USAGE OF SIMPLIFIED N2 METHOD FOR ANALYSIS OF BASE ISOLATED STRUCTURES

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ABSTRACT:

The paper examines the usage of a simplified nonlinear method for seismic analysis and performance evaluation (N2 method) for analysis of base isolated structures. In the paper the N2 method is applied for analysis of a fixed base and base isolated simple four-storey frame building designed according to EC8. Two different sets of base isolation devices were investigated: a simple rubber (RB) and a similar lead rubber bearing (LRB) base isolation system. For each system a Soft, Normal and Hard rubber stiffness and three different damping values were used. The paper shows how we can obtain base displacement and top (relative) displacement for different bearing stiffness and selected damping. The target base displacement was determined as an intersection of the capacity curve of single degree of freedom system with rigid behavior of the superstructure and demand spectrum curve for selected damping of isolators. In the following step the pushover analysis of the whole isolated structure was performed up to the target base displacement using constant load distribution. The results are presented in terms of base and top displacements and ductility factors for those base isolation systems which were not able to protect the superstructure. It has been shown in the paper that N2 method might be a valuable tool for design, analysis and verification of behavior of base isolated structures with different linear or nonlinear seismic devices. Nonlinear pushover analyses were performed with the computer program SAP2000.

KEYWORDS: Base isolation. RB and LRB seismic isolators. Seismic design. N2 method. Pushover analysis. Effective damping.

1. INTRODUCTION

The idea to use seismic isolation to reduce forces induced by earthquake ground motions is not new and it presents a relatively well researched topic. Nevertheless, in recent years, simplified non-linear methods based on pushover analysis, equivalent single degree of freedom (SDOF) system and response spectrum approach have been implemented in guidelines, standards and codes for seismic resistant design of new buildings and evaluation of existing buildings. The methods have been developed for fixed base structures. One of simplified non-linear methods is the N2 method, which is based on extensive studies of inelastic response building structures performed by the Prof. P. Fajfar and his research team at the University of Ljubljana [1-7]. The method was successfully applied for the analysis of symmetric [1,2] and asymmetric buildings [3,4] with different type of building systems, most recently for infilled frame structures [5,6] and bridges [7]. The method combines pushover analysis of a multi degree of freedom (MDOF) model with the response spectrum analysis of an equivalent SDOF model. Two main assumptions of the method are: (i) the response of a structure is governed by one mode and (ii) this fundamental mode does not change significantly when the structure is subjected to different seismic intensities. Both assumptions seem to be perfectly fulfilled for base isolated structures, which response is characterized by a motion of rigid upper block on much more flexible bearings.
In this paper, the N2 method has been applied for analysis of a seismically base isolated structure. Some suggestions to use pushover analysis for base isolated structures have been already reported in the literature [8,9]. According to our knowledge there were no attempts to use the N2 method for base isolated structures. Two different sets of base isolation devices were used: a simple rubber (RB) and a similar lead rubber bearing (LRB) base isolation system. For each system a Soft, Normal and Hard rubber stiffness and three different damping values were used. The results are presented in terms of base and top displacements and ductility factors for all selected base isolation systems. The proposed approach is subjected to limitations and needs further research. The aim of the study reported in this paper is to demonstrate the application of the N2 method to base isolated RC building structures, and to make a contribution to the evaluation of the procedure and its limitations.

2. TEST BUILDING

2.1. General

The analyzed reinforced concrete frame building is presented in Fig. 1. The cross sections of the structural members are equal in all frames and in all storeys. The building was designed using Eurocodes 2 and 8. The design spectrum for soil class B scaled to the peak ground acceleration 0.35g was used. The behavior (reduction) factor q was equal to 3.75 (ductility class medium). Storey masses amounted to 295 and 237 tons in bottom storeys and at the roof, respectively. The design base shear was equal to 23% of the total weight. In order to achieve the uniformity of structural elements, all columns in a storey have equal reinforcement. All frames in Y direction (i.e. frames Y1 to Y6) are identical. Identical are also frames X1 and X4, as well as frames X2 and X3. The same building structure with various reinforcement distribution considering stronger outer and weaker middle frames as well as the influence of asymmetry, was already used in several previous research papers of the first author, which addressed the problems of nonlinear torsional response of buildings. More detailed descriptions of the selected frame structures can be found in [10-12]. The observed direction in our study is Y direction only. The corresponding period of the structure amounts to 0.42s for un-cracked cross sections and to 0.56s considering cracked cross section stiffness obtained by $E \cdot I/2$.

