

BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI  
Publicat de  
Universitatea Tehnică „Gheorghe Asachi” din Iași  
Tomul LXI (LXV), Fasc. 2, 2015  
Secția  
CONSTRUCȚII. ARHITECTURĂ

## NON-LINEAR STRUCTURAL ANALYSIS OF STRUCTURES THAT INCLUDE LOAD-BEARING WALLS BASED ON PERFORMANCE CRITERIA

BY

ONEA FLORIN ȚEPEȘ\* and MARIAN ENE

University Ovidius of Constanța  
Faculty of Civil Engineering

Received: June 15, 2015

Accepted for publication: June 26, 2015

**Abstract.** Following the research in the field of static non-linear analysis done in recent years on the “Pushover” analysis method, some improvements and adjustments were made that give the designer more calculation methods than the traditional pushover analysis.

The purpose of this study (non-linear static calculation) is to confirm that the design solution is a proper one and if this is the case, also suggest improvements or corrections of the design solution.

By using the “pushover” analysis method we can estimate the ductile nature of a load-bearing structure, the method being one that takes into consideration the maximum displacement at the top of a structure which is acted upon by a seismic force at the base.

The non-linear static analysis is not used to design the load-bearing structure, but actually to verify the design solutions given by elastic design methods, with the possibility to improve on this solution and thus assisting the designer to reach the performance requirements.

**Key words:** non-linear; pushover; performance; design.

---

\*Corresponding author: *e-mail*: tflorin@univ-ovidius.ro

## 1. Detailing the Non-Linear Static Analysis

The F-d (force-displacement, Fig.1) curve highlights the evolution of the plasticizing mechanism of the structure, hence the degradation of it, on the basis that the lateral seismic force is increased, which simulates inertia forces, while the vertical loads remain at a constant value throughout (P100-1/2013).

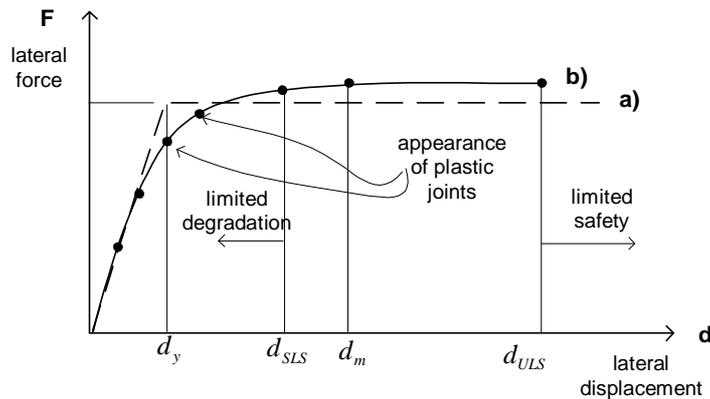


Fig. 1 – The assimilation of the force-displacement diagram with the diagram of an elastic-plastic system; *a* – ideal elasto-plastic; *b* – plastification structure evolution mechanism ( $d_{SLS}$  – displacement service limit state;  $d_{ULT}$  – the ultimate limit state)

In its simplest form, the distribution of horizontal forces is considered constant, while increasing proportionally after a certain initial configuration.

Non-linear static analysis implies the following main steps:

a) Assessing the load-bearing and deformation capacities of the structural components.

b) The assembling of the lateral force-top displacement curve.

The horizontal loads shall be increased monotonously up until the point in which the structure reaches the imposed displacement or the collapse of the structure occurs. The force-displacement curve will be drawn incrementally once the horizontal loads are monotonously applied.

In order to obtain an eloquent collapse mechanism, the imposed displacement needed to reach the performance level of the final stage is enhanced by 50% in such a way that the incremental stages obtained step by step will indicate the progression of the structural collapse.

c) Assimilating the MDOF (multiple degree of freedom) structure with a SDOF (single degree of freedom) system.

d) Evaluating the displacement requirements (P100-1/2013).

For new buildings, with a load-bearing structure made up of reinforced concrete, elements designed according to the P100-1/2013 code, the inelastic displacement spectrum  $S_D(T)$  can be approximated using this equation:

$$d^* = S_D(T^*) = cS_{De}(T^*),$$

where:  $c$  is the amplification factor of displacement;  $S_{De}(T^*)$  – elastic response spectrum.

e) Controlling structural displacements.

