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NONLINEAR STATIC SEISMIC ANALYSIS OF MULTI-STORY RC BUILDING

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Summary: *This paper focuses on the application of nonlinear static seismic analysis as a tool for assessing the performance of a multi-story RC building, irregular in plan, when subjected to earthquake. Assessment of performance is done according to EN 1998-3:2005 by evaluating capacity (pushover curve), calculation of demands (target displacements), comparing them on global level and performing safety checking on local (member) level, while modelling nonlinear deformations through definition of plastic hinges.*

Keywords: *N2 method, performance assessment, plastic hinge, building, irregular in plan*

1. INTRODUCTION

Pushover analysis combines non-linear static analysis with response spectrum approach. Seismic demand is calculated for equivalent SDOF system using inelastic response spectra. Transformation from MDOF to SDOF system is needed and this represents the main limitation of the applicability of pushover-based methods.
Several variants of pushover-based analysis have been proposed. In this paper, the method implemented in Eurocode 8, the N2 method is applied.
A non-linear static pushover analysis is performed by subjecting a structure to a monotonically increasing pattern of lateral forces, representing the inertial forces which would act on structure when subjected to earthquake. Gravity loads are kept constant. Under incrementally increasing lateral loads, structural elements yield sequentially. At each event structure experiences a loss of stiffness.
Using a pushover analysis, a characteristic non-linear force-displacement relationship of the MDOF system can be determined. Base shear and roof displacement are chosen as representative forces and displacement.
The expected performance can be assessed by comparing the seismic demands, determined by non-linear static analysis, with capacities for the relevant performance level. Comparisons are made both at global and at the local level. Relevant quantities for the global level are roof displacement and the story drifts, whereas at the local level a relevant quantity is chord rotation. Forces and accelerations are relevant for brittle elements.

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Collapse prevention is the main objective of any design [1]. An adequate safety margin against collapse under the expected maximum seismic load needs to be assured. In [2], the NC limit state is introduced as a conservative approximation of structural collapse. At the level of the structure, a commonly accepted quantitative definition of NC limit does not exist. The capacities of structural elements are empirically based. In Eurocode 8, information for the quantification of the capacity of components is provided in the relevant Informative Annex of its Part 3 (Annex A for RC structures).

It is worth mentioning that NC limit state is not the demand under the design seismic action as per Part 1 of Eurocode 8, instead the demand corresponding to the NC limit state is typically based on a mean return period of 2475 years.

2. NUMERICAL EXAMPLE – 3D RC FRAMED BUILDING

A spatial (3D) existing 5 storey framed reinforced concrete building, shown in Figure 1, was analysed. Building is L shaped in plan with outter dimmensions 20 x 20 m and inner 12 x 12 m, with the wing width 8 m. Storeys are all 3.5 meters tall, with roof level at 17.5 meters.

Analysis was conducted using Midas GEN 2016 software, specialized for analysis and design of buildings.

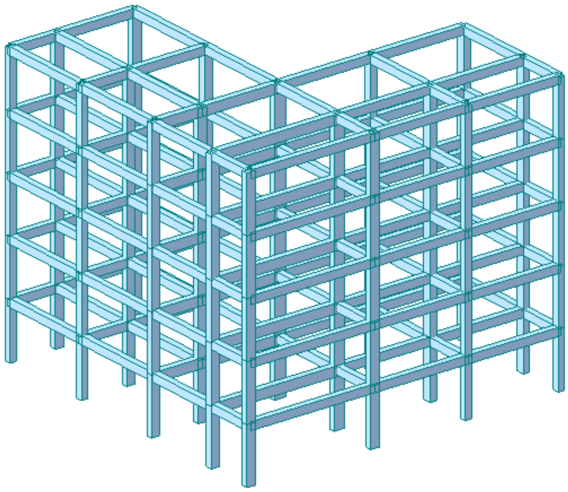

Figure 1 - 3D model of building

Concrete material for beams and columns is C20/25 according to [3], and rebar is Class A (fy = 400 MPa).

