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Professional paper

ASSESSMENT OF THE SEISMIC BEHAVIOR OF REINFORCED CONCRETE FRAME STRUCTURES USING NONLINEAR STATIC PUSHOVER ANALYSIS

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Abstract

Structures designed in seismically active regions such as the Republic of North Macedonia must meet two basic requirements: The first one, the structure must be designed to be loaded during usage (limit state of use), and the second one: the structure must be durable enough to avoid collapse during an earthquake (ultimate limit state). Apart from linear-elastic calculations, nonlinear methods are also very often used.

Nonlinear static pushover analysis helps us to evaluate the performance of existing and new structures to provide adequate information on seismic demands based on the structural system and its components.

In this paper, we decided to analyze a simple concrete structure with a four-story building with different sections of columns on the top floor, using Eurocode 8 methods (EN 1998-1:2004). The main reason for this paper is to summarize the basic concepts on which the pushover analysis can be based and evaluate the expected performance of structural systems by estimating the performance of the structural system, by estimating its strength and deformation demands in design earthquakes using static nonelastic analysis.

Keywords: Earthquake, Pushover, Nonlinear, Structures, Static.

1 Introduction

Designing seismic structures is difficult because the fundamental concept of seismic resistance is different from designing under the influence of other loads, such as wind or gravitational loads. While even the slightest damage is not acceptable for wind or gravitational loads, the usual design for an earthquake is since in the event of a major earthquake, the structure may be severely damaged, but collapse should be avoided. At today's level of development of construction science, earthquake loading is a complex scientific and design task.

Most buildings behave in a linearly elastic manner when loading the service. Thin structures are an exception such as some suspension systems, arches, and tall buildings and structures that are subject to early localized cracking. But before their resistance limit is reached, almost all structures would show a significant nonlinear response. Therefore, if the linear elastic analysis is the highest available level, the design engineer must find another way to consider the effects that the analysis cannot simulate. The answer may lie in any of the following: **a)** *Individual reasoning,* **b)** *code formulas* that accept the results of linear elastic or simplistic analysis and allow nonlinearity in some empirical or semi-empirical way, or c) *additional theoretical or experimental studies.*

In nonlinear analysis, an attempt is made to improve the analytical simulation of the behavior of the structure in a certain regard. The main goal is to improve the quality of the design by providing the engineer with a more reliable prediction of the performance of the system which is under design or investigation. In making this closer connection between structural analysis and actual behavior, the traditional distinction between the terms "analysis" - determination of forces and displacements under given loads and "design" - the proportion of members and connections to counteract certain effects - becomes blurred. We will emphasize the analytical side of the problem but determining one aspect of the behavior is the primary goal in the structures we consider.

2 Pushover – In general

Pushover analysis is a static analysis used to examine how far a building can go in the nonelastic range before being on the verge of complete or partial collapse. The building model is computer-aided, with all the load-resistant elements together with their force-deformation ratios, both before and after the crash and with dead loads plus average live loads. A small set of horizontal forces is then applied to simulate the effects of ground movements and the deformations are calculated. The forces are then increased in steps to develop a plot of the movement of the base versus deformation. Examination of this plot reveals the largest basic movement the building can resist.

This approach has been developed to allow an analysis of existing buildings and to study the effectiveness of schemes to strengthen these buildings and provide greater elasticity. The reinforced building shows a certain elasticity that will make the collapse much less likely. Pushover analysis is now also often used to assess the expected performance of new building projects.

The analysis process consists of presenting the structure with a two- or three-dimensional analytical model that will cover all important both linear and nonlinear characteristics, then applying horizontal loads to pre-determined loading patterns that would represent the corresponding inertial forces generated in concentric masses. The structure is "pushed" under the action of these loads to a specific target displacement (Figure 1.)

