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USABILITY OF PUSHOVER ANALYSIS FOR ASYMMETRIC BASE-ISOLATED BUILDINGS

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Abstract. *The paper deals with the applicability of a simplified nonlinear method (N2 method) to base-isolated plan-asymmetric building structures. In the first part of the paper the modifications that have been implemented into the originally proposed N2 method – such as the new three-linear idealization and inclusion of isolator damping by reduction factor* R_ξ *– are shortly described. In the paper the proposed procedure is used for the seismic analysis of a base-isolated 4-storey RC asymmetric building isolated with lead rubber bearings (LRBs). For the base isolation system we have considered three different types of isolators with different stiffness. The results of nonlinear dynamic time-history analyses are compared with the results of the N2 method in terms of obtained top, base and relative displacements. Comparisons of the results of the simplified method with the 'exact' results of the nonlinear dynamic analyses have shown a very good agreement. It has been shown that the presented simplified approach might be a valuable tool for design, analysis and verification of the behavior of symmetric as well as moderately asymmetric base-isolated structures.*

1 INTRODUCTION

Over the last decade simplified non-linear methods based on pushover analysis, the equivalent single degree of freedom (SDOF) system, and the response spectrum approach have been implemented in guidelines, standards and codes for the seismic resistant design of new buildings and the evaluation of existing buildings. One of these simplified non-linear methods is the N2 method, which has been successfully applied to the analysis of symmetric [1] and asymmetric buildings (extended N2 method – [2]) with different building system types. The method combines the pushover analysis of a multi degree of freedom (MDOF) model with the response spectrum analysis of an equivalent SDOF model. In the paper the method is applied for symmetric and moderately asymmetric base-isolated structures with the mass centre of the superstructure coinciding to the stiffness centre of the isolation system. The modifications of original method include: 1) a new three-linear idealization of the pushover curve based on the first yield of the superstructure, and 2) the introduction of the reduction factor R_ξ to account for damping of isolators [3,4].

2 PROPOSED CAPACITY CURVE FOR BASE-ISOLATED STRUCTURES

For the idealization of the capacity curve of a base-isolated structure the authors have considered that the first yielding point of the superstructure is far more important that the "average yielding" point of the structure used for bilinear idealization in the original N2 method for fixed base structures. In this way the N2 method should be able to detect the first yielding of the superstructure, as well as to estimate the behavior of the superstructure further into the nonlinear range directly in relation to the first yielding of the superstructure.

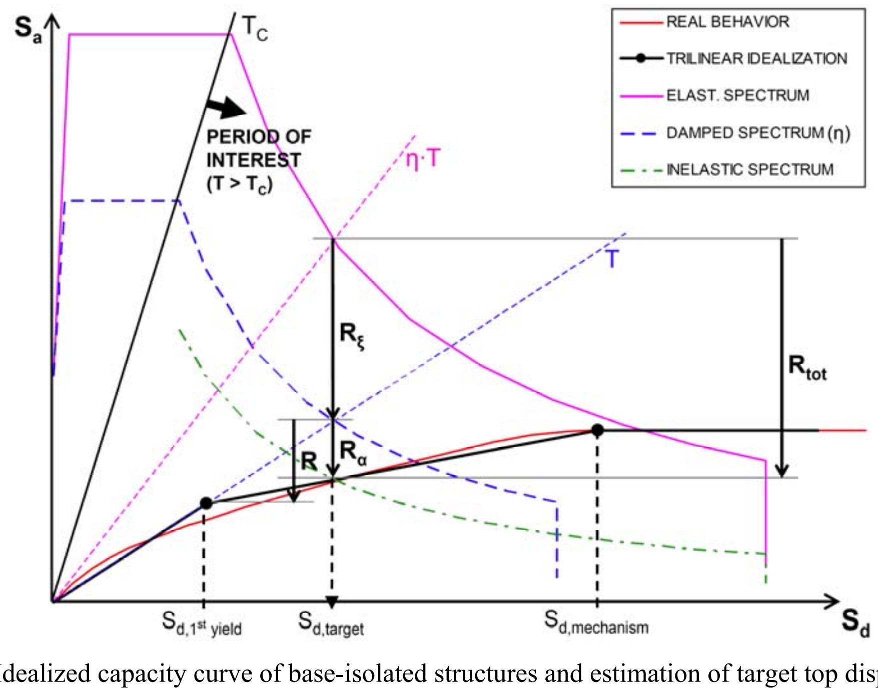


Figure 1: Idealized capacity curve of base-isolated structures and estimation of target top displacement.