Floor construction is one-way ribbed concrete floor.

There are 3 types of column cross sections, 40/40 with longitudinal reinforcement 12Ø16 (ρ_s = 1.51 %), 40/55 with longitudinal reinforcement 16Ø16 (ρ_s = 1.46 %) and 40/70 with longitudinal reinforcement 20Ø16 (ρ_s = 1.34 %). Transverse reinforcement is the same for all column types - Ø10/7.5. There are 2 types of beam cross sections, 40/50 and 40/60 with varying ammount of longitudinal (2 – 7 Ø16) and transverse (Ø8/5/20) rebar.

Information about the existing rebar is imported into the software, so it could be used later in the formulation of plastic hinges. Model is formed using 1D finite elements for beams and columns. Floor construction is not modelled, but rigid floor diaphragm effect was considered. All columns are fully fixed. Applied loads consist of dead load, uniform distributed load with magnitude of 6 kN/m^2, live load, uniform distributed load with magnitude of 2 kN/m^2 and outter walls with weight of 10 kN/m. Definition of plastic hinges according to Eurocode, Part 3, is fully implemented in software Midas GEN. In this software, user defines global hinge type and applyies them to certain element ends. In this paper two global types of plastic hinges were defined, one for beams and one for columns. Column type global plastic hinge takes into account the interaction between axial force and bending moments, while beam type global plastic hinge does not. Based on the information about the existing rebar on member ends, software automatically calculates yield strength, yield rotation and ultimate rotation according to formulas given in Annex A of the Eurocode 8, Part 3.
A total of 8 Pushover load cases were defined. For all 8 load cases the increment method was controlled by displacements and maximum displacement of 0.4 m for the master node, shown in Figure 2. P-Delta effects were not considered. In particular casses in some increments convergence might not be reached. Convergence problems can be solved by varying number of substeps, maximum iteration, criterium for convergence (displacement, force, work), increment step number and maximum displacement of control point (master node).

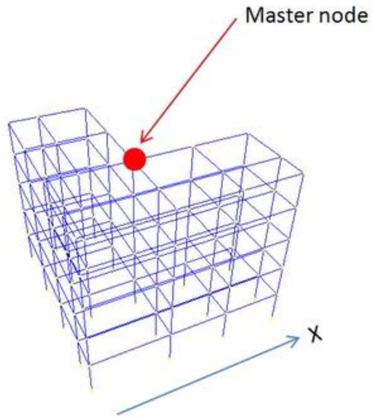

Figure 2 - Master node definition

In this example, for preliminary analysis, convergence was reached by setting the number of substeps to 10, maximum iteration to 10 and number of increments to 50, and for final analysis, number of increments was set to 100 for obtaining more accurate results and more smoother pushover curve, as well. Pushover load casses was defined for two lateral force distribution, the uniform lateral load distribution and modal lateral load distribution, and for two dirrections, the global X and global Y dirrection for both in both positive and negative dirrection (X+/ X- and Y+/Y-). The modal load distribudion is scaled by the appropriate mode shape from the Eigenvalue analysis, mode shape 1 for global X dirrection and, mode shape 2 for global Y dirrection.

3. RESULTS

All the numerical analysis were performed with Midas GEN and the pushover curves obtained from analysis are shown in the Figure 3. Maximum base shear foce of 2705.76 kN for displacement of 0.26 m is obtained for pushover load case of X+ uniform and minimum base shear force of 1930.95 kN for displacement of 0.28 m is obtained for pushover load case Y- modal. Difference betwene these 2 values is cca. 40 %. This shows that 2 sests of frames in X dirrection are „stronger“ than frames in Y dirrection.

