displacements and also for the study of the behavior of the equipment are obtained from the same analysis carried out for the primary structure, which is usually a response spectrum analysis (RSA) that considers a response modification factor to take into account in a very approximate manner the possible energy dissipation behavior of the primary structure. This procedure is used even in those cases where the secondary structure or equipment is fully represented in the analysis model.

The seismic design codes allow estimating the “expected displacements” of the structure when subject to the design level earthquake action through the amplification of the displacements obtained from the RSA for reduced earthquake action by a factor similar or equal to the response modification factor, following the well known “equal displacement rule”. This procedure is usually extended to the computation of the displacements in the secondary structure. However, in the actual structure the nonlinear behavior inherent to the secondary structure or equipment, if it exists at all, is completely independent from the nonlinear behavior of the primary structure. Furthermore, in most cases the "structural" configuration of the secondary structure or equipment is not comparable to the configuration of the primary structure and therefore the applicability of the provisions of the codes is at best uncertain.

In this study, which has the aim to explore the problem and to identify the relevant parameters, some insight is provided on how to correctly estimate the expected seismic demand (displacements, forces) on a secondary structure or a component of an equipment mounted on a primary structure, using the results of an analysis performed using the standard engineering practice approach (RSA based on a reduced design spectrum).

2. Methodology

A parametric evaluation of the displacements of a range of secondary structures (defined in terms of the ratio of the fundamental period of the secondary and the primary structure) has been carried out using nonlinear time-history analysis considering different levels of nonlinear behavior in the primary structure (defined in terms of a design based on using different values of a response modification factor, R). Average results over a set of ground motions have been compared with the estimates obtained from the RSA results for a range of periods of the primary structures.

2.1 Analysis Models

The structural system model chosen for this exploratory analysis is a simple plane frame as shown in Fig.1, which consists of a three-story "shear behavior" type building (that will be called the primary structure) with a secondary structure (representing an equipment) attached at the intermediate floor of the building. Both the primary and the secondary structure models consider lumped masses at the different levels and therefore only three lateral displacements degrees of freedom (at the corresponding floor levels) are needed for each the primary and the secondary structure.

Three different primary structures have been considered for the study. The three floor weights (masses) have been defined to be identical for the three buildings, W_p=5000kN. The values of the story stiffness have been selected, in the ratios shown in Fig.1, to obtain values of the fundamental period of 0.223, 0.447, and 0.670 seconds for each of the three structures respectively. The three primary structure models are identified as Primary 1, Primary 2, and Primary 3 respectively, ordered as their fundamental period increases.

For each primary structure 5 different secondary structures have been considered, obtaining a total of 15 different analysis models. The floor weights (masses) of the secondary structures/equipment have been defined in the proportions shown in Fig.1 with W_s=500kN for all of them. Thus the secondary structures represent 28.5% of a single floor mass and 11.8% of the total mass of the structure. The values of the story lateral stiffness, that are the same for the three levels, have been selected to obtain values of the fundamental period of $0.5T_p$, $0.75T_p$, T_p, $1.5T_p$, and $2T_p$; where T_p is the value of the fundamental period of the primary structure.

The lateral story stiffness chosen for each primary and secondary structure of the 15 combined models considered are summarized in Table 1 together with the values of fundamental period obtained for each case of primary structure, secondary structure, and combined analysis models.

The range of fundamental periods covered by the combined analysis models goes from 0.242s to 1.378s, considering primary structures with fundamental periods of 0.223s, 0.447s, and 0.670s showing the significant impact of the secondary structures in defining the final dynamic behavior properties of the system. An example of this is the observation that the first mode of the combined analysis models having $T_s > T_p$ have modal participating mass ratios of 28% and 18%, being these vibration modes associated to the secondary structure. Because of this, also the second vibration modes, which have the largest modal participating mass ratios, also have been included in Table 1.

2.2 Earthquake action

2.2.1 Horizontal ground motion acceleration records

Ten records of horizontal direction ground accelerations recorded during the large Chilean earthquake of 2010-02-27 (Mw=8.8) [2] have been used for the evaluation of the displacements of the secondary structures. The records have been selected by visual inspection, to approximately match the shape of the pseudo acceleration spectrum of each record normalized to PGA = A_o = 0.4g with the shape of the acceleration design spectrum defined by the Chilean code for the seismic design of Industrial Installations NCh2369 [1] for A_o = 0.4g, Soil Type B, and 5% damping ratio. The records selected for the analyses are shown in Table 2.

2.2.2 Response spectrum

The acceleration response spectrum used as input for the response spectrum analysis (RSA) has been obtained as the average of the 5% damping ratio response spectra of the 10 horizontal acceleration records (normalized to PGA=0.4g) selected for the study. Fig.2 below shows the 5% damping ratio response spectra of all the acceleration records and the resulting average response spectrum used for the analysis.

2.3 Analysis procedure

The analyses have been carried out using the SAP2000 software [3], where the models of the structures were implemented. The modal analyses were carried out using eigenvectors and the full set of modes of the structures was considered in all cases (6 mode shapes).