The first yielding of the superstructure is determined by a pushover analysis for the selected lateral load distribution. The initial stiffness is obtained by equalizing the areas below and above the actual pushover curve of the base-isolated structure. The secondary slope is obtained in such a way that it best fits the real pushover curve. Alternatively it can be determined from the failure mechanism obtained by pushover analysis. After the mechanism has occurred, a zero slope is suggested. A consequence of such idealization is a much more pronounced hardening secondary slope which does not correspond to the assumptions used in the original N2 method (see Figure 1). A similar model with a higher secondary slope was suggested also by [5] for structures with incorporated hysteretic dampers. It should be noted that the range of interest for base-isolated structures is practically limited to the secondary hardening part of the idealized curve, since it is not expected that base-isolated structures would experience damage close to the failure mechanism.

3 DESCRIPTION OF THE PROCEDURE

Due to the non-zero hardening slope α, the actual reduction factor R_α is smaller than the assumed factor R from original N2 method. The relations between R and R_α depend on the hardening slope α and can be obtained by using equation (1). Assuming that the equal displacement rule applies the equations can be obtained by using relatively simple geometric relations.

$$R_\alpha = \frac{R}{\alpha R - \alpha + 1} \tag{1}$$

The use of the N2 method remains practically the same as was suggested in the original N2 method [1]. The inelastic spectra can be obtained as:

$$S_a = \frac{S_{ae}}{R_{tot}} \tag{2}$$

where R_{tot} can be obtained as a product of the reduction factor R_ξ and the reduction factor R_α:

$$R_{tot} = R_\xi \cdot R_\alpha \tag{3}$$

R_α represents the reduction due to the nonlinear behavior and damping of the superstructure, whereas R_ξ represents the strength reduction due to the higher damping of the isolators:

$$R_\xi = \frac{1}{\eta^2}, \text{ where } \eta = \sqrt{10/(5+\xi)} \geq 0.55 \tag{4}$$

where η is the correction factor which takes into account damping effects (see [6], equation (3.6)) and ξ is the damping of the isolation system. A graphical representation of the procedure is presented in Figure 1. The reduction factor that relates the proposed procedure with the quantities from the general N2 method can be expressed as a product of R_ξ and R. It should be noted that the damping of the isolation system ξ used in equation (4) depends on the achieved base displacement D_d. In our study we have obtained it by means of Jacobsen's equation [7]:

$$\xi_{LRB}(D_d) = \frac{4\,Q\,(D_d - D_y)}{2\,\pi\,K_{eff}\,D_d^2} \tag{5}$$

where D_y and K_{eff} are the yield displacement and effective stiffness of the selected LRB isolator and Q is its characteristic strength. Since the actual base displacement D_d it is not known in advance, some iteration steps are required in order to obtain the correct results. In each step the top displacement of the MDOF system is obtained as $D_{top} = \Gamma \cdot S_d$, whereas the corresponding base displacement can be obtained by pushover analysis. The new damping value is then calculated by substituting D_d in equation (5) by the obtained D_{base}, until a satisfactory agreement is reached.

The extension of the N2 method to fixed base plan-asymmetric building structures has been described in detail in [2]. It has been proposed to combine the results obtained by usual 3D pushover analysis with the results of a linear dynamic (spectral) analysis in order to determine the torsional correction factor (c_T) to correct the results obtained by pushover analysis. This factor is defined as the ratio between the normalized top displacements obtained by elastic modal analysis and by pushover analysis (equation (6)). The normalized top displacement is the top displacement at an arbitrary location divided by the top displacement at the centre of mass (CM). If the normalized top displacement obtained by elastic modal analysis is smaller than 1.0, it is suggested to assume it to be equal to 1.0. This recommendation, which in case of base-isolated structures seems to be too conservative, was not applied in the presented case study. Correction factors are defined for each horizontal direction separately and they depend on the considered location in the plan. Then all the relevant quantities obtained by pushover analyses for considered location (e.g. distance from the CM) should be multiplied with appropriate torsional correction factor for this location in order to obtain the target values of relevant quantities.

$$c_T = \frac{\bar{u}_e^{top}}{\bar{u}_{push}^{top}} \qquad \bar{u}^{top} = \frac{u^{top}}{u_{CM}^{top}};\ \text{if}\ \bar{u}_e^{top} < 1.0,\ \text{take } 1.0 \tag{6}$$

In the presented case study we have used the same presumptions as for symmetric base-isolated structures and we have treated the frame in the vertical plane passing through the CM in the same manner as the frame in a symmetric structure. All quantities were therefore observed in this plane, where also the horizontal loads for pushover analysis have been also applied [8, 9].