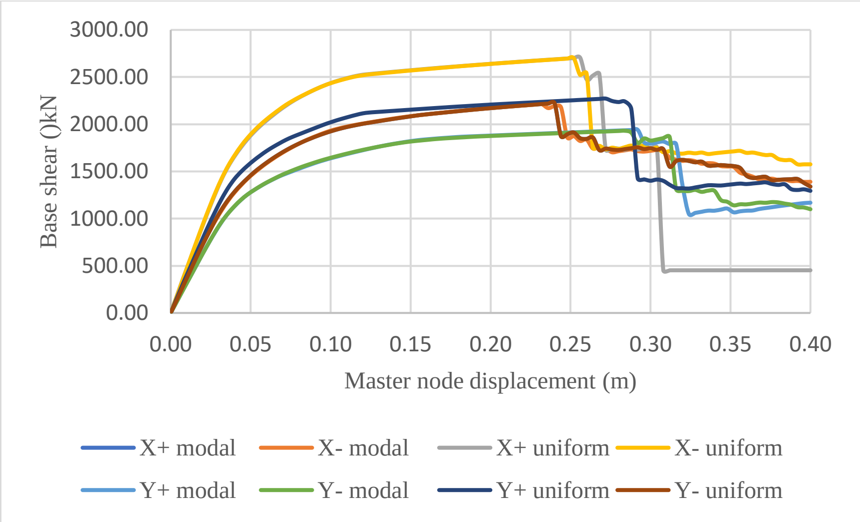

Figure 3 - Pushover curves for all pushover load casses

This is also very well visualized in the Figure 4 plotting maximum base shear forces for all of the 8 pushover load casses.

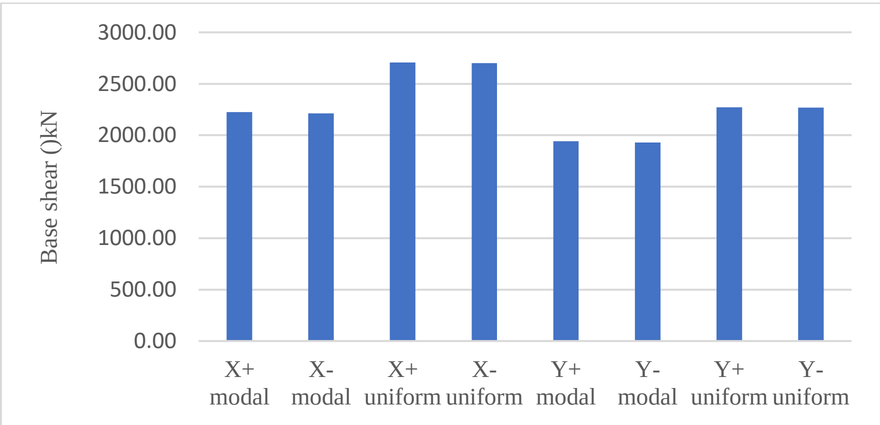

Figure 4 - Maximum base shear vs. pushover load case

Emerging of plastic hinges for two of the characteristic pushover load cases (X+ uniform and Y- modal) are analyzed in detail. For X+ uniform pushover load case behavior is linear to the point on the pushover curve which corresponds to displacement of 0.04 m and base shear force of 1756 kN. Until the increment number 60/100 seismic demand is pretty uniformly distributed throughout the structure. Plastic hinges are formed in almost all of the column's bases with demand between SD and NC state and in a lot of beams. Then, for the nest few increments the maximum base shear is reached leading to drastic reduction in when first two columns reach demands higher than NC limit state in their base and with next few increments the remaining columns reach the same limit as well. For Y- modal pushover load case behavior is linear to the point on the pushover curve which corresponds to displacement of 0.05 cm and base shear of 1301 kN. In this load case the seismic demand is distributed more in the beams than in the columns, so the plastic hinges first reach NC limit state in beams and form the so called "beam-sway" mechanism when reaching the maximum base shear force, but collapse and drastic reduction of stiffness happens when columns start reaching the NC limit state. Evaluation of pushover curves for all pushover load cases is followed by determination of target displacements for SD limit state for all the pushover load cases. Midas GEN automatically calculates target displacements according to Eurocode 8 after defining the ground type, C, spectrum type, type 1, reference peak ground acceleration, 0.25 g, importance factor, 1.0, and viscous damping ratio, 5 %.