For this study linear modal and "nonlinear modal" (FNA) time-history analysis methods as implemented in the software have been used instead of the linear direct integration and nonlinear direct integration time-history methods in order to expedite the process due to the number of analysis cases carried out. The FNA approximate method provides results with errors up to 6% with respect to the direct integration method when results of internal forces for a single record are compared. For the average values of the results over the set of records selected, the errors in the FNA procedure with respect to the direct integration method do not exceed 2%.

The damping for all the modal time-history analysis models has been specified as Rayleigh type (mass and stiffness) proportional damping with coefficients obtained from defining 5% damping ratio for the first and last (sixth) vibration mode of each of the 15 linear analysis models.

2.3.1 Linear modal time-history analysis (THA)

The maximum axial forces in the three braces of the primary structure have been computed for the 10 ground motion acceleration records using linear modal time-history analysis. The values of the maximum axial forces in the braces have been averaged over the set of 10 records to obtain the “elastic” design force (R=1) of the braces of each story for each of the 15 linear analysis models.

2.3.2 Nonlinear modal time-history analysis (FNA)

The design forces of the primary structure braces obtained from the THA have been used as reference values to define the nonlinear force-deformation relationship of the brace elements to be used in the FNA analyses for different levels of nonlinear behavior. Three levels of inelastic response have been chosen for the nonlinear analyses by using three different values of the response modification factor: R=2.0, R=3.0, and R=4.0.

The force-deformation curves for the nonlinear behavior of the brace elements have been defined by a multilinear plastic model that uses Takeda hysteresis type, specifying the “yield force” equal to the elastic design force of each brace divided by the response modification factor considered, as it is normally done in seismic design of structures. The post-yield stiffness has been defined to be 20% of the initial stiffness of the element. The nonlinear behavior model was implemented using “link” elements, included in the element library of the SAP2000 software [3], which have the capability to represent several types of nonlinear behavior, among then the "Takeda Model".

The nonlinear modal time-history analysis or FNA has been carried out for 45 nonlinear analysis models obtained from including nonlinear behavior by using link elements with strength based on R=2.0, R=3.0, and R=4.0 in each of the 15 cases of linear analysis models previously defined.

2.3.3 Response spectrum analysis (RSA)

The response spectrum analysis has been performed for the 15 cases of linear analysis models using the average “elastic” response spectrum (R=1) computed from the horizontal acceleration records. The results obtained from these analyses are used to compare the drifts of the secondary structures obtained from the nonlinear time-history analyses with the drifts of the linear response spectrum analysis, as commonly used in professional practice.

3. Results

The 45 nonlinear analysis models have been subjected to the 10 records of horizontal ground acceleration obtaining a full set of results for each case. As an example, Fig.3 shows the input of horizontal ground acceleration of the "Constitución L" record normalized to PGA=0.4g, and Fig.4 shows one of the observed response quantities: the relation between the first story drift response and the base shear response of the primary structure for the nonlinear analysis case Primary 2, $T_s = 0.5T_p$ with R=3.0 for this record.

In the following discussion of the results obtained, the story forces and interstory drifts of the primary structure obtained from the nonlinear FNA and the linear RSA analyses are compared and found to behave as described previously by other researchers [4, 5, 6, 7]. Then the most relevant results of this work are presented in terms of the comparison between the drifts of the secondary structures coming from the nonlinear FNA and linear RSA analyses for the complete set of analysis models considered.

3.1 Story forces of primary structure

The story force values of the nonlinear analysis models considered are averages of the maximum values of story forces over the set of 10 horizontal acceleration records. For example, the value of the story force for the second story of nonlinear analysis case Primary 2, $T_s = T_p$ with R=4.0 has been obtained averaging the maximum values of the story force of the second story of the structure computed for each of the 10 records.

The ratio between the average over the set of ground motions considered of the maximum story forces obtained from the FNAs and the story forces obtained from the RSA have been computed to obtain the average "effective response modification factors" of the structures for each story. For each nonlinear analysis case, the "yield strength" of the nonlinear link elements is defined as the corresponding story force as obtained from the RSA divided by the defined R factor for the complete structure. After the FNA is carried out, the average of the results for the link element maximum forces over the set of ground motions is computed. Since this maximum force includes the effect of the post-yield stiffness of the link element, the actual maximum values of the forces in the elements are larger than the "yield strength" of the elements, and the "effective response modification factors" are smaller than the R factor selected for the design of the complete structure.

Table 3 shows the values of the effective response modification factors of the story forces of the different analyses cases carried out for R=2.0, R=3.0, and R=4.0. The average values over the entire set of analyses cases for each response modification factor R are also included with the corresponding values of standard deviations.

3.2 Story drifts in the primary structure

The values of the story drifts of the primary structure of the nonlinear analysis models considered are averages over the 3 stories of the averages of the maximum story drifts of the ten cases of ground acceleration records. For example, the value of the drift value of nonlinear analysis case Primary 2, $T_s = T_p$ with R = 4.0 has been obtained averaging the maximum story drifts of the FNAs results over the 10 ground acceleration records and then over the three stories obtaining a single drift value for the primary structure. Similarly, the drift values of the linear analysis models considered are the averages over the 3 stories of the drifts obtained from the RSA.