### 1.1. Structural Modelling for the Inelastic Computation

The inelastic computation is done using SAP 2000 software, which uses different modelling for load-bearing walls than frame elements.

The wall modelling is achieved using surface elements which have the added advantage of highlighting the actual properties of concrete and steel, materials that behave different than the idealized behavior used in current calculation methods, and explicitly show in which areas of the wall the plastic deformations occur.

The wall layers have an independent behavior, but the elements have equal displacements in nodes. In SAP 2000, each layer of each elements has 4 monitored points. The stiffness matrix is obtained by integrating (Gauss integration method) the stiffness characteristics of these 4 points whilst considering the tangent modulus of elasticity of the monitored points.

The stiffness matrix of an element is obtained by summing the stiffness matrices of each individual layer (Postelnicu *et al.*, 2012; Damian, 2011).

In the case of linear elements such as beams and columns, the plasticity modelling is achieved by introducing plastic hinges at the end of these elements. For reinforced concrete load-bearing columns, the modelling is not as simple as in the case of the beams, because the bearing capacity depends highly on the axial force, which in most cases varies during an earthquake. In this particular case the plastic hinges modelling is based on the plasticity theory.

## 2. Structure Design. Linear Analysis.

The analyzed structure has a basement, ground floor and 10 stories.

It is placed in the city of Constanta, having an office building.

The building has a length of 26.00 m and a width of 23.00 m, having a 2 dimensional regular shape both on the  $X$  and  $Z$  axes.

In order to limit the overall size of the columns and beams, the load-bearing structure is designed to include load-bearing walls which are independent or coupled. The height of a story is constant at 3.00m even in the basement. The ductility class for this building is  $H$  class (high ductility).

The materials used are as follows: Concrete C 30/37 Class; Steel S500C.

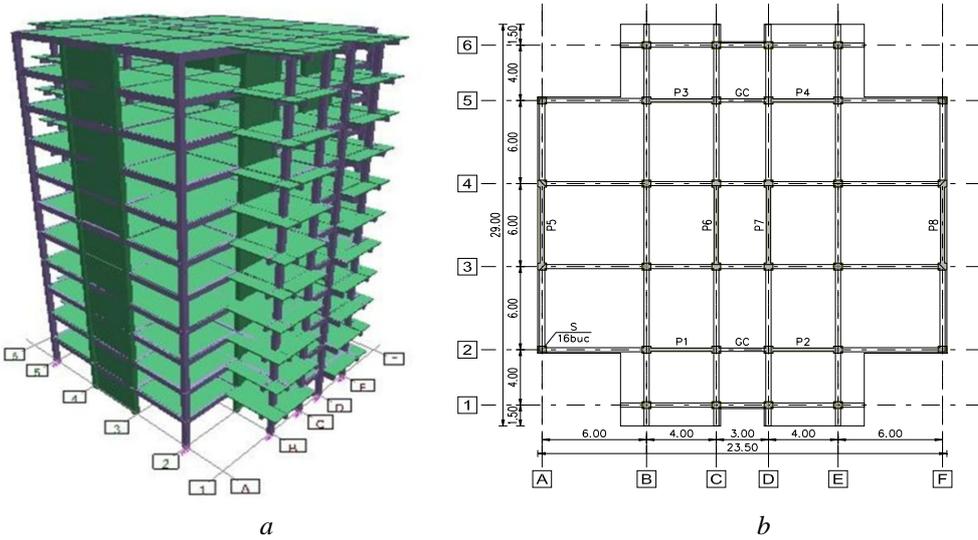


Fig. 2 – The analyzed structure: *a* – Overvie; *b* – plan configuration of the structure (walls: P1-P8).

The design of the structure is done in the first stage. This contains the following:

- a) Lateral stiffness checking at serviceability limit state (SLS).

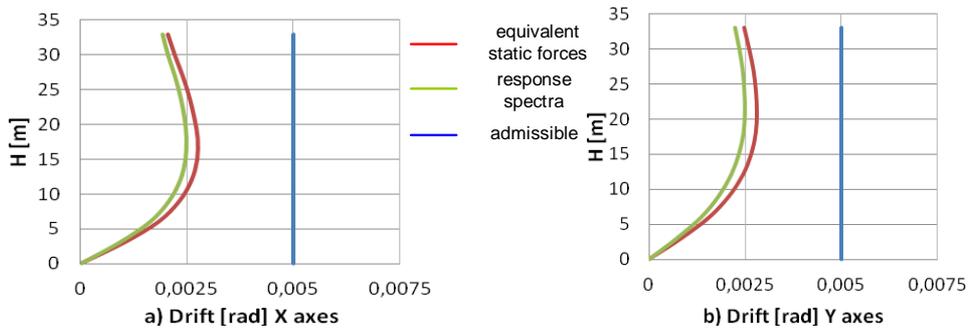


Fig. 3 – *a* – angular drifts on the X axes; *b* – angular drifts and Y axes at SLS

