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# SEISMIC STRENGTHENING OF R/C FRAME STRUCTURES USING PERFORMANCE BASED DESIGN APPROACH

**Z. Bonev[1], St. Dospevski[2]**

***Keywords***: *performance based seismic design, target capacity spectrum, seismic strengthening*

***Research area***: *seismic assessment using performance based design approach*

## ABSTRACT

A procedure for assessment of necessity of seismic strengthening of building structures is developed and proposed. It allows for verification of the benefit of strengthening and its efficiency. Two modern and approximate methods are employed – capacity spectrum method and N2 method. The nonlinear performance of the structure is accounted for, the seismic loading is defined using two varieties: through elastic demand spectrum and through design demand spectrum. Calculation procedure for target capacity spectrum is discussed in details. The properties of existing and strengthened structures are assessed by making use of comparable analysis between capacity spectra. The necessary conclusions are made.

## 1. Introduction

The modern understanding in structural engineering is mostly directed towards development of performance based seismic design philosophies. The use of performance based design methods reduces the possible scatter between designed response and measured / observed behavior. The paper deals with application of performance based design methods for seismic retrofit of damaged structures. Two issues should be considered as very

[1] Zdravko Bonev, Prof. PhD, Dpt. "Structural Mechanics", UACEG, 1 H. Smirnenski Blvd., Sofia 1046, e-mail: zbp_uacg@abv.bg
[2] Stanislav Dospevski, PhD Eng., Dpt. "Structural Mechanics", UACEG, 1 H. Smirnenski Blvd., Sofia 1046, e-mail: stdospevsky@abv.bg

important for this subject – to prove the necessity of strengthening at first, and to prove the benefit of strengthening by recalculation of seismic demands and their possible reduction.

## 2. Performance Based Seismic Evaluation of Existing Structures and Improvement Verification after Strengthening

Part 3 of Eurocode 8 (EN 1998-3), [5], is very ambitious attempt to create new regulations for design of strengthened structures. It is compulsory to proof two important issues: 1) the necessity for strengthening, and 2) the benefit of strengthening. In the most projects and case studies the existing structure does not comply the performance requirements of [5] because capacity design rules are not implemented in old generation of codes. Seismic demands are not sufficient to cover performance requirements. It is implied in the most cases that the existing structure has insufficient initial (elastic) stiffness and insufficient seismic capacity. The need for strenghtening is evident.

The basic idea of the paper is to elaborate methodology for assessment of seismic demands associated with existing and strengthened structure. It should be taken into account that after strengthening, as a matter of fact, new strengthened elements are becoming members of a composite structure. There is a need to prove that the improvements carried out on the existing structure provide better seismic performance and seismic capacity. Seismic demands of the new (strengthened) structure should be studied carefully in order to provide reliable assessment of the structure. The positive effect of the strengthening should be verified by calculations theoretically based on performance based seismic design approach.

### 2.1. Actual Capacity Spectrum Determination

The *Actual Capacity Spectrum (ACS)* is defined as capacity spectrum of the existing structure. Strengthening is still not carried out. The basic strategy implies that for such category of structures seismic demands may essentially exceed the corresponding capacities. This means that Eurocode 8 requirements (ref. [4], [5]) are not satisfied and the seismic performance of the structure is not safe from the viewpoint of the seismic resistance.

Actual capasity spectrum is corresponding to a certain structure, which is designed according to EN 1998-1 or according to some other seismic resistant design code. Actual capacity spectra however can be determined also for structures which are designed without proper design criteria and performance requirements. At first base shear force – roof displacement diagram (pushover curve) is calculated as the output of nonlinear static analysis of the structure, subjected to monotonically increasing forces. At first, vertical forces are applied to simulate the effect of forces such as dead and service loads. Action effects for vertical loads are considered as initial values and inherent action effect when loading with monotonically increased lateral forces is initiated. Horizontal forces are applied at the floor levels.

The model of the plane frame structure is composed of beams and columns. Both types of members are elastic, but have inelastic rotational springs at both ends. Thus, beam and column members have inelastic behavior when the frame is subjected to progressively increasing static lateral loads. Plastic deformations are developed in "zero length plastic hinges" which are modeled by elastic-plastic rotational springs. The main objectives of pushover analysis are to determine the seismic displacement demands. In general, determination of seismic demands of structures subjected to a specific earthquake and this is not a deterministic problem. When design seismic action is used to calculate the seismic demands, seismic input is no longer oriented towards specific data and action effects are obtained in generalized form.