2.2. Modeling of the Superstructure

Nonlinear pushover analyses were performed with the recent version of program SAP2000 (10.1.1) [13]. The nonlinear behavior was modeled with the simple uniaxial bi-linear moment hinges without load drop, ready available in the program and placed on both ends of each beam and column. Damping of the superstructure was taken to be a combination of mass and initial stiffness proportional damping. The damping coefficients were determined for 5% damping to 1st and 2nd modes. The damping of the bearings was considered independently. The necessary nonlinear hinge behavior parameters for SAP2000 are presented in Tab. 2.1. The plastic hinge lengths were determined according to [14]. Relatively simple model proves to be extremely effective and accurate enough for our needs, since we basically need to track the appearance of yielding in a beam or column with pushover analysis to judge the effectiveness of selected seismic isolation system.

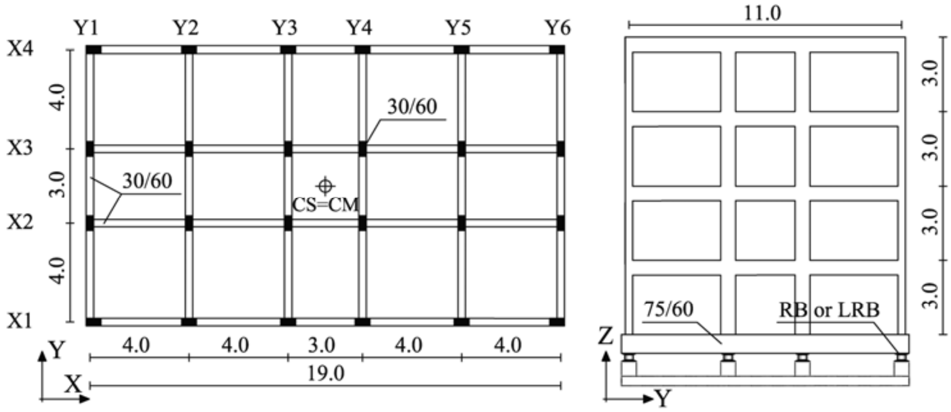

Figure 1 Analyzed structure: typical floor plan and cross section

Table 2.1 Characteristics of nonlinear hinges for SAP2000: L_p – plastic hinge length [m], N – axial force [kN], M_y/M_u – yield/ultimate moments [kNm], Φ_y/Φ_u – yield/ultimate curvature [10^{-2}/m]

Hinge	Storey	L_p	N	M_y^-	Φ_y^-	M_y^+	Φ_y^+	M_u^-	Φ_u^-	M_u^+	Φ_u^+
Beam	1-2	0.32	0	295.8	0.51	253.6	0.49	309.4	5.61	263.2	6.52
Beam	3-4	0.30	0	163.3	0.47	96.2	0.43	171.2	6.35	100.0	8.53
Column-centre	1-2	0.28	-437.8	446.6	0.61	446.6	0.61	520.1	1.98	520.1	1.98
Column-edge	1-2	0.28	-245.8	166.0	1.31	166.0	1.31	207.9	3.81	207.9	3.81
Column-centre	3-4	0.26	-169.0	287.7	0.55	287.7	0.55	361.4	2.61	361.4	2.61
Column-edge	3-4	0.26	-95.9	124.7	1.20	124.7	1.20	155.7	4.90	155.7	4.90

3. BASE ISOLATION SYSTEM

The base isolation system objective is to prevent/minimize the damage in the structure due to earthquake ground motion, as well as to keep the base displacement under certain reasonable level to avoid damage of bearings and other facilities. We have selected a widely used base isolation system consisting of orthogonal mesh of RC foundation beams (60/75cm) and 24 equal bearings positioned centrically under all columns. Additional mass of foundation system amounts to 218 tons. We have used two types of bearings: normal rubber bearings (RB) and lead rubber bearings (LRB).

3.1. Rubber Bearings (RBs)

We have used three different types of rubber, e.g. soft (S), normal (N) and hard (H). Independently, each rubber could have different damping characteristics: for each rubber type we have considered the values of 5%, 10% and 20% of critical damping. The corresponding periods of the isolated buildings and main properties of selected bearings are presented in Tab. 3.2 and Fig. 2.