- b) Lateral stiffness checking at ultimate limit state verification (at ultimate limit state).
- c) Torsion verification.

d) Designing the isolated load-bearing walls.

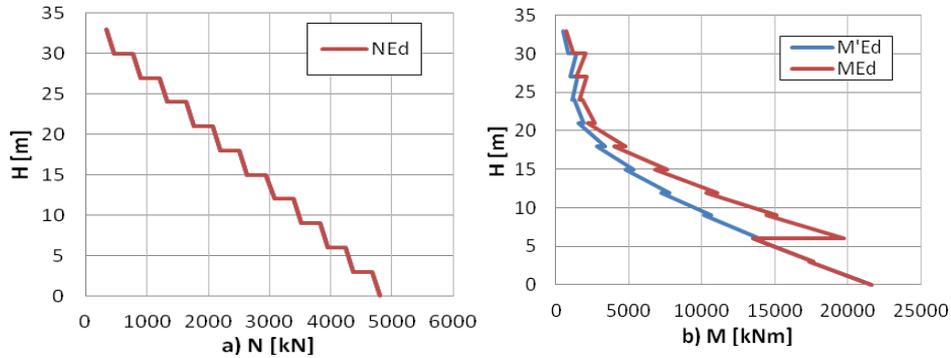


Fig. 4 – Axial force (a) and moments (b) in the special group, the ones associated with the global plasticization mechanism on the Y axis and for the isolated walls 5 and 8 (Fig. 2 b).

$N_{Ed}$  is the plan axial forces;  $M_{Ed}$  – design bending;  $M'_{Ed}$  – bending moment of seismic design loads, including any adjustments resulting from redistribution efforts between the walls.

a) For A zone:

$$M_{Ed} = M'_{Ed,0}$$

b) For B zone B:

$$M_{Ed} = k_M \Omega M'_{Ed} < \Omega M'_{Ed,0}$$

$k_M$  – a correction factor to bending moments of walls (A:  $k_M = 1$ ; B:  $k_M = 1.3$ ).

In Fig. 4 b is observed that bending moment design decreases due to redistribution of the walls.

e) Designing the coupled load-bearing walls.

f) Designing of the frames using DCH class.

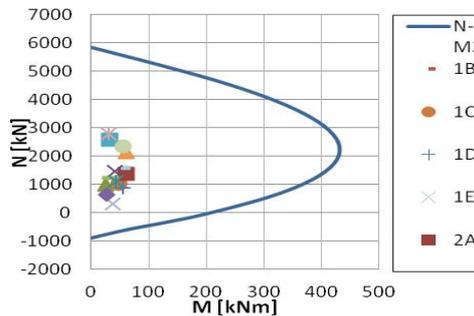


Fig. 5 – Axial force-bending moment interaction diagram. The strains on the bottom of the columns using the seismic group on the X axis.

Interaction curves in Fig. 5 resulted in minimum percent. All the columns fit inside curve interaction.

### 3. Non-Linear Calculation of the Load-Bearing Structure. Evaluation of the Strength and Deformability Properties of the Contained Elements

The non-linear static calculation essentially implies the construction of a force-lateral displacement curve on which we mark the seismic displacement requirement. Corresponding to the imposed displacement we obtain plastic rotations in the plastic hinges. The safety requirement is satisfied only if the plastic rotation capacity is higher than the requirement in each of the plastic hinge.

In Fig. 6 are shown the concrete properties used for design.