Deflected shape of the frame subjected to vertical and lateral loads is shown in Fig. 1. For frame structures lateral displacements are dominating over the vertical.

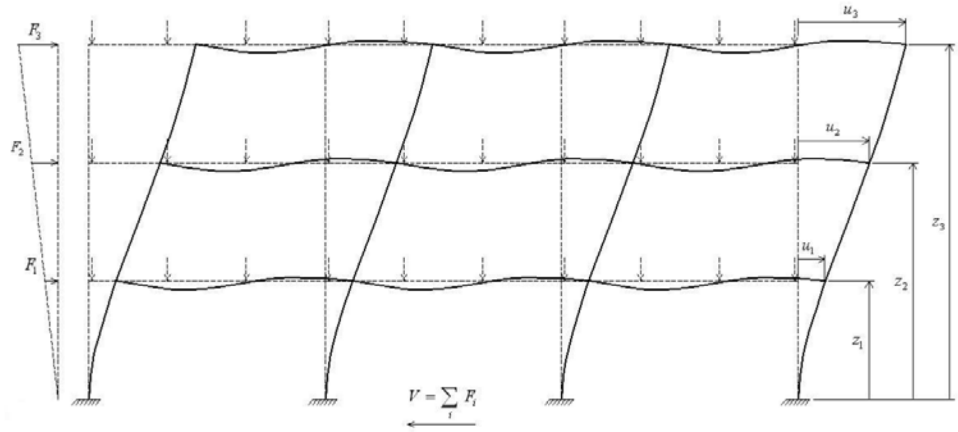


**Fig. 1. Loading patterns for vertical and horizontal forces used in static pushover analysis and structural model**

Determination of the seismic displacement demands requires bi-linear capacity curve to be implemented. It is suggested and used in theoretical development and obtained basing on energy balance principle as shown in Fig. 2. The pushover curve demonstrates the dependence of the base shear force on the roof displacements. This curve is the key issue for obtaining the actual capacity spectrum implying the relationship "first floor acceleration – roof displacement" being very important for performance based assessment procedure.

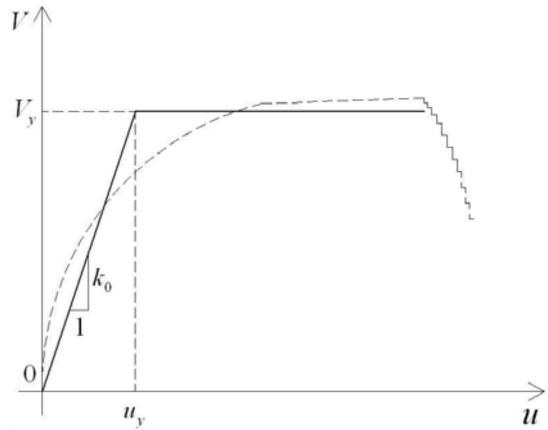


**Fig. 2. Determination of actual capacity spectrum from pushover curves: actual (dashed line) obtained through computations and idealized (solid line) bi-linear curve following equal work principle**

## 2.2. Teoretical Background of Assessment Procedure

This method is approximate. The accuracy of the method depends on how large is the scatter between assumptions and reality. Fig. 4 shows three storeys three bays frame wich forms local plastic mechanism, known as "soft first storey mechanism" (F). This is the most unfavorable and unsafe mechanism because concentrates all damages within the first storey and other storey remain undamaged. The background of the assessment procedure requires to verify the seismic displacement demands even if (F) mechanism happens are less than the displacement capacity. So, the basic inequality of [4] should be proven for the most unfavorable case as well.

The idealized (F) mechanism is presented in Fig. 3 as a pattern in the verification procedure.