Table 3.2 Properties of analyzed RBs and periods of isolated structures

Rubber type	K [kN/m]	T_{eff} [s]	$T_{SAP2000}$ [s]	Effective damping [%]	$K_{vert.}$ [MN/m]
S	321	2.62	2.67	5 / 10 / 15	1545
N	650	1.84	1.91	5 / 10 / 15	1815
H	1026	1.47	1.55	5 / 10 / 15	2120

Considered shear modulus G of the rubber amounted to 500, 1000 and 1600 kN/m^2 for the S, N and H bearings, respectively. The behavior of the bearing in the vertical direction was assumed to be elastic. The bearings with normal rubber stiffness (N) were intentionally designed to bring the superstructure exactly to the limit of elastic range. The other two stiffnesses were produced artificially in order to obtain substantially higher and lower bearing stiffness needed to examine the effectiveness of the N2 method.

3.2. Lead Rubber Bearings (LRBs)

In this case a lead core has been inserted to the RB isolators described in chapter 3.1. The behavior of such bearing is bi-linear and we can account for additional hysteretic damping that can be obtained from Eqn. 3.1 [15,16]. The properties of selected LRB isolators are presented in Tab. 3.3 and Fig. 2. In this case the bearing effective stiffness and damping can not be treated as independent as in the case of RB isolators. They depend also on obtained bearing displacement during actual response. The considered relations between bearing stiffness and displacement for RBs with different damping and considered stiffness-displacement relationship for LRBs are presented in the Fig. 7.

$$\xi_{eff} = \frac{4\,Q\,(D - D_y)}{2\,\pi\,K_{eff}\,D^2} \qquad (3.1)$$

Table 3.3 Properties of analyzed LRBs (characteristic strength Q = 40.04kN; core diameter 77mm; bearing diameter 350mm; yielding force F_y = 47.32kN; post-yielding stiffness K_{el}/K_{pl} = 0.154; Q/W = 7.3%)

Rubber type	K_{eff} [kN/m]	T_{eff} [s]	$T_{SAP2000}$ [s]	Effective damping [%]	K_{el} [kN/m]	D_d [cm]	$K_{vert.}$ [MN/m]
S	597	1.92	1.98	24.8	2085	14.5	1545
N	958	1.51	1.59	18.7	4225	13.0	1815
H	1360	1.27	1.37	14.7	6673	12.0	2120

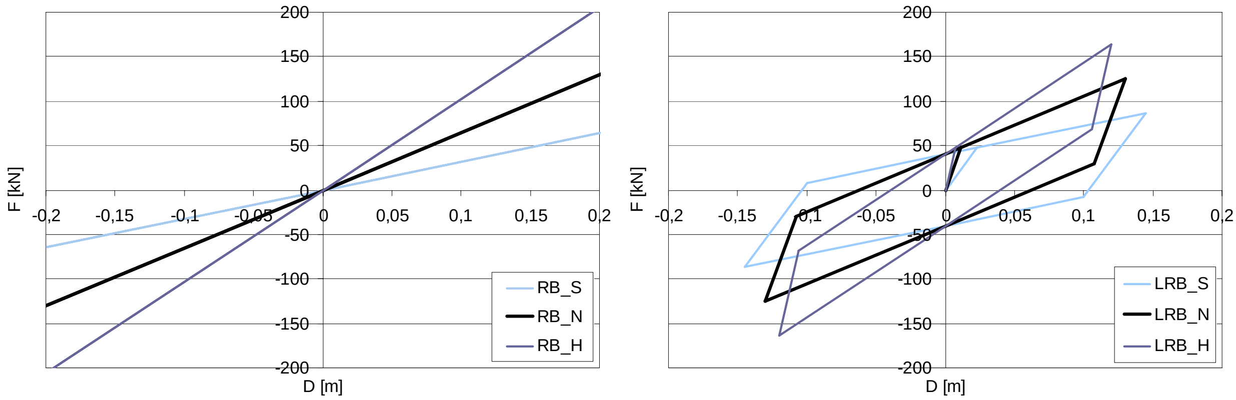

Figure 2 Force-displacement diagrams for selected rubber bearings and lead rubber bearings