Compressed Concrete (Table 1) is considered appropriate degree of confined properties of transverse reinforcement exercised. This is determined based on the model given in SR EN 1992-1-1:

$$f_{cm} = f_{ck} + 8 \text{ N/mm}^2 = 38 \text{ N/mm}^2.$$

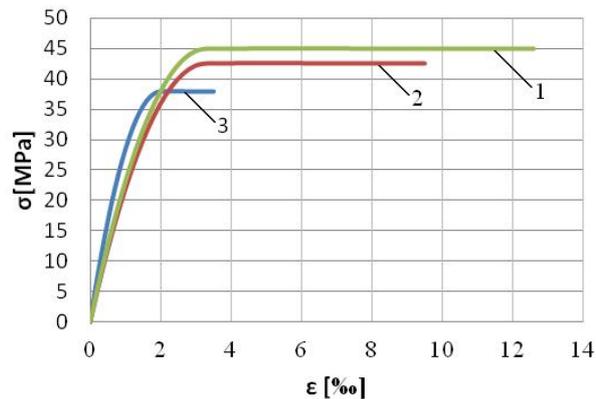


Fig. 6 – Stress-strain diagram for concrete: 1 –  $f_{cm}$  C30/37 walls heart;  $f_{cm,c}$  C30/37 bulbs;  $f_{cm,c}$  C30/37 columns.

**Table 1**

*Concrete Characteristics*

Element	Walls		Beams	columns
	Bulbs	Heart		
$\alpha$	0.63	0.2	0.2	0.63
$\rho_{sw}$	0.0057	–	–	0.0040
$f_{cm}$	38	38	38	38
$f_{cm,c}$	42.5	–	–	45.0
$\varepsilon_{e2,c}$	0.0033	0.002	0.002	0.0032
$\varepsilon_{cu2,c}$	0.0095	0.0035	0.0035	0.0126

For the steel (Table 2, Fig. 7), the average hardness is determined with the following equation:

$$f_{ym} = 1.15f_{yk} = 575 \text{ N/mm}^2,$$

$f_{yk}$  is the yield strength of reinforcement;  $f_{ym}$  – design yield strength of reinforcement.

**Table 2**  
*Steel Reinforcement Characteristics*

Steel	S500C
$f_{ym}$	575
$E_s$	200,000
$\varepsilon_{sy}$	0.0029
$\varepsilon_{s,u}$	0.075

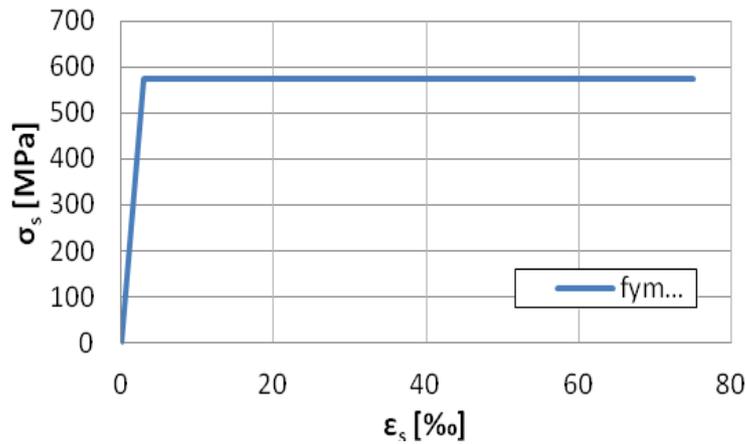


Fig. 7 – Stress-strain diagram for the steel reinforcements.

### 3.1. The Construction of the Lateral Force-Top Displacement Curve

In Figs. 8 and 9 the force-displacement curves on the  $X$  and  $Y$  axes are represented, as well as the bilinear of these two, the displacement requirements and the order in which the plastic hinges occur.

These curves represent the relation between the shear force that is associated with the fundamental translation mode and displacement at the top of the structure. The value of the associated shear force is 8,300 kN on the  $X$  axis and 8,550 kN on the  $Y$  axis.

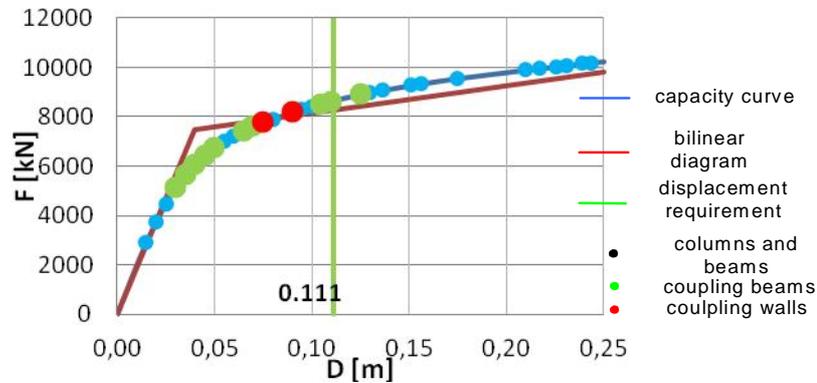


Fig. 8 – Force-displacement curve, bilinear diagram and the top displacement requirement on the  $X$  axis.