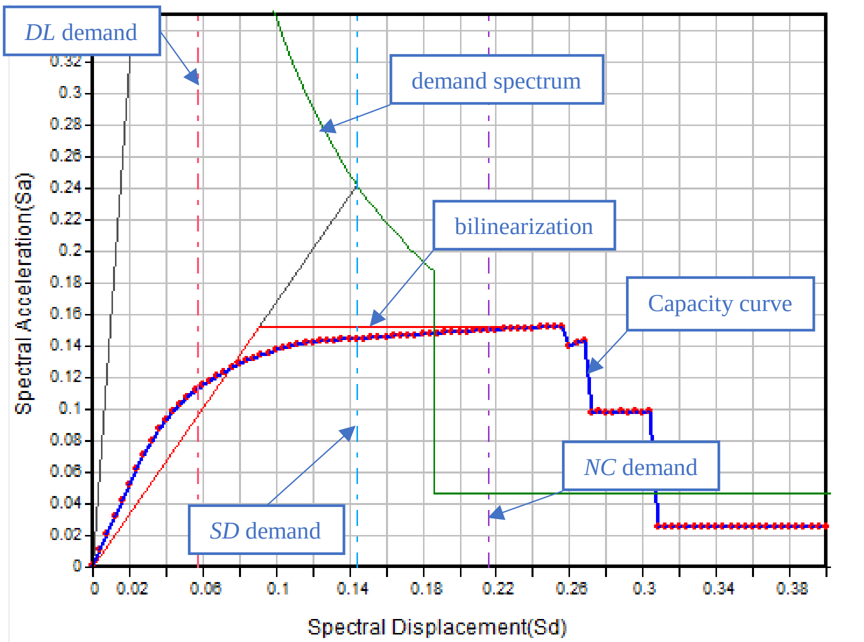

Figure 5 - Capacity Spectrum vs. Demand Spectrum for X+ uniform pushover load case

Figure 5 shows graphical determination of target displacement in acceleration-displacement (AD) format. Starting from the usual acceleration spectrum (acceleration vs. period), inelastic spectra in acceleration-displacement (AD) format is determined for an

SDOF system. Idealization of pushover curve per Eurocode 8 is based on the equal-energy principle and is performed at the SDOF level. The initial stiffness of the idealized system is determined in such way that areas under the actual and the idealized force-deformation curves, up to the displacement at the formation of a plastic mechanism, are equal. The graphical procedure used in N2 method requires a post-yield stiffness equal to zero.
Displacement demand for SD limit state is, then, divided by 2.5 to obtain the target displacement of DL and multiplied by 1.5 to obtain the target displacement of NC limit state. [4-6] Also, the drift ratio diagrams are obtained for all pushover load cases for steps corresponding to 3 limit states, respectively, DL, SD and NC limit state. For convenience, diagram drift ratio is shown only for X+ uniform load case in
Figure *6*.