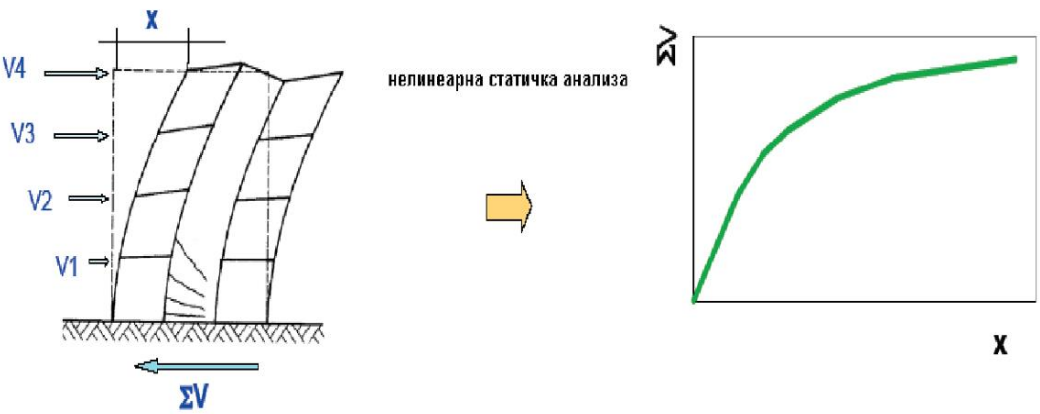

Figure 1: Schematic representation of Pushover analysis

Objectives, why do we use the **PUSHOVER** analysis?

- To confirm or revise the values of the a_u/a_1 ratio
- To Assess the expected plastic mechanisms and the distribution of damage
- To assess the structural performance of existing or extended buildings
- As an alternative to the design based on linear-elastic analysis that uses the behavior factor q. In that case, the designated target displacement (target displacement) should be used as the basis of the design.

3 Numerical Example

As an example, a response to a four-story reinforced concrete structure will be given. I was using SAP2000 v14 software.

Nonlinear static analysis can be performed using a program in which the nonlinear characteristics of the elements can be modeled. However, due to the different simplifications in the modeling and behavior of the elements in the post-plastic area, there may be variations in the results obtained with different software. To correctly interpret the obtained results, the principles of operation of the software must be known. In this paper, analyses of reinforced concrete frames have been performed using the SAP2000 program using different transverse load distributions.

Generally, the procedure for performing the analysis is as follows:

- *It is necessary to make a model of the construction that will include all components that contribute to the weight, strength, rigidity, and stability and whose participation is important for obtaining a realistic picture of behavior during an earthquake. The structure is burdened with a static vertical load, just as it is loaded in reality before the horizontal seismic load acts.*
- *Material nonlinearity should be modeled. There are two ways of representing the behavior of the elements after reaching the point of flow: distributed plasticity (plastic zone) and concentrated plasticity (plastic joints).*
- *Loading the structure with a horizontal load, as previously described. At least two modes of distribution must be used for each direction, especially if a three-dimensional structure is modeled.*
- *The loading process continues until unacceptable behavior of the structure is noticed, i.e., until the maximum displacement is reached.*

A diagram of total horizontal force is drawn - moving the control point for different levels of load and thus the nonlinear response to the response of the structure is obtained.

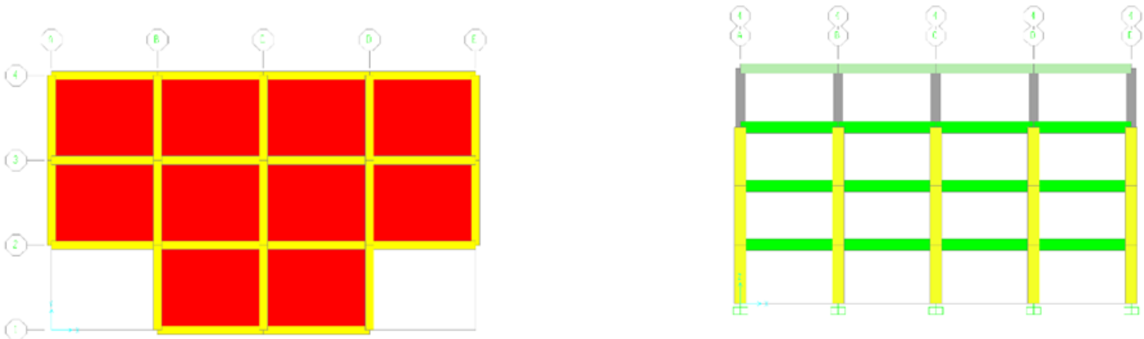

Figure 2: Base and Cross section of the building in SAP2000

Features of the building:

- Facility: P + 3
- Spans: x - direction 6m, y-direction 5m, z - direction 3m.
- Type of building: Reinforced Concrete Framework system
- Material: Reinforced Concrete with a compressive strength of 25 Mpa
- Pillars: 0.4m x 0.6m (Ground floor, Floor I and Floor II) and 0.4m x 0.5m (Floor III)
- Beams: 0.4m x 0.6m (Ground floor, Floor I and Floor II) and 0.4m x 0.5m (Floor III)
- Slab: 0.15 m
- Loads: Permanent (Dead) 2.5 kN/m2, Useful (Live) 3.0kN/m2, Facade 8,0kN/m’, Roof 1.5kN/m2
- Additional workloads: Gravity-Nonlinear
- Hinge (plastic joints): on 5% and 95% of the elements
- Push X – analysis

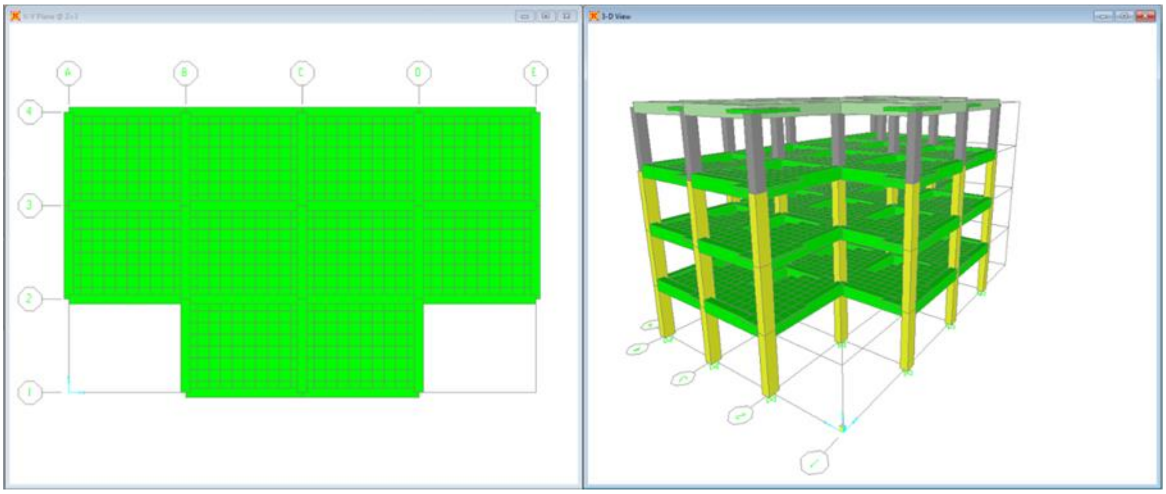

Figure 3: 2D and 3D view of the construction

After the dead and live loads on the construction are applied, a dynamic analysis is performed. The data required to perform this analysis are the total mass of the structure and the acceleration of the masses.

It is assumed that the mass is concentrated in points of the structure - one on each floor. The mass is determined by converting the load into a mass and multiplying them by an appropriate coefficient. The coefficient for constant (dead) loads is 1, while for useful (live) loads is 0.5. After obtaining the total mass of the structure, the mass matrix of the structure is easily determined. Because the geometric features of the structure are known, the stiffness matrix is also known, so the program with a defined number of iterations by the user determines the periods and frequency.

After applying all the loads, the possible load combinations are made. The SAP2000 uses two basic types of nonlinear elements when I used linear elements that define the pressure-strain level that plastic joints can receive. Each linear analysis starts with an unloaded state and takes place as if the nonlinear parameters are not present. It is possible to insert any number of joints at any location, and each joint is modeled as a discrete point on the model. Then, any plastic deformations, displacements, or rotations occur at this point. This means that it is necessary to determine an adequate length through which plastic dilatations or curvatures will be integrated. It is possible to approximate the plasticity that is distributed over the entire length of the elements so that more joints can be inserted at a short distance. However, this increases the duration of the analysis and may not have any effect if they are not activated, ie until they start to flow.