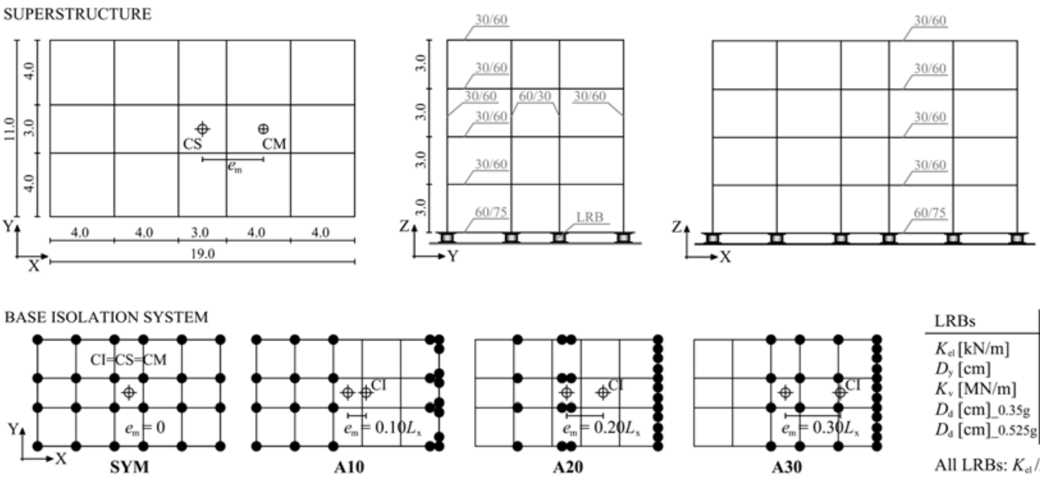
4 CASE STUDY: A BASE-ISOLATED RC FRAME STRUCTURE

4.1 Building description

A four-storey base-isolated RC frame building, which is presented in Figure 2, was used as a test example. The symmetric variant of the same structure was already used for example in [4], where all data about the geometry, masses, and periods can be found, as well as some design details for the fixed-based variant of the building (a_g = 0.35g). More detailed data about asymmetric variants can be found in [10]. For the purpose of this study, only one-directional asymmetry was introduced by moving the mass centre CM by 10% (A10), 20% (A20) or 30% (A30) of the larger floor plan dimension (L_x). The torsional to lateral frequency ratio (Ω_s) of the original (symmetric) superstructure amounts to 1.0.

4.2 Base isolation system

A widely used base isolation system, consisting of an orthogonal mesh of RC foundation beams and 24 identical round lead rubber bearings, was used. In order to verify the applicability of the proposed simplified N2 method, the stiffness of the isolator compound was intentionally varied so as to correspond to three different protection levels: a) "Hard" isolators (H), which cannot adequately protect the superstructure; b) Elastic limit or “normal” (N) isolators, which have been designed to bring the symmetric superstructure subjected to the design ground acceleration (a_g = 0.35g, soil class B and q = 1) exactly to the limit of its elastic range; c) "Soft" isolators (S), which could be actually used in practice. The used isolators are described in detail in [4]. The positions of individual isolators have been adjusted for the given eccentricity level of the superstructure (Figure 2) in order to ensure that the centre of the isolation system CI corresponds to the centre of mass of the superstructure CM. In this case, torsion is a consequence of the eccentricity between the CS and CM of the superstructure.



LRBs	S	N	H
K_{el} [kN/m]	2085	4225	6673
D_y [cm]	2.27	1.12	0.71
K_v [MN/m]	1545	1815	2120
D_d [cm]_0.35g	14.5	13.0	12.0
D_d [cm]_0.525g	25.1	24.6	22.2

All LRBs: K_{el}/K_{pl} = 6.50 and Q = 40 kN.