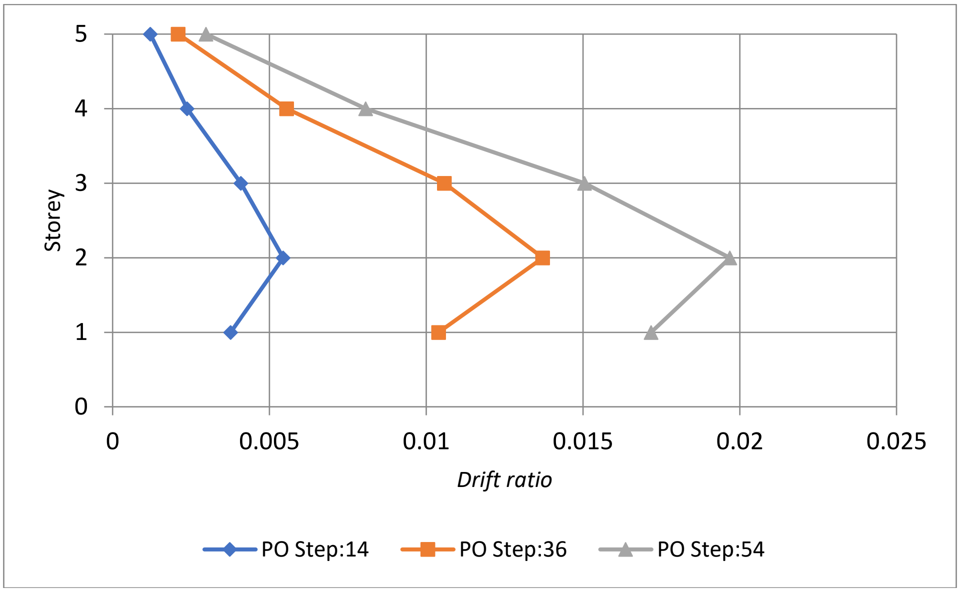

Figure 6 - Storey vs storey drift ratio for X+ uniform pushover load case

Figure *6* shows that drift ratio shows that seismic demand in terms of storey drift is largest in the first 3 floors. As step increments increase (step 14 corresponding to DL limit state, step 36 to SD and step 54 to NC) seismic demand in terms of storey drift rapidly increases in the first 3 floors.
Finally, after the calculation of target displacements, safety checkings have been performed. Software Midas GEN has option for automatic safety checkings. Safety checkings are performed on local level, the level of plastic hinges. It is necessary to perform safety checkings for combinations of load cases. As there are 8 non-linear pushover load cases, while it is not allowed to combine cases in which the 2 directions are the same, there are 24 possible load combinations. For every element, there’s need to perform 4-8 safety checkings, so there are number of combinations (24) times number of elements (95 columns and 140 beams) times number of checks (4-8), depending on if there

are checks for both ductile and fragile mechanisms (My, Mz and/or Ty, Tz) which gives us more than 23000 checks.

This number of checks exceeds possibility for manual checks, so the specialized software is required. For checking of ductile mechanisms software compares capacities with seismic demands resulting from pushover analysis for chord rotation, and for fragile mechanisms elastic shear force capacity is compared with seismic demand.

By choosing step for demand and confidence factor the safety checking calculations are performed for all elements.

Figure 7 shows hinge statuses with colors indicating status. Blue color is indicating hinge status that corresponds to damage limitation limit, green color corresponding to significant damage limit and orange (not reached in neither of three cases) corresponding to no collapse limit state.