The ratio between the average drifts of the primary structure obtained from the linear analysis using RSA and the average drifts obtained from the nonlinear analysis cases using FNA have been computed to obtain the parameter C_{dp}/R for each of the 45 nonlinear analysis models, where C_{dp} is the deflection amplification factor by which the drifts of a linear analysis using RSA and a "reduced" spectrum shall be multiplied to obtain the expected maximum drifts from nonlinear analysis computed using FNA. The parameter C_{dp}/R provides the proportion of the response modification factor R that shall be used as C_{dp} to obtain the expected maximum drifts from nonlinear analysis from the results of the linear analysis using the reduced response spectrum.

The curves shown in Fig.5 illustrate the behavior of the ratio C_{dp}/R for the range of secondary structures, in terms of secondary to primary structure fundamental period ratio, defined for each of the three primary structures cases and considering R=2.0, R=3.0, and R=4.0. Fig.6 shows the same curves, but plotted against the actual values of the fundamental periods of the combined analysis models.

3.3 Drifts in the secondary structure

The drift values of the secondary structure of the nonlinear analysis models considered are averages over the three stories of the averages of the maximum interstory drifts over the ten cases of horizontal acceleration records. For example, the value of the drift value of nonlinear analysis case Primary 2, $T_s = T_p$ with R=4.0 has been obtained averaging over the 10 records the maximum interstory drifts obtained from the nonlinear FNAs and then averaging over the 3 stories obtaining a single drift value for the secondary structure. Similarly, the drift values of the linear analysis models considered are averages over the three stories of the interstory drifts of the secondary structure obtained from the RSA cases.

The ratio between the average drifts of the secondary structures obtained from the RSAs and the average drifts obtained from the FNAs have been computed to obtain the parameter C_{ds}/R for each of the 45 nonlinear analysis models, where C_{ds} is the deflection amplification factor by which the drifts computed from the linear RSA using a reduced spectrum shall be multiplied to obtain the maximum values of the drifts computed using nonlinear analysis. The parameter C_{ds}/R provides the proportion of the response modification factor R that shall be used as C_{ds} to obtain the maximum values of inelastic behavior drifts from maximum values obtained from RSA using a reduced spectrum.

The curves shown in Fig.7 illustrate the behavior of the parameter C_{ds}/R for the range of secondary structures, in terms of secondary to primary structure fundamental period ratio, defined for each of the three primary structures considering R=2.0, R=3.0, and R=4.0. Fig.8 shows the same results, but plotted against the actual values of fundamental periods of the analysis models.

3.4 Discussion

The analysis models used in this study consider a secondary structure or equipment that has a total mass that is relevant compared to the mass of the primary structure, and more so compared to the mass of a single story; therefore, the equipment has a major influence on the dynamic behavior properties of the system. This is clearly seen for example in the variation of the fundamental period of the combined structure model as the ratio of the secondary structure fundamental period to primary structure fundamental period is changed.

The post-yield stiffness of the brace elements that provide the nonlinear story force-deformation curves was defined as 20% of the elastic stiffness of the stories; then, when the "equal displacement" rule is applied it is not feasible to define a system that uses values of the R factor larger than 5.0. On the other hand, the so called "effective R factors" obtained from the comparison of the analysis results are always smaller than the value of R selected and percentage in which they decrease with respect to the R value selected increases as R becomes larger. Based on this, the response modification factor values have been limited to R = 4.0 (see Table 3).

The results obtained for the C_{dp} /R ratio of the primary structure are consistent with results from previous studies (see for example [4], [5], [6], and [7]) showing that to consider C_{dp} = R for structures that are rigid (short period) and have large ductility (large R) is not conservative. Fig.6 clearly shows this effect where the curves for primary structures with T_p = 0.223s (Primary 1) show that C_{dp} > R is required to correctly estimate the interstory drifts, being those cases with larger R values the ones that deliver a worse estimate for the drift of the primary structure when C_{dp} = R is used. The relationship between the R value with the quality of the drift estimation using C_{dp}=R disappears for structures with fundamental period larger than 0.7s as was also shown in reference [4].

In Fig.5 the trend described above can be easily identified and the results clearly show that the responses are grouped into sets of 3 curves corresponding to the primary structure period. The maximum values of the ratio C_{dp}/R are obtained for the analysis models which consider $T_s = T_p$, caused by the dynamic amplification effect due to the tuning of the secondary structure with the primary structure. This amplification effect is attenuated for primary structures with larger fundamental period.

In the case of the drift of the secondary structures it is observed that the ratio C_{ds}/R is always less than one for all cases considered (Fig.7 and Fig.8). Therefore it is always conservative to consider C_{ds} = R for estimating the drift of the secondary structure from the RSA results considering a reduced spectrum. However, it is evident that there is range of structures (as R increases) where this approach can be extremely conservative.