The program has the option for the user to define joints or use already-defined ones. SAP2000 has standard, already-defined joints according to FEMA-273 for steel structures and ATC-40 for concrete structures. Joints that are already defined cannot be modified and depend on the defined cross-section of the element.

Figure 4. shows five specific points marked A, B, C, D, and E that are used to define the behavior of the joints. Point A marks the beginning and point B the flow. Until the flow is reached, the deformations are linear and occur in the bearing element and not in the joint. The plastic deformations that will occur in the joint are above point B, and in case the joint is relieved elastically, it will be along a line parallel to A-B. Point C is the capacity limit. When the joint reaches point C, the force will decrease, and when it reaches point D, the displacement starts to increase again. Point D represents residual stiffness for pushover analysis, and point E is a complete fracture.

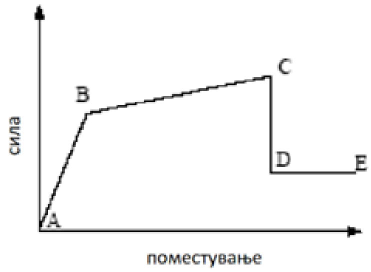

Figure 4: Defining a plastic joint in SAP2000

The location of the plastic joints is chosen in the cross-sections of the structural elements where it is expected the initial achievement of the static quantities causes creep. Under the action of horizontal loads, such cross-sections are usually located at the ends of the structural elements. Thus, the plastic joints are placed at the ends and in the middle of all the beams and at the ends of all the pillars of the structure, as places where the limit moments would be reached first. In these elements, until the criterion of creep is reached, the plastic joints behave ideally elastic, while after that their behavior is by the defined nonlinear characteristics of the cross-section. The defined location of the joints is shown in Figure 5.