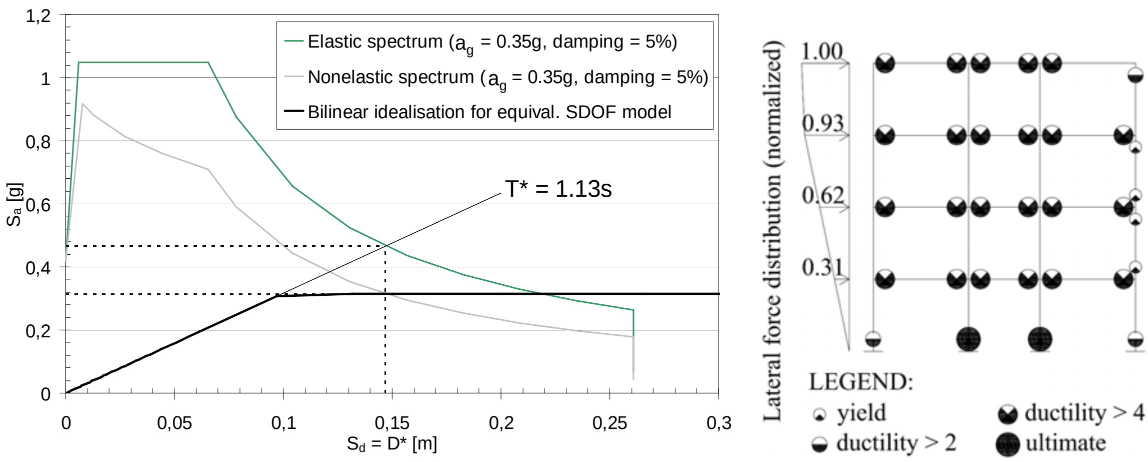

Figure 3 Seismic demand versus capacity curves for fixed base structure and formed plastic hinge pattern at target top displacement ($D_t = \Gamma \cdot D^*$ = 18.2cm)

4. RESULTS OF N2 METHOD

4.1. Fixed Base Structure

In order to enable a comparison with base isolated structures we present also selected results of N2 method for fixed base structure (Fig. 3). The used force pattern was proportional to mass distribution and height level [17] what in our case induces very similar displacement shape vector as the first mode does. The obtained target displacement amounted to 18.2cm (~1.5%·H) and obtained rotational ductility factors exceed the value of 4 at numerous beam ends. The ultimate rotations are exceeded at the bottoms of both middle columns. The plastic mechanism is just about to be formed.

4.2. Isolated Structure

The response of isolated structures to a great extent depends on characteristics and behavior of bearings. The behavior of the superstructure is generally expected to be elastic and dynamic response of base isolated structure is practically governed by one (first) mode. It can be further assumed that this mode does not change significantly when the structure is subjected to different seismic intensities. These observations coincide well with main assumptions of the single mode N2 method [1-7]. For the isolated structures however, the damping of bearings is also an extremely important parameter that should be accounted for. Since the superstructure and the base isolation system has different damping characteristics we should have considered an average damping value for the whole system. Instead of going this way, we decided to obtain a target base displacement instead of target top displacement. For capacity-demand curve we have assumed that the isolated structure behaves as the single degree of freedom (SDOF) system – as the isolated structure with a rigid superstructure. Such an assumption according to [18] gives very good estimates of base displacements in an actual structure. In this way the target base displacement can be simply obtained as an intersection of the capacity curve of SDOF system with the demand spectrum curve for appropriate damping of bearings. It should be noted that the capacity curves are elastic only for RB isolators (Fig. 4) and that they are bilinear for LRB isolators (Fig. 6). In the following step the pushover analysis of the whole isolated structure was performed up to the point when the target base displacement was reached at the base of the building. The corresponding difference between obtained top displacement and target base displacement presents the relative displacement that produces the damage of the superstructure (Fig. 7). For selected distribution of loads for the pushover analysis the relative displacement at the first plastic hinge yielding can be also obtained in advance, what enables a reversing of design process by first selecting the desired relative displacement (or acceleration) of the superstructure and than obtaining the appropriate stiffness of bearings and base displacement for specific damping (Fig. 5). In this way the method can fit better in perform design idea, as well as it eases the decision on selection of specific bearing type, stiffness, base displacement and damping, which can be cumbersome in a usual design process. In this paper we have used only a constant distribution of loads for pushover analysis, which corresponds best to actual displacement shape of base isolated structures. In this case the values of gamma (Γ) and equivalent mass (m*) always amounted to 1.0 and no transformations were needed between SDOF and MDOF system. Recent studies of different vertical distribution of lateral forces on isolated structures can be for example found in [16,19].