In Fig.7, it can be seen that the response curves of the analysis models are grouped according to the values of the R factors considered where, in general, structures with larger R values show smaller C_{ds}/R ratios. Contrary to the dynamic amplification effect observed for the interstory drift of the primary structure, the analysis models where $0.75\ T_s \leq T_p \leq T_s$, show the lowest values of the C_{ds}/R ratio.

A simplified criterion to set design values for C_{ds}/R ratio may be defined according to the T_s / T_p ratio. When $T_s > T_p$, use C_{ds}/R = 1.0; and when $T_s \leq T_p$, use C_{ds}/R = 0.8. In the cases where $T_s \leq T_p$, the dependency of the C_{ds}/R ratio on the R value is stronger, so it is considered possible to establish a relationship of the form C_{ds} / R = (1 - R/10). However, since this study did not include values of the T_s / T_p parameter smaller than 0.5 or values of the R factor larger than 4.0, it is not clear that a simple relationship like this can be extrapolated beyond the range of cases considered.

The dependency of the C_{ds} and the C_{dp} factors on the parameters can be examined by looking at the results of the ratio of the two quantities as shown in Fig. 9 and Fig. 10. The curves for the results have, in general, the same shapes and are clearly grouped in 3 sets depending on the value of the fundamental period of the primary structure. They show the same trend as the value of R changes and as the ratio between secondary and primary structure fundamental periods changes. As a consequence, it is quite clear that the two quantities cannot be estimated by the same function of T_p, R, and T_s/T_p, and that the three parameters examined are quite relevant. The differences in the values of C_{dp} and C_{ds} appear to be larger for primary structures with shorter periods, and the influence of the R factor seems to decrease as the fundamental period of the primary structure increases.

4. Conclusion

Based on a straight forward comparison of the interstory drifts results in a simple model of a primary structure that includes a secondary structure obtained from a set of linear analyses using RSA and nonlinear analyses using FNA for 45 different cases of analysis models subjected to 10 ground motion records of the large earthquake of 2010 in Chile, the following conclusions can be obtained:

- The C_{dp}=R rule considered for the estimation of inelastic deflections of the primary structure from elastic analyses results as recommended by the NCh2369 Chilean code, and similarly used by other seismic codes around the world, provides values that are smaller than the true results and the effect is worse for structures designed with large R factors and that have short periods.

- It is conservative to consider the $C_{ds} = R$ rule for estimating the drifts of the secondary structures or internal deformations of equipment from the results an elastic response spectrum analysis using a reduced spectrum.
- A simplified and conservative criterion to provide design values for the C_{ds} deflection amplification factor to be used in secondary structures or equipment can be proposed as:

$$C_{ds} = R, \quad \text{for } T_s > T_p;$$

$$C_{ds} = 0.8R, \quad \text{for } T_s \leq T_p.$$

5. References

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Table 1 – Periods and modal participating mass ratios of the first two vibration modes of the combined analysis models; and story stiffness and fundamental period of primary and secondary structures.