Figure 2: Geometry, basic characteristics and positions of LRBs for the analyzed structural variants.

4.3 Mathematical modeling and seismic ground motions

The nonlinear analyses were performed using the program SAP2000 (v12.0.1) [11]. The nonlinear behavior of the superstructure was modeled using bi-linear moment hinges without a load drop, located at both ends of each beam and column. An ensemble of seven accelerograms was used to represent the seismic action (2 from Friuli 1976, 3 from Montenegro 1979, 1 from Banja Luka 1981 and 1 from Vrancea 1986). The accelerograms were further modified to match the target EC8 [6] elastic spectrum for soil type B, scaled to a peak ground acceleration of a_g = 0.35g (considered as the design basis earthquake – DBE) and 0.525g (considered as the maximum credible earthquake – MCE). More detailed data about the used ground motion records can be found in [3, 4, 10]. Only uni-directional input has been considered where the N-S components of the accelerograms were applied in the Y direction of the building. For the pushover analyses three different lateral load distributions were investigated: (a) "triangular"; (b) "1st mode"; and (c) "PSC" – the proposal of the Protective Systems Committee of SEAONC [12].

4.4 Comparison of selected top, base and relative displacements

The results are presented in terms of the maximum top, base and relative displacements of the base-isolated structure where the relative displacements of the superstructure were calculated as the maximum total difference between the top and base displacements (in NLDA they do not necessarily occur at the same time). Figures 3-6 present comparisons of the displacements and ductility factors obtained by the extended N2 method and NLDA for selected analyzed models. The displacements are presented as absolute values at the CM (u_{CM}), and as normalized values (u/u_{CM}) for the flexible and stiff sides, in order to present the effects of the torsional twist. In the presented results, the correction factor c_T was taken exactly as calculated from equation (6), taking into account the obtained top displacements.

Observing the displacements at the CM (Figures 3 and 4), it is evident that the softer isolators – as expected – result in larger top and base displacements and smaller relative displacements than the harder ones. It can be seen that the agreement between the results of NLDA and the ext. N2 method is fairly good, and within the standard deviation boundaries until the eccentricities of the superstructure do not exceed a certain level for selected type of isolator (approximately 20% for normal and 15% for hard type of isolator). For larger eccentricities, where much more damage occurs in the superstructure, all the displacements obtained by the ext. N2 method tend to be underestimated. The best results were obtained in the case of the 1st and PSC distributions, which give similar results, whereas the results of triangular distribution tend to be underestimated, especially for the top and base displacements. Similar conclusions were obtained in the case of the symmetric base-isolated structures [3, 4].

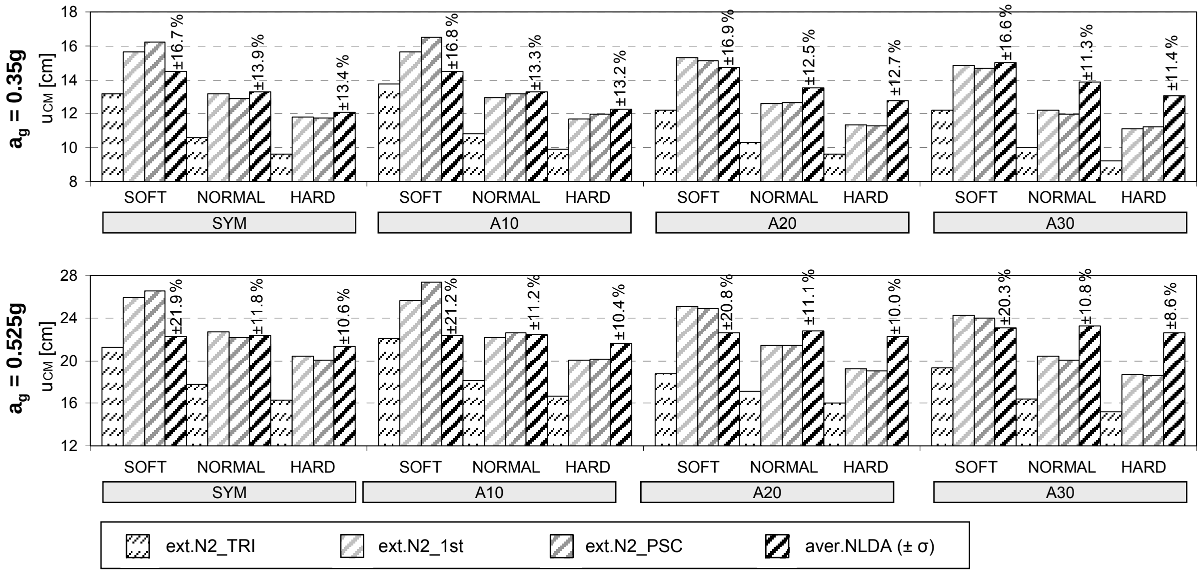


Figure 3: Top displacements (at the CM).