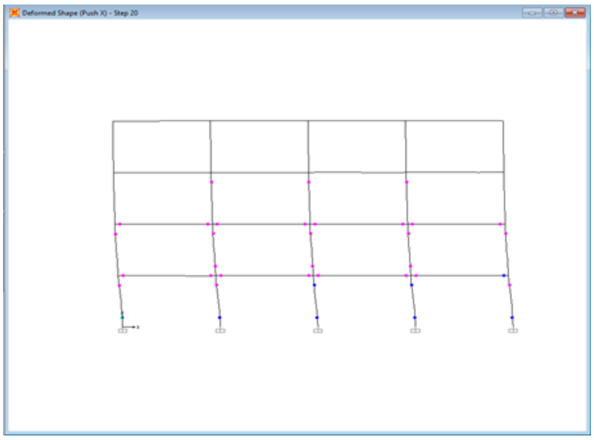

Figure 5: Location of plastic joints

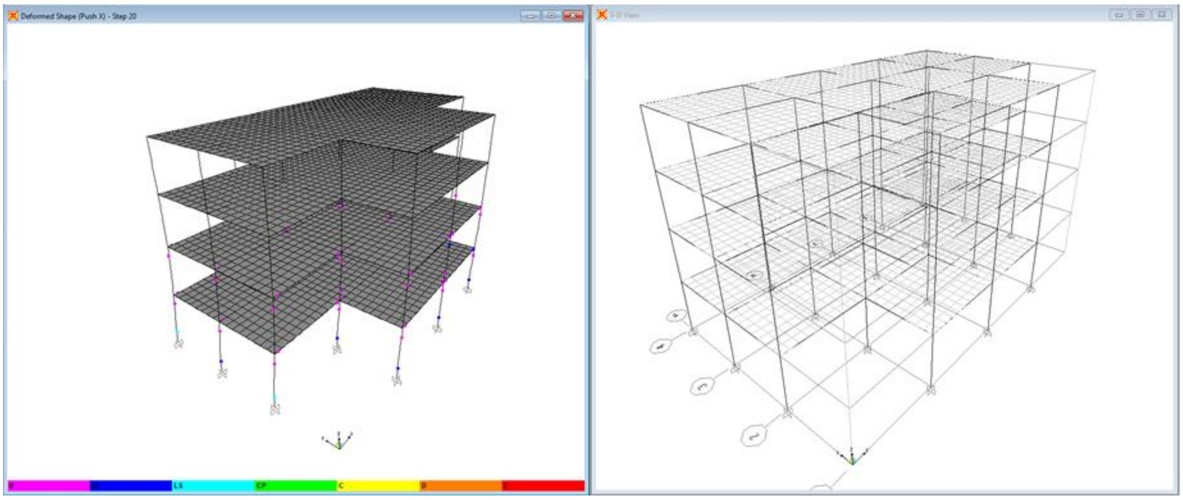

Figure 6: Deformed state of Nodes – Plastic Joints (Push X) - Step 20

The nodes (hinges, plastic joints) in my building are placed on 5% of the elements (pillars and beams) and 95% of the elements. Plastic joints are points of construction where cracking and sagging are expected to occur with relatively greater intensity so that they show a large displacement of bending (or shear) as it approaches their ultimate strength under cyclic loading. These are locations where crossed diagonal cracks are expected to be seen in a real building structure after seismic chaos, and it is found that they are located at both ends of the beams and columns, and the "cross" of the cracks is a short distance from the joint - that is the place where the nodes (plastic joints) are expected to be inserted into the beams and columns of the corresponding computer analysis model. The nodes (plastic joints) are of different types – namely: bending nodes, shear nodes, and axial nodes. The first two are inserted at the ends of the beams and columns. Given that the presence of masonry deposits has a significant impact on the seismic behavior of the structure. Axial nodes are inserted at both ends of the diagonal supports modeled in this way to simulate charge cracking during analysis.

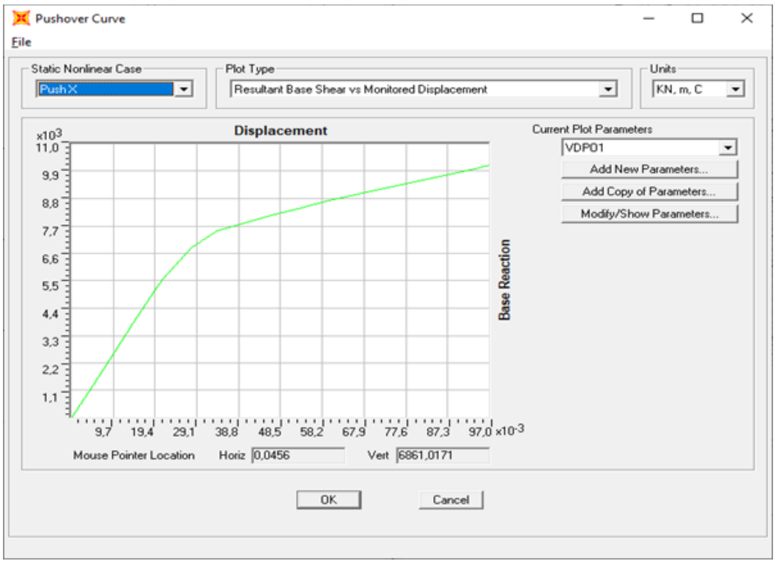

Figure 7: Pushover Curve (Resultant Base Shear vs Monitored Displacement)

A very important factor in finding the target displacement is the response spectrum used. By defining the spectrum, the seismic demand of the structure is shown.

Pushover analysis with maximum displacement Dt (roof) provides displacements for the whole structure, and local seismic requirements (in terms of relative floor displacements and joint rotations). The resulting envelopes are obtained by pushing from left to right and vice versa.

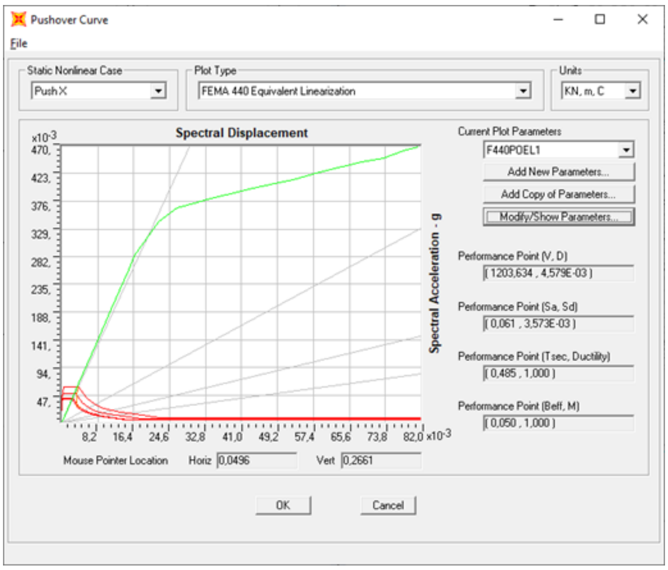

Figure 8: Pushover Curve (FEMA 440 Equivalent Linearization)