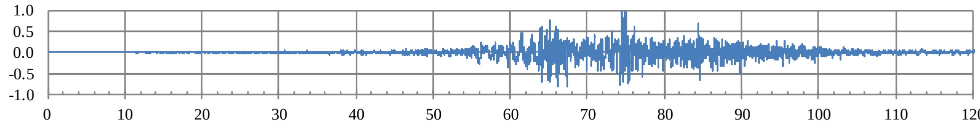
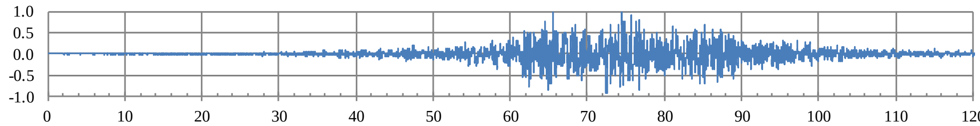
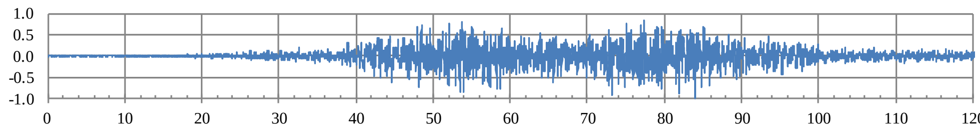
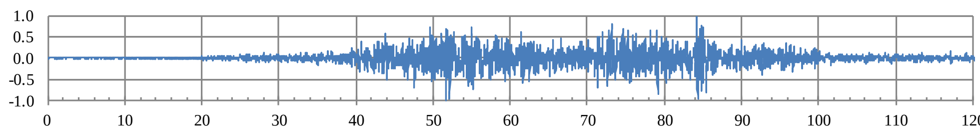
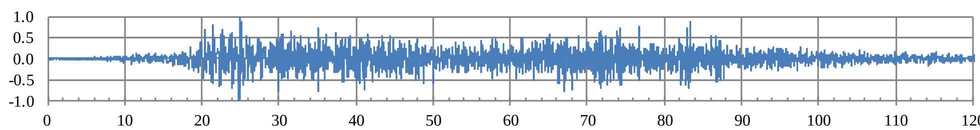
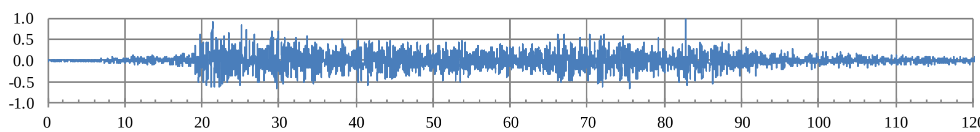
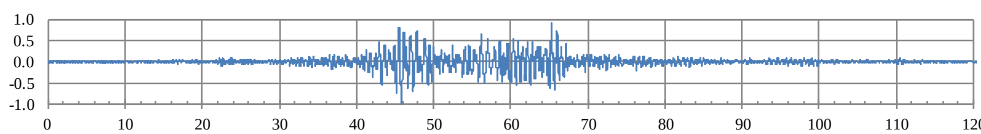
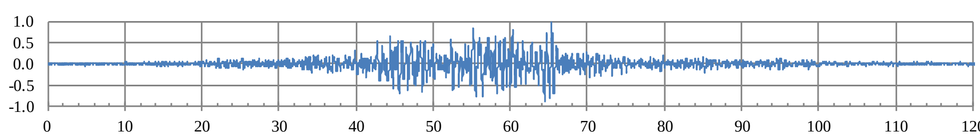
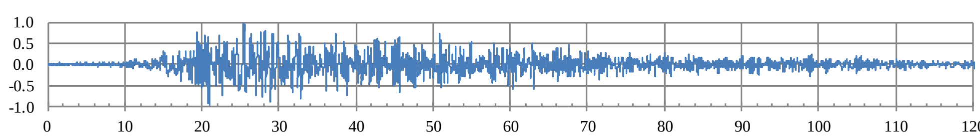
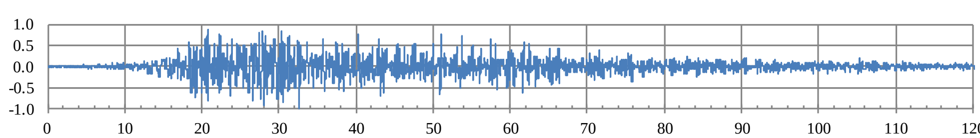
Combined analysis models					**Secondary Structure**		**Primary Structure**	
Properties	**T_1 (s)**	**M_1^* (%)**	**T_2 (s)**	**M_2^* (%)**	**k_s (kN/mm)**	**T_s (s)**	**k_p (kN/mm)**	**T_p (s)**
Primary 1, T_s=0.5T_p	0.242	85	0.113	0	1210	0.112	3009	0.223
Primary 1, T_s=0.75T_p	0.250	82	0.156	3	538	0.168		
Primary 1, T_s=T_p	0.269	65	0.190	20	302	0.224		
Primary 1, T_s=1.5T_p	0.354	28	0.215	57	134	0.337		
Primary 1, T_s=2.0T_p	0.459	18	0.220	67	76	0.449		
Primary 2, T_s=0.5T_p	0.484	85	0.226	0	302	0.224	752	0.447
Primary 2, T_s=0.75T_p	0.499	82	0.311	3	134	0.337		
Primary 2, T_s=T_p	0.538	65	0.380	20	76	0.449		
Primary 2, T_s=1.5T_p	0.708	28	0.430	57	34	0.673		
Primary 2, T_s=2.0T_p	0.919	18	0.441	67	19	0.898		
Primary 3, T_s=0.5T_p	0.726	85	0.40	0	134	0.337	334	0.670

Combined analysis models					Secondary Structure		Primary Structure	
Properties	**T_1 (s)**	**M_1^* (%)**	**T_2 (s)**	**M_2^* (%)**	**k_s (kN/mm)**	**T_s (s)**	**k_p (kN/mm)**	**T_p (s)**
Primary 3, T_s=0.75T_p	0.749	82	0.467	3	60	0.505		
Primary 3, T_s=T_p	0.807	65	0.570	20	34	0.673		
Primary 3, T_s=1.5T_p	1.061	28	0.645	57	15	1.010		
Primary 3, T_s=2.0T_p	1.378	18	0.661	67	8	1.347		

Table 3 – Effective response modification factors computed for story forces of the primary structure.