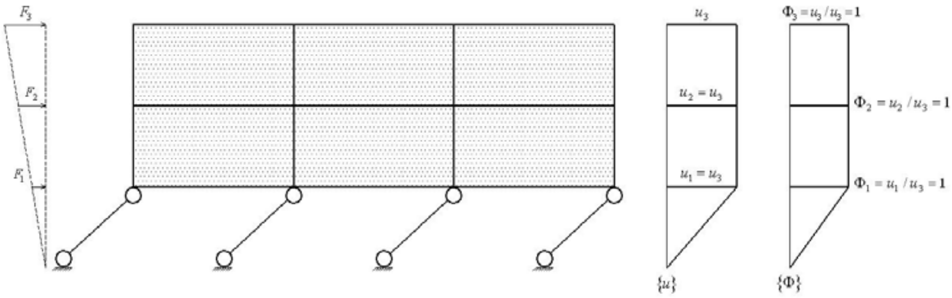


**Fig. 3. Soft first storey plastic mechanism as simplified presentation**

The vector of dimensionless lateral floor displacements $\{\Phi\}$ for (F) mechanism takes simplified form of presentation containing only unity as components:

$$\{\Phi\}^T = \{1 \quad 1 \quad 1\}^T \, . \tag{1}$$

The equation of the motion associated with equivalent single degree of freedom system (ESDOF system) is derived from the system of equations of the original model of the structure (MDOF system), (see ref. [2], [3], [6], [7] and [8]). This equation looks like this:

$$\ddot{u}(t) + \frac{V}{m} = -\ddot{u}_g \, , \tag{2}$$

where $m$ is the total mass of the floors above the first storey, $u(t)$ is the roof displacement relative to the base, which is unknown before solution of (2), $\ddot{u}(t)$ is the relative acceleration of the storey group, $V$ is the base shear force as a function of the time. When inelastic performance takes part $V$ becomes displacement dependent function of unknown argument $u$ and this is the source of nonlinearity. The notation $\ddot{u}_g$ represents the function of ground accelerations, being the seismic input for the analysis. It is implied that when the plastic mechanism is formed, the distribution of the lateral floor displacements in elevation is proportional to the shape, shown in Fig. 4. Equation (2) is valid only if the plastic mechanism is formed and the displacements are to be increased.

### 2.3. Definition of the Target Capacity Spectrum

Target capacity spectrum (TCS) should comply with the performance requirements in largest extent. It should cover deformation criteria such as limited elastic displacement $u_y$ for (F) mechanism and limited first storey elastic drift $u_y / H$, ductility demand should be less than ductility capacity (basic requirement of [4]). For (F) mechanism the elastic deformation criterion can be written in the form (see Fig. 4):

$$u_y \le \frac{H}{250}, \tag{3}$$

where $H$ is the first storey height. The ESDOF system should have limited performance with respect to deformations and this is the main reason deformation criteria to be used in definition of TCS.

Determination of TCS seems to be a geometric problem which is settled by making use of geometric ruls considering the disposition of specific point used for limitation of ESDOF system performance. In other words TCS is a pattern for structural performance where all deformation criteria comply with the limits. TCS is capacity spectrum of a structure whose behaviour proceeds as it should be.

Determination of TCS can be performed following the steps listed below:

1. Specify $u_y$ using equality sign in (3) as upper limit for yielding displacement.

2. Calculate the ductility demand on the basis of the position of point PP.

3. Find the point EPP (elastic performance point) basing on the observation of Newmark for equal displacements.

4. Find the elastic (initial) stiffness for ESDOF system connecting EPP with the origin of the coordinate system.

5. Find the acceleration at yielding $V_y / m$ ($m$ - total mass of the structure).

6. Find the behavior factor $q$ as a ratio of (ordinate of EPP)/(ordinate of PP).

If the results from items 2), 3) 4), 4) and 5) do not comply with the prescribed values of same quantities then reduce $u_y$ and go back to items 2), 3), 4), 5) and 6).

### 2.4. Analysis Method and Assessment Procedure

Determination of TCS is carried out using both CSM (Capacity Spectrum Method) and N2 method (Method of double nonlinearity). Fig. 4 shows the determination of TCS using basic principles of earthquake engineering. The following data are used in calculations: Ground Type C, reference ground acceleration 0.25g, importance factor 1.0 (thus the design ground acceleration is 0.25g), ref. [4]. National Annex of Bulgaria and Nationally determined parameters are used to define the spectral seismic action. Dashed line represents the elastic demand spectrum whereas solid line below denotes the design demand spectrum, which is drawn assuming behavior factor of 2.0. The analysis method employed to determine TCS is discussed in details in ref. [1]-[3], [6]-[8], [10] and [11].