The target displacement and ductility of the displacement of the structure are obtained using the procedure shown in Figure 8, according to FEMA-440.

Design approach:

Although the properties of the hinges can be obtained from the graphs of the average values included in FEMA356, ATC-40, and FEMA 440 (which are only rough estimates), accurate results require details of the reinforcement provided to calculate the exact properties of the plastic joints. (Using concrete models such as the Confined Mander model available in the SAP2000 software package). And the structure needs to be designed to get the reinforcement details.

Thus, the methodology that emerges for an accurate seismic project is:

- First linear seismic analysis based on which a primary structural project is made;
- Insertion of hinges (plastic joints) determined based on design,
- Pushover analysis, followed by
- Modifying the design and details, whenever necessary, based on the latest analysis.

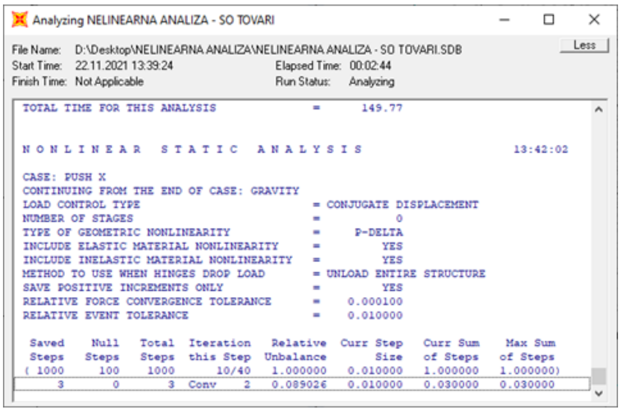

Figure 9: Nonlinear Static Analysis

Conclusions

What I have intended here is to explain the method with as much simplicity as possible to introduce the basic concepts to those who are already familiar with the conventional seismic analysis. I hope I have achieved my goal at least to some extent. Of course, there are many aspects that I did not mention in this article - such as obtaining the properties of nodes (plastic joints) from the details of the section, incorporating the effects of the interaction of the soil structure, deciding on different parameters for suppression analysis, a method for modeling shear walls and flat slabs with joints, etc. - because this is not intended to handle the procedure to that extent.

This research provided some basic information on the use and accuracy of different suppression analysis methods in seismic assessment and structural design. The research contained the following aspects: The basic concept of pushover analysis was explained and the different methods of suppression analysis were described. A comprehensive review of previous pushover findings was provided for analysis.

The use of inelastic response spectra can lead to difficulties in interpreting results when performing suppression analysis because, to increase the elasticity factor, the displacement of demand sometimes decreases.

Pushing curves tend to underestimate the actual energy consumed which implies that damage assessment in buildings can be erroneous.

The load distributions available to engineers will generally provide different results for different material models and rollover methods. The results were found to depend on the severity of the earth's motion and the frequency content and frequency distribution of the earth's motion.

The ductility of displacements obtained according to FEMA 440, as well as the maximum displacements using a triangular distribution are greater than in an even distribution.

The way of modeling the nonlinearity has a great influence on the results. The distributed plasticity model takes into account the stiffness degradation and gives more realistic results for the loads in concentrated plasticity (SAP2000).

Using the features of plastic joints embedded in SAP2000 software can lead to unrealistic results. It is recommended to use characteristics obtained by detailed analysis of the dependencies of the intersections, the moment of curvature, and the moment of axial force.

To obtain general conclusions and to be able to choose an accurate and more realistic transverse load model for pushover analysis, it is necessary to analyze the behavior of many structures and load models, and compare the results with a nonlinear dynamic analysis conducted for various records of real earthquakes.

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