	R = 2.0			**R = 3.0**			**R = 4.0**		
Model	**Story 1**	**Story 2**	**Story 3**	**Story 1**	**Story 2**	**Story 3**	**Story 1**	**Story 2**	**Story 3**
1a	1.70	1.79	1.82	2.17	2.33	2.29	2.44	2.54	2.47
1b	1.67	1.75	1.71	2.08	2.23	2.08	2.33	2.44	2.16
1c	1.48	1.61	1.55	1.76	1.87	1.70	1.91	2.00	1.71
1d	1.46	1.54	1.71	1.67	1.73	2.07	1.77	1.84	2.13
1e	1.43	1.49	1.61	1.75	1.83	2.13	1.90	2.00	2.32
2a	1.66	1.75	1.78	2.25	2.31	2.31	2.71	2.70	2.68
2b	1.67	1.71	1.64	2.24	2.24	2.09	2.64	2.64	2.41
2c	1.57	1.60	1.51	2.03	2.04	1.86	2.36	2.38	2.10
2d	1.49	1.53	1.58	1.91	1.92	2.14	2.27	2.26	2.55
2e	1.53	1.54	1.52	2.00	2.08	2.03	2.39	2.41	2.44
3a	1.79	1.77	1.67	2.38	2.44	2.28	2.92	2.96	2.72
3b	1.78	1.76	1.66	2.39	2.40	2.24	2.94	2.93	2.69
3c	1.73	1.71	1.54	2.27	2.26	2.05	2.75	2.76	2.50
3d	1.65	1.58	1.56	2.14	2.11	2.19	2.53	2.47	2.72
3e	1.58	1.63	1.53	2.15	2.12	2.06	2.57	2.57	2.55
Average	1.63			2.10			2.43		
Std. Dev.	0.10			0.20			0.32		

Table 2 – Horizontal ground acceleration records, Maule 2010 earthquake, M_w = 8.8.

Record	**PGA(g)**	**A(t)/PGA**
Santiago T	0.308	
Santiago L	0.215	
Curicó EW	0.414	
Curicó NS	0.475	
Talca T	0.416	
Talca L	0.471	
Viña Centro EW	0.331	
Viña Centro NS	0.219	
Constitución T	0.626	
Constitución L	0.538	

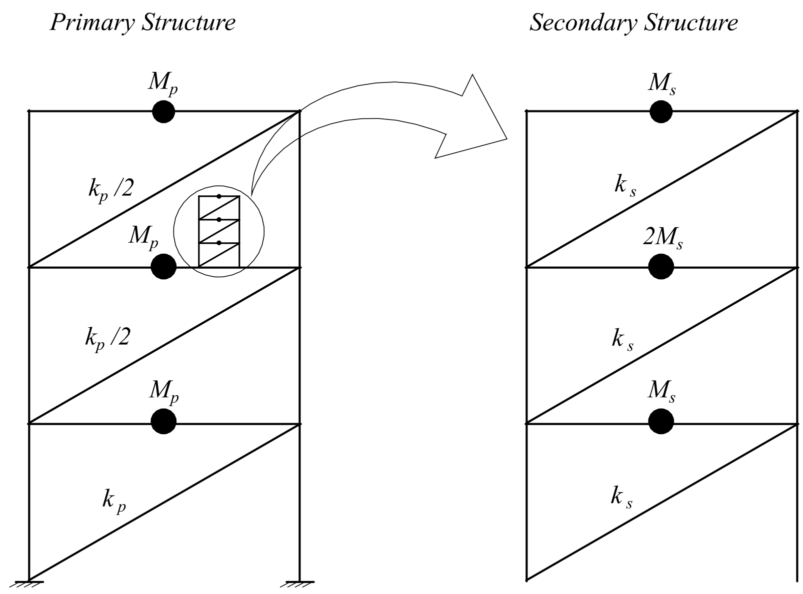


Fig. 1 – Mass and Stiffness configuration of the different combined analysis models

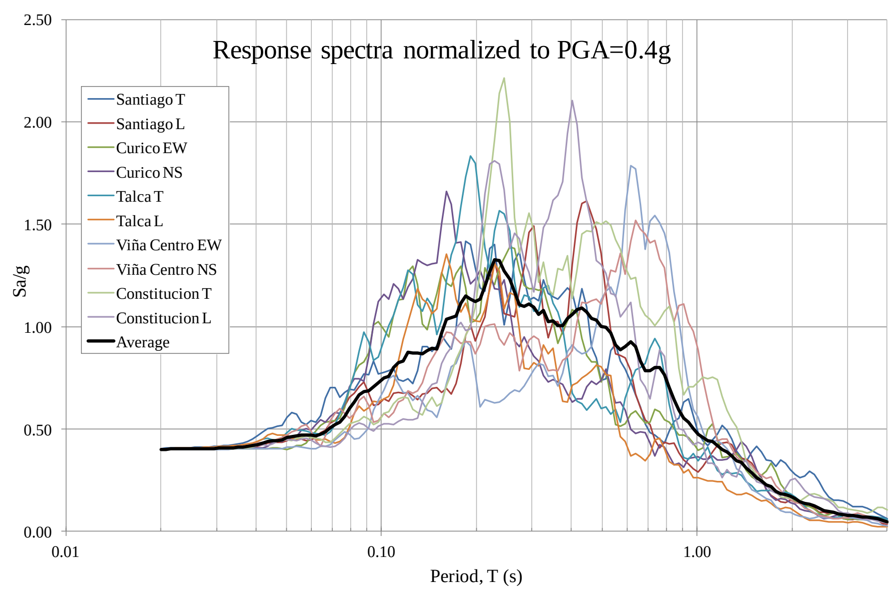


Fig. 2 – Response spectra of the acceleration records for 5% damping ratio, normalized to PGA=0.4g.