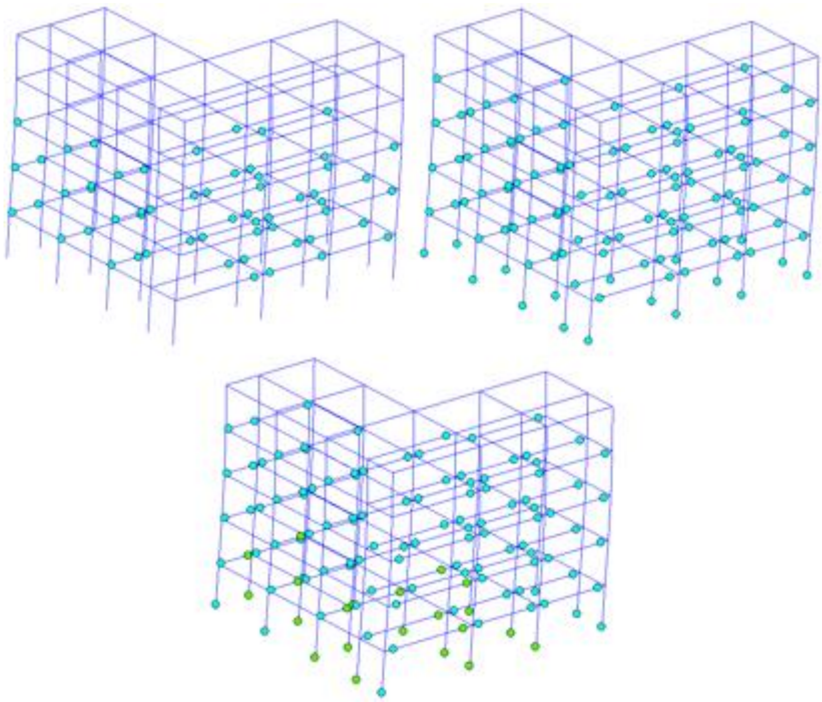

Figure 7 - Hinge status for increment steps corresponding to, respectively, DL, SD and NC limit state for X+ uniform pushover load case

Analyzing hinge statuses for the three cases corresponding to the three displacement demands shows satisfying behavior of building. In neither of the elements demand has exceeded the capacity and safety checkings have also confirmed this for all three cases.

4. CONCLUSION

Nonlinear static seismic (Pushover) analysis was fully implemented in the numerical example of existing multi-storey RC framed building. Numerical analysis was performed using Midas GEN 2016 software in order to assess the performance of the building when subjected to ground shaking, by applying the monotonically raising lateral load at constant gravity loads.
Target displacement was determined using the N2 method which is implemented in Eurocode 8, implemented in this paper, representing the seismic demand. Performance was evaluated on both global and local levels and compared to seismic demand.
Analysis, also, gave the emerging order of plastic hinges, and their status for relevant displacement demands corresponding to three limit states (DL – damage limitation, SD – significant damage and NC – no collapse).
Analysis were conducted for two lateral load distributions, uniform and modal. Greater values of base shear forces were evaluated using uniform lateral load distribution. Also, bigger displacements corresponding to maximum shear forces were reached for modal lateral load distribution.
Table 1 summarizes the maximum base shear forces reached and corresponding displacements of master node.

Table 1 - Maximum base shear force and corresponding displacement for 8 pushover load casses

	X+ modal	*X- modal*	*X+ uniform*	*X- uniform*
*base shear (*kN*)*	2224.29	2213.28	2705.76	2700.21
*displacement (*m*)*	0.24	0.232	0.256	0.252
	Y+ modal	*Y- modal*	*Y+ uniform*	*Y- uniform*
*base shear (*kN*)*	1940.65	1930.95	2271.80	2267.16
*displacement (*m*)*	0.292	0.284	0.272	0.272

Results summarized in the table above clearly show that frames in X direction have greater resistance (greater base shear force).
Analyzing the plastic mechanisms arising from two different lateral force distributions show that modal force distribution favors emerging plastic hinges in beams first, and then after reaching NC limit in couple of beams, reaching NC limit in columns as well. While for the uniform lateral load distribution seismic demand is uniformly distributed through all columns, and columns are also first elements that reach NC limit state and then progressively lead to formation of mechanism with all columns reaching NC limit state in their base. Seismic demand is relatively uniformly distributed throughout the building for increment steps corresponding to limit states considered, showing that performance of this building may be labeled as satisfactory. Although there are some limitations to this method (Pushover method), it still gives a lot of useful information about the structure performance. Some modification of the elementary pushover method has led to definition of new pushover based methods. For the further research this analysis may include P-Delta effects and implement fiber model instead model with plastic hinges.

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НЕЛИНЕАРНА СТАТИЧКА СЕИЗМИЧКА АНАЛИЗА ВИШЕСПРАТНЕ АБ ЗГРАДЕ

Резиме: *У овом раду примењена је нелинеарна статичка сеизмичка анализа као метод за процену понашања вишеспратне АБ зграде, нерегуларне у основи подвргнуте земљотресном дејству. Процена понашања врши се у складу са EN 1998-3:2005 одређивањем капацитета (pushover криве), одређивањем захтева (циљног померања), поређењем њих на глобалном и спровођењем провера на локалном нивоу (нивоу елемената), при чему се нелинеарно понашање моделира пластичним зглобовима.*

Кључне речи: *pushover, процена понашања, пластични зглоб, зграда, нерегуларност у основи*