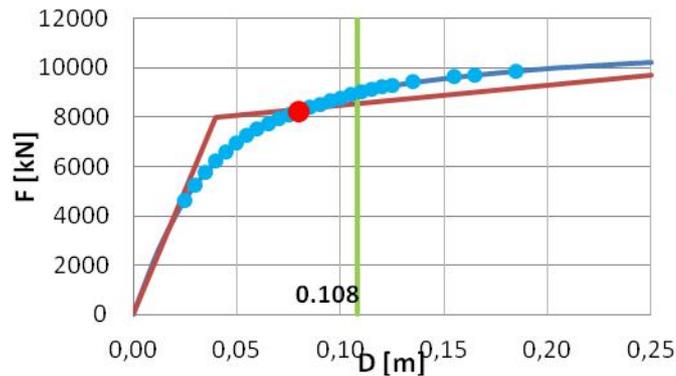


Fig. 9 – Force-displacement curve, bilinear diagram and the top displacement requirement on the  $Y$  axis.

### 3.2. Verifying the Structural Elements

In order to describe the structural response the next results are checked:

- a) Shear force assurance.
- b) Relative level displacements.**

In Fig. 10 the relative level displacements are shown for each level of the structure on both  $X$  and  $Y$  axes, which are obtained by using the 2 methods.

- c) Deformation capacity in the post elastic field

The ratio between the rotational requirements and capacity represents a seismic safety measure.

- d) The energy dissipation mechanism ( the plastic hinge table during the seismic action).

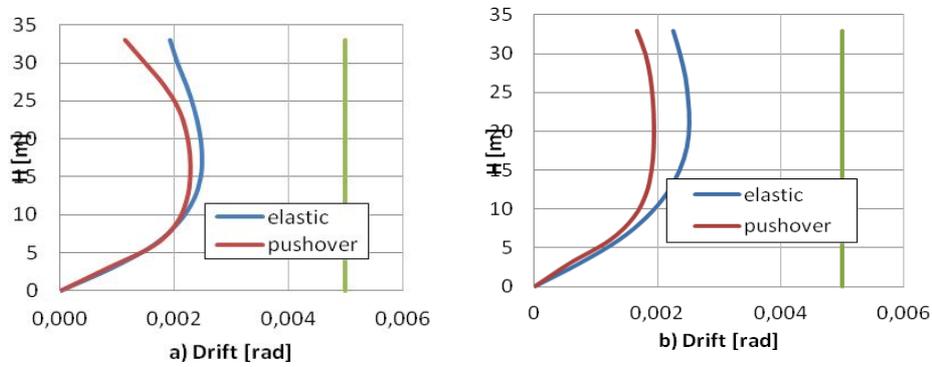


Fig. 10 – Displacement requirement values associated with SLS obtained using an elastic calculation (the response spectrum method) and non-linear static calculation: (a) X axis (b) Y axis. Compared admissible.

A favorable plasticization mechanism is described by the forming of plastic hinges in the coupling beams between the load-bearing walls and where the walls are embedded in the foundation. In this manner the structural elements are mobilized to dissipate the seismic force that acts upon the whole building producing limited displacement requirements which are uniformly distributed.