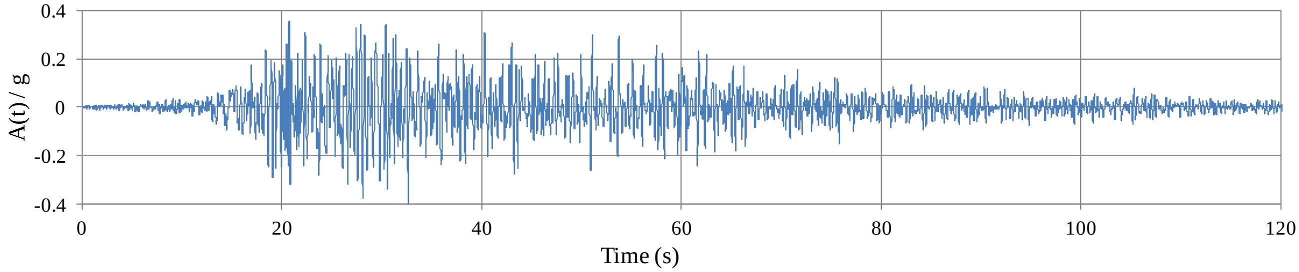


Fig. 3 – Constitución L record normalized to PGA=0.4g.

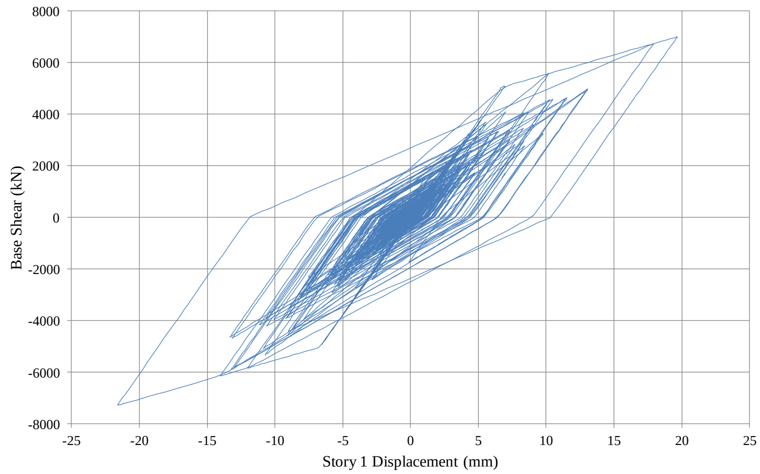


Fig. 4 –Results of Base shear (kN) and First story displacement (mm) for Primary structure, Nonlinear analysis case Primary 2, $T_s = 0.5T_p$ with R=3.0, for the Constitución L record.

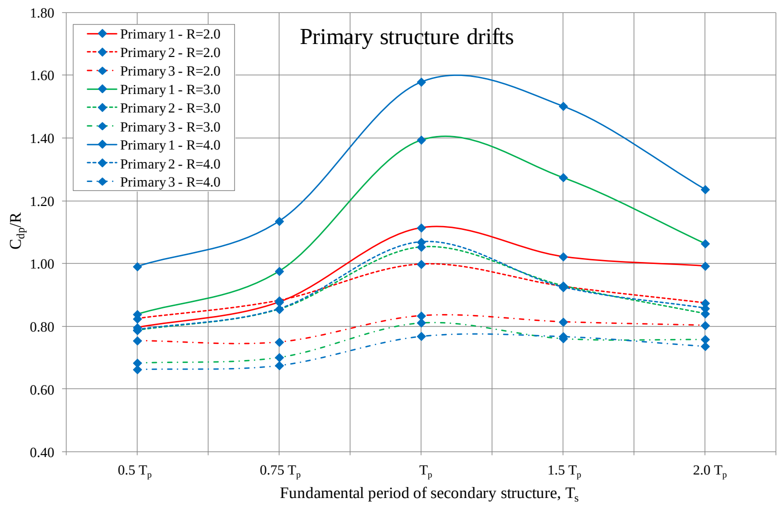


Fig. 5 – C_{dp} / R ratio for all cases considered, as a function of the ratio of Secondary to Primary structure fundamental period.

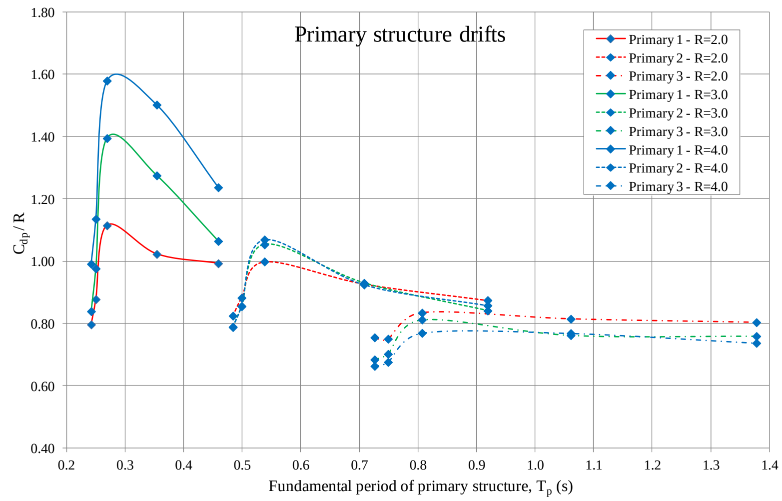


Fig. 6 – C_{dp} / R ratio for all cases considered, as a function of the combined structure fundamental period.