4.2.1 Base Isolated Structure with Rubber Bearings (RBs)

Fig. 4 presents the seismic demand versus capacity curves for selected RBs for soft, normal and hard rubber stiffness. The demand spectra are the Eurocode 8 elastic spectra for $a_g = 0.35$g for 5%, 10% and 15% damping. The obtained target base displacements are presented together with corresponding relative displacements of the superstructure. As expected, the stiffer isolators with higher damping give smaller target base displacements (D_{Base}) as softer ones with lower damping. In our case the smallest target base displacement was obtained for the hard RB with 15% damping (e.g. 13.7cm). It can be seen however, that the obtained relative displacements (D_{Rel}) of the superstructure are smaller if the softer isolators are used. The smallest relative displacement was obtained for the soft isolator with 15% damping (e.g. 1.3cm). The biggest relative displacement can be therefore expected if we use stiffer isolators with smaller damping, e.g. hard isolator with 5% damping gives D_{Rel} = 3.7cm. The designer task is to select the appropriate bearings by balancing the desired relative displacement of the superstructure with desired displacements and damping of bearings and bearing price. In this case the demand-capacity curves might help the designer with clear graphic presentation of all involved parameters.

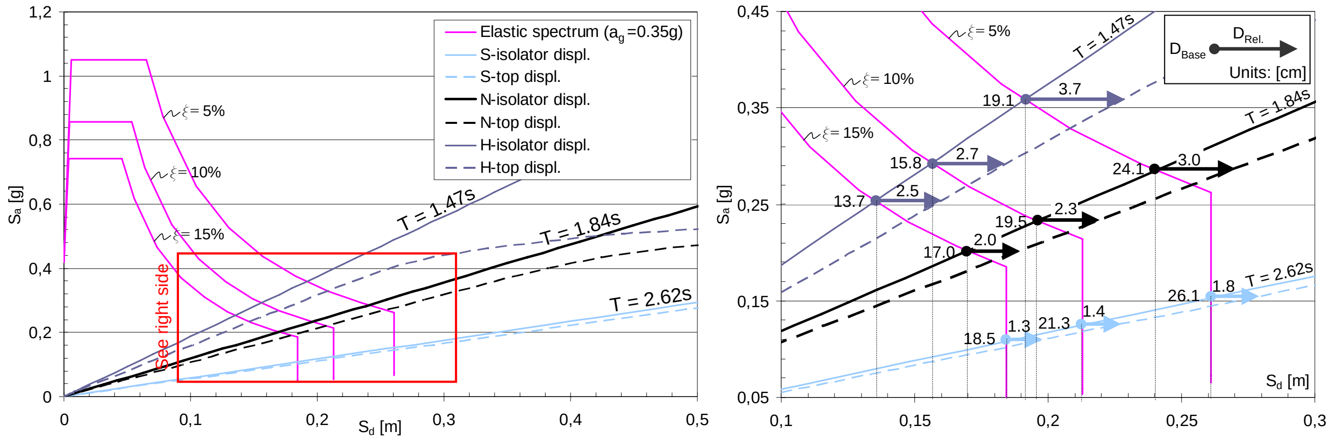

Figure 4 Demand versus capacity curves for isolated structure with different RBs (left) and obtained target base displacements together with corresponding relative displacements of the superstructure (right)

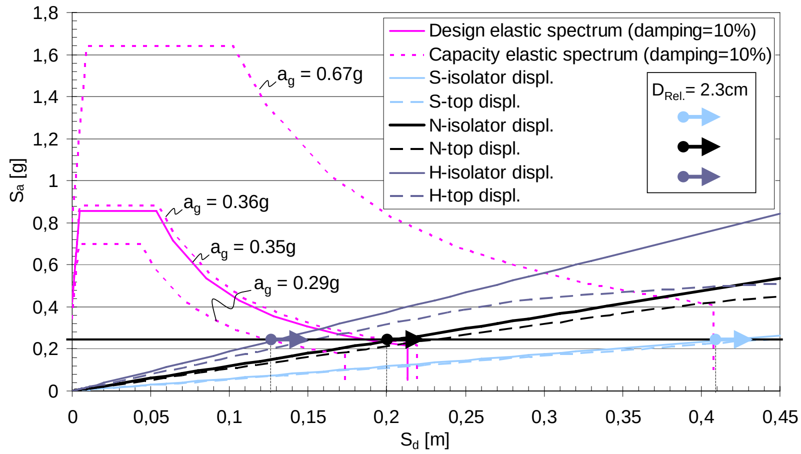

Figure 5 Demand versus capacity curves used to obtain maximal ground acceleration for which the selected RBs are still able to protect the superstructure