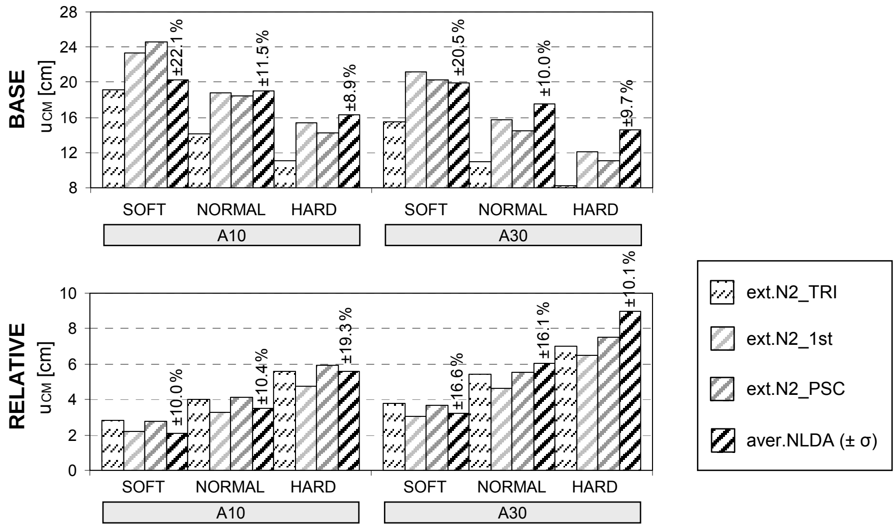


Figure 4: Base and relative displacements (at the CM) for $a_g = 0.525g$.

Observing the normalized displacements (Figure 5) it can be seen that, on the flexible side, the agreement with the results obtained by NLDA is very good; although it appears that the ext. N2 method slightly underestimates the demands for eccentricities equal to 20% or larger. The severest effects of torsion were observed in the case of the harder types of isolators. The amplification factors are in very good correlation with those obtained by NLDA. There is no significant difference between the lateral load distributions; however the best correlations with NLDA were obtained for the 1st mode and PSC distribution.