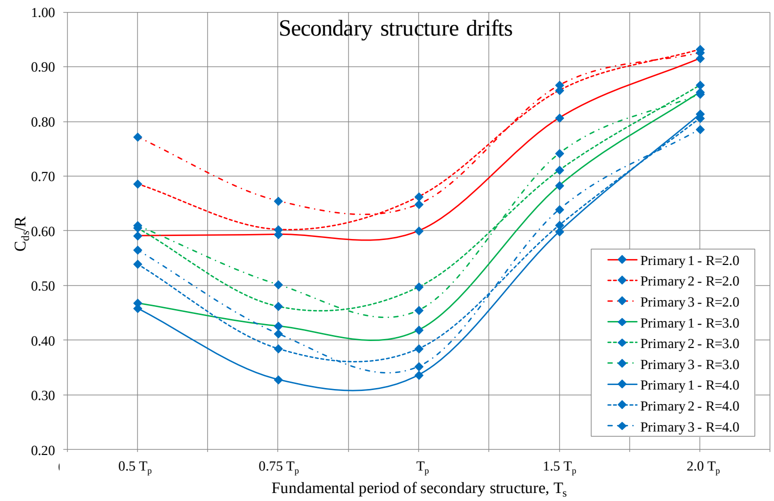


Fig. 7 – C_{ds} / R ratio for all cases considered, as a function of the ratio of Secondary to Primary structure fundamental period.

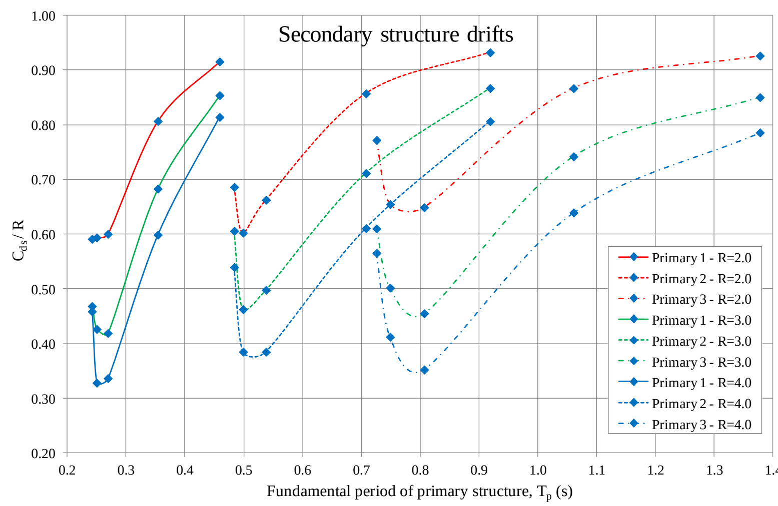


Fig. 8 – C_{ds} / R ratio for all cases considered, as a function of the combined structure fundamental period.

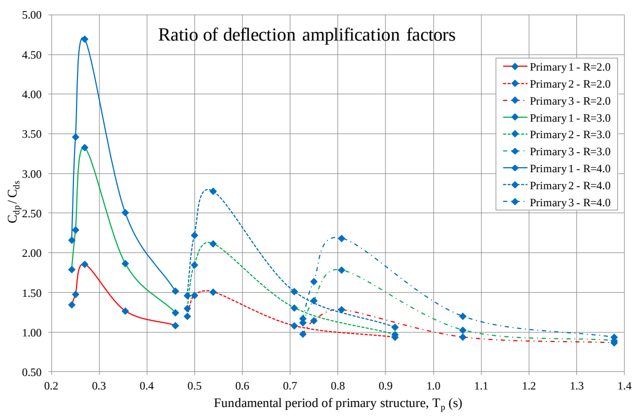


Fig. 9 – C_{dp} / C_{ds} ratio for all cases considered, as a function of the combined structure fundamental period.

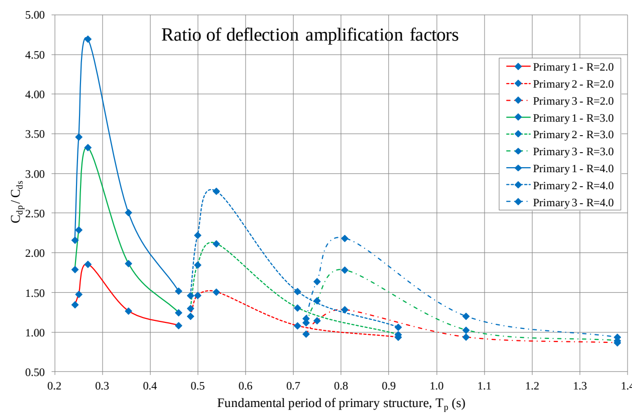


Fig. 10 – C_{ds} / C_{dp} ratio for all cases considered, as a function of the combined structure fundamental period.