Fig. 5 presents "to some extent" reversed design process. In this case we have first performed the pushover analysis of the superstructure in order to determine the desired relative displacement of the superstructure. The desired displacement might depend on allowable interstorey drifts in order to protect secondary structural elements or directly on desired acceleration required to protect the building content. In our particular case we have selected the relative displacement of 2.3cm (~0.2%·H) which is required to produce the first yielding in the superstructure for the uniform load distribution. Than we have found the same displacement difference on capacity curves for base isolation system and for the superstructure which has been obtained for $S_a = 0.24g$. By modifying the base ground acceleration the demand curves were than plotted in order to match the obtained target base displacement (10% damping was used in this case). In this way we have obtained the maximal ground acceleration which – for selected bearings – brings the superstructure exactly to the limit of elastic range. It can be seen that the hard RBs protect the superstructure only up to 0.29g. With these isolators the structure would not be protected for design base acceleration 0.35g (see also damage in the Fig. 7). Much better behavior was obtained for softer bearings. The normal RBs protect the structure up to 0.36g and the soft ones up to 0.67g. In this case the target base displacement amounts to ~41cm what might not be an acceptable displacement for selected bearings (~270% of rubber height).

4.2.2 Base Isolated Structure with Lead Rubber Bearings (LRBs)

Fig. 6 presents the seismic demand versus capacity curves for selected LRBs for soft, normal and hard rubber stiffness. The demand spectra are the Eurocode 8 elastic spectra for $a_g = 0.35g$ and corresponding damping of LRB isolators, e.g. 14.7%, 18.7% and 24.8% (see Tab. 3.3). The main difference from RBs is the considered nonlinear (bilinear) capacity curve for LRBs which can be directly transferred into acceleration-displacement response spectrum format. In this case we do not need the effective stiffness in order to obtain the target base displacement. For LRBs the same general conclusions can be obtained as for RBs. The smallest target base displacement was again obtained for the hard RBs (e.g. 11.8cm). The smallest relative displacement was obtained for the soft isolators with the highest damping (e.g. 1.7cm). In comparison with RBs, LRBs give smaller base displacements, but similar relative displacements, while the increase of damping reduces base as well as relative displacements.

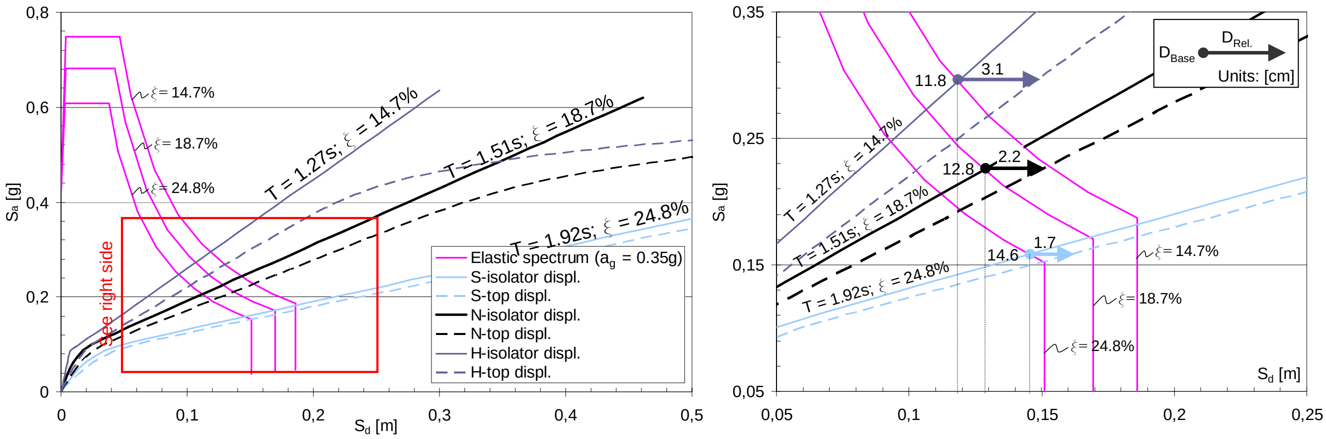

Figure 6 Demand versus capacity curves for isolated structure with different LRBs (left) and obtained target base displacements together with corresponding relative displacements of the superstructure (right)