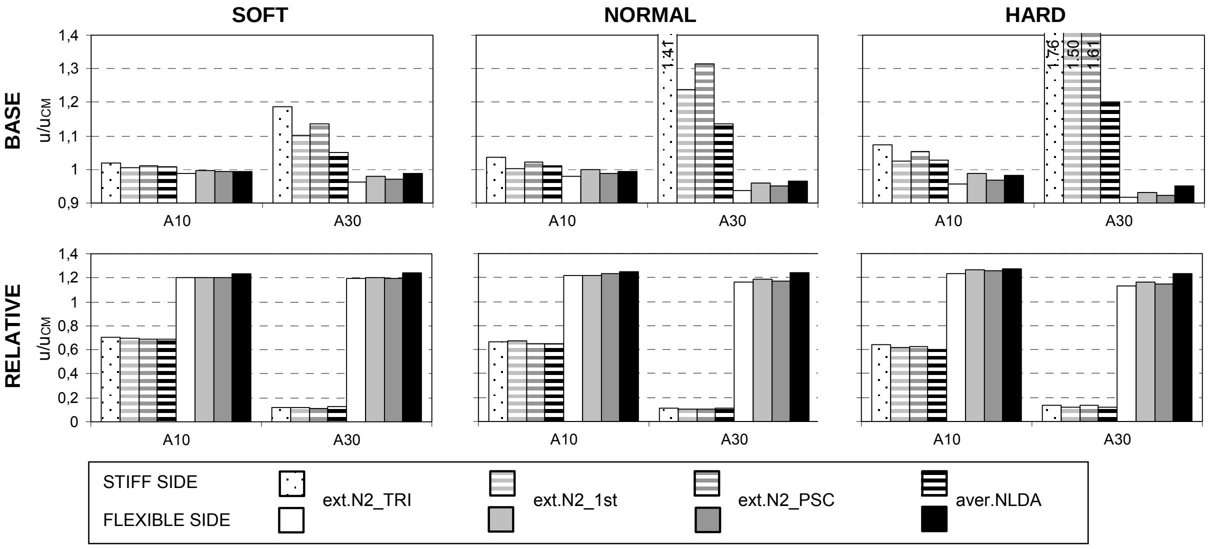


Figure 5: The torsional amplification factors for the base and relative displacements for a_g = 0.525g.

In Figure 6 the rotational ductility factors obtained by the ext. N2 method (for the PSC lateral load distribution) are presented and compared with the average ductility factors obtained by NLDA for a_g = 0.525g. The damage patterns are shown for all analyzed types of isolators but only for the A10 model and they are presented for the stiff as well as the flexible frames. It can be seen that there is more damage in the case of harder isolators, whereas in the case of soft isolators the structure practically remains elastic (ductility < 1.0). In all the analyzed cases, it turns out that the ext. N2 method is able to follow the spread of damage in the superstructure with sufficient accuracy. The agreement with the results obtained by NLDA is satisfactory, and the results obtained by the ext. N2 method remain conservative for presented eccentricity (A10). In the case of larger eccentricities, however, it was shown that the ductility factors (damage patterns) obtained by the ext. N2 method may slightly underestimate the response of the superstructure. In all cases the obtained correction factors (c_T) have values which are close to 1.0, which means that in all these cases the usual 3D pushover analysis would give similarly good results.

In the presented case study we have analyzed the base isolation system with the CI corresponding to the CM and we have treated the frame in the vertical plane passing through the CM as the plane under observation where also the horizontal loads for pushover analysis have been applied. In general, the distribution of the isolators could be also asymmetric where the CI does not correspond to the CM. In our previous studies we have found out that the distribution CI=CS or even CI=-CM are even more effective for the protection of the superstructure because they minimize the rotations of the superstructure [10]. In those cases where the CI does not correspond to the CM, we have proposed that the loads for pushover analysis should be applied at the plane through the mid-point between the CI and the CM (Figure 7) where also all quantities should be observed [9]. The point of application of the lateral loads might be eventually also determined with higher accuracy considering additional influencing parameters, but here we should be also aware of the limitations of simplified methods to follow all the changes of parameters in complex dynamic nonlinear 3D structural response.