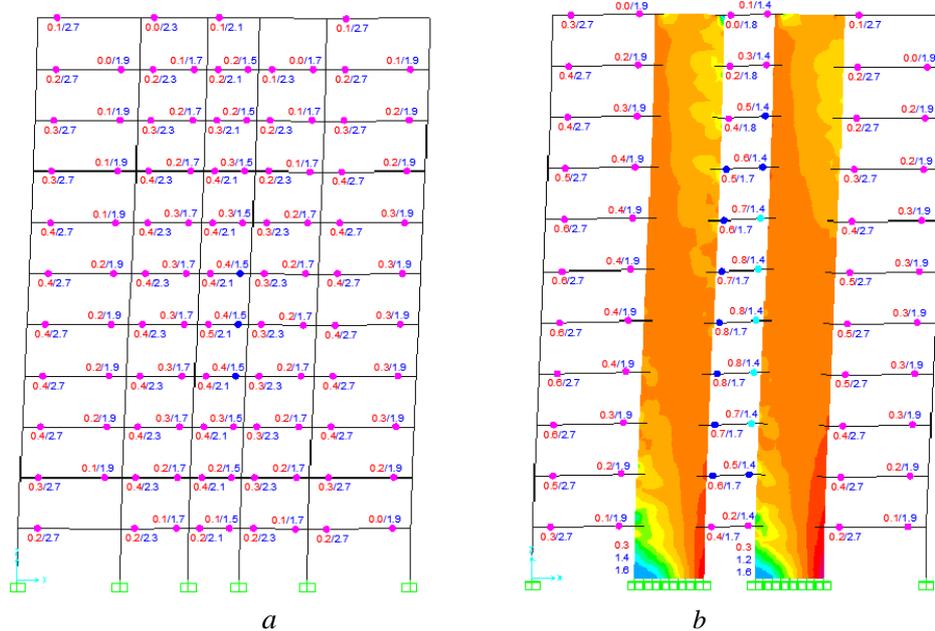


Fig. 11 – Plastic hinge table which resulted from the nonlinear analysis: (a) 2<sup>nd</sup> axis elevation (b) 3<sup>rd</sup> axis elevation (design earthquake).

#### 4. Conclusion and Recommendations

1) In this case study we have found that the analyzed structure had a reduced sensibility to rotation and an overall favorable behavior when acted upon by an earthquake.

a) No breakings of the main elements due to shear forces occur, although the stress transfer between the tensioned and compressed columns is reduced to 13% from 27% in the case of distribution by bending capacity of the columns.

b) The plastic- rotation demands is under the capable one, in the limit of 25% for the load-bearing walls and 50% for the coupling beams.

c) The structure have a favorable plasticization mechanism, characterized by the formation of plastic hinges in the coupling beams and the frame beams followed by the plasticization of the load-bearing walls at the level of embedding in the foundation.

2) Under these conditions we can certainly say that this structure can be put in the medium ductility class DCM, which accepts lower construction restrictions meaning the reducing of the overall material usage.

3) In the case of tall buildings, where the vibration modes are very important, the result of the non-linear static calculation must be verified by additional non-linear dynamic analyses which provides a much more realistic behavior model.

#### REFERENCES

- Damian I., *Particularități ale modelării neliniare a pereților structurali*. Rev. AICPS, 1-2, 156-165 (2011).
- Postelnicu T., Zamfirescu D., Damian I., Morariu E., *Proiectarea structurilor de beton armat în zone seismice*. Vol I, II, III, București (2012).
- \* \* Etabs, Computers and Structures, [www.csiberkeley.com](http://www.csiberkeley.com).
- \* \* Sap 2000, Computer and Structures, [www.csiberkeley.com](http://www.csiberkeley.com).
- \* \* *Cod de proiectare a construcțiilor cu pereți structurali de beton armat*. CR 2-1-1.1/2013.
- \* \* *Cod de proiectare seismică*. Partea I: *Prevederi de proiectare pentru clădiri*. P100-1/2013.
- \* \* *Proiectarea structurilor de beton*. Partea I. *Reguli generale și reguli pentru clădiri*. SR EN 1992-1/EC 2-1.

---

ANALIZA NELINIARĂ A STRUCTURILOR CU PEREȚI STRUCTURALI PE  
BAZA CRITERIILOR DE PERFORMANȚĂ

(Rezumat)

În urma cercetărilor efectuate în ultimii ani analiza statică neliniară denumită și analiza „Pushover” a fost îmbunătățită și ajustată oferind proiectanților mai multe metode de calcul nelinar față de limitările analizelor pushover tradiționale.

Scopul studiului (calcul static neliniar) este de a confirma soluția proiectată prin metoda curentă și să sugereze, dacă este cazul, măsuri de corectare ale acesteia

Prin analiza de tip pushover se poate estima caracterul ductil al structurii de rezistență, fiind o metodă ce ia în calcul deplasarea maximă la vârf a structurii ce corespunde unei forțe laterale provenită din acțiunea seismică.

Analiza statică neliniară nu este folosită pentru a proiecta structura de rezistență ci pentru a verifica soluțiile alese prin metodele de proiectare elastică cu posibilitatea de a le îmbunătăți caracteristicile astfel ajutându-le să se încadreze în cerințele de performanță impuse.