After the target base displacement was determined, pushover analyses have been performed. The uniformly distributed loads were increased, until the target base displacement was reached. Because only LRBs with normal rubber stiffness were appropriately designed to protect our test structure, other isolators had produced some damage of the superstructure. The damage was, as expected, obtained only for the isolators with hard rubber and for the normal rubber with 5% damping. The number of plastic hinges formed is presented in Tab. 4.4. The damage pattern for all cases where the superstructure did not remain elastic is presented in Fig. 7. It can be also seen that the number of plastic hinges and overall damage is bigger in the case when damping is smaller. Fig. 7 presents also the considered relations between stiffness and displacement for RBs with different damping and considered stiffness-displacement relationship for LRBs.

Table 4.4 Number of formed plastic hinges at limit isolator displacement

Isolator	S	N	H
RB (ξ = 5%)	no damage	2* (see Fig. 7a)	5* (see Fig. 7b)
RB (ξ = 10%)	no damage	no damage	3* (see Fig. 7c)
RB (ξ = 15%)	no damage	no damage	1* (see Fig. 7d)
LRB	no damage	no damage	3* (see Fig. 7e)

* only ductility below 2.0 is reached

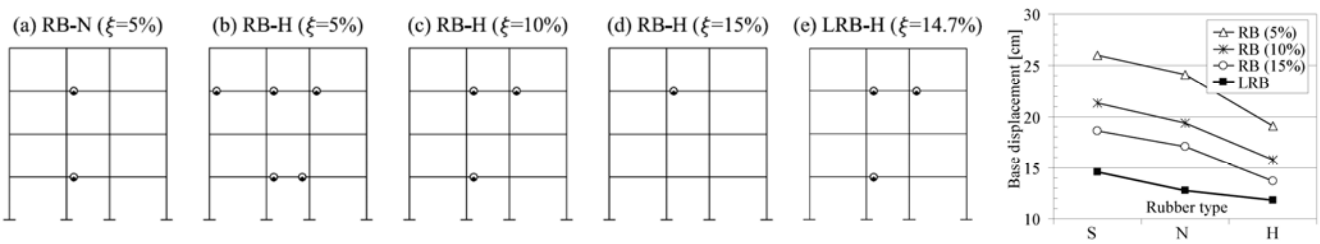

Figure 7 Damage at limit isolator displacement (diagram on right side) for selected isolators (see Tab. 4.4)

5. CONCLUSIONS

In the paper the N2 method has been applied for analysis of a seismically base isolated structure. Since the behavior of such structures is practically governed by their first mode which does not change significantly when the structure is subjected to different seismic intensities, the main assumptions of N2 method seem to be fulfilled. For capacity curves we have assumed that the isolated structure behaves as the SDOF system – as the isolated structure with a rigid superstructure. The target base displacement was obtained as an intersection of the capacity curve with demand spectrum curve for appropriate damping of bearings. It is important to note that the capacity curves are elastic only for RB isolators and nonlinear for LRB isolators. In this way a target base displacement for any type of nonlinear behavior of bearings could be obtained. In the following step the pushover analysis of the whole isolated structure was performed up to the point when the target base displacement was reached at the base of the building. The analysis of the test structure clearly show how the stiffer isolators with higher damping give smaller target base displacements as softer ones with lower damping. It can be also seen that the relative displacements of the superstructure are smaller if the softer isolators are used. The smallest relative displacement can be expected if we use softer isolators with higher damping. If the used isolators are too stiff they can not protect the superstructure. For the analyzed test structure the damage obtained by the pushover analysis was recorded only for the isolators with hard rubber and for the normal rubber with very low damping. It has been shown that N2 method might be a valuable tool for analysis of structures with different linear or nonlinear seismic devices. It was also shown that the method could easily fit in perform design idea, as well as it eases the designers decision on selection of specific bearing type, stiffness, base displacement and damping, which can be cumbersome in a normal design process.

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