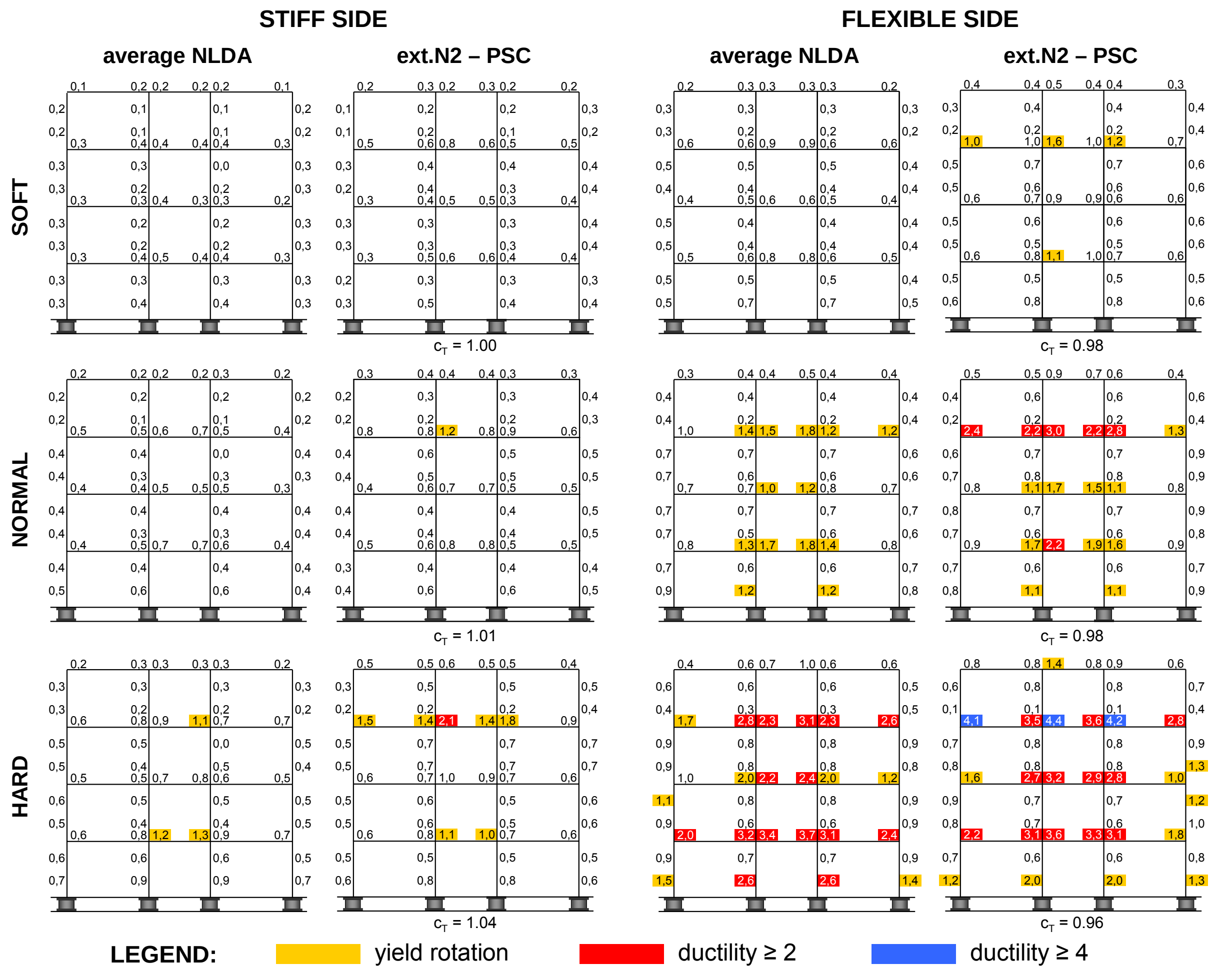


Figure 6: Maximum ductility factors for the stiff and flexible side, for the model A10 and a_g = 0.525g.

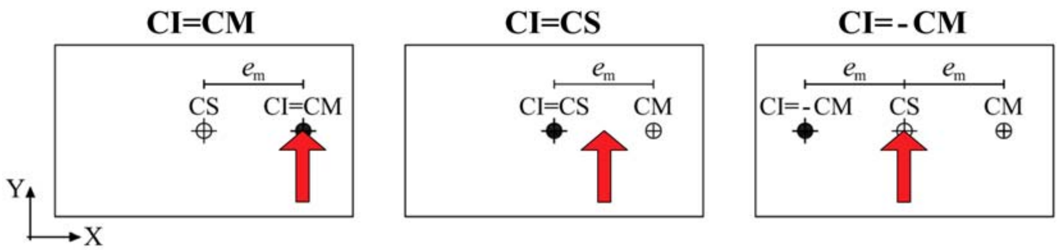


Figure 7: Points (vertical plane) of lateral load application in case of different positions of the center of the isolation system (CI).

5 CONCLUSIONS

It was found that the proposed N2 method procedure provides results which are in very good agreement with the results obtained by NLDA, if the eccentricity of the superstructure is moderate (e.g. in extreme cases limited to approximately e_m = 20%). In case of larger eccentricities all the displacements obtained by the ext. N2 method tend to be underestimated, especially in the cases with harder isolators, where the superstructure is exposed to deeper nonlinear behavior and consequently, the centre of stiffness of the superstructure (CS) is shifted towards the stiff side. The influence of different lateral load distributions and the effect of the ground motion intensities on the torsional amplifications were shown not to be very important. However, the distribution with additional force at the base (PSC) tends to work better, while the triangular load distribution seems less appropriate. For the analyzed CI=CM distribution of the isolators, the usual 3D pushover analysis yields good results, and the usage of the correction factor c_T is not absolutely necessary. The originally proposed ext. N2 method requires that the corrected displacement on the stiff side should not be taken smaller as in CM. For base-isolated structures this requirement leads toward a considerable overestimation of displacements on the stiff side, which is, however, on the conservative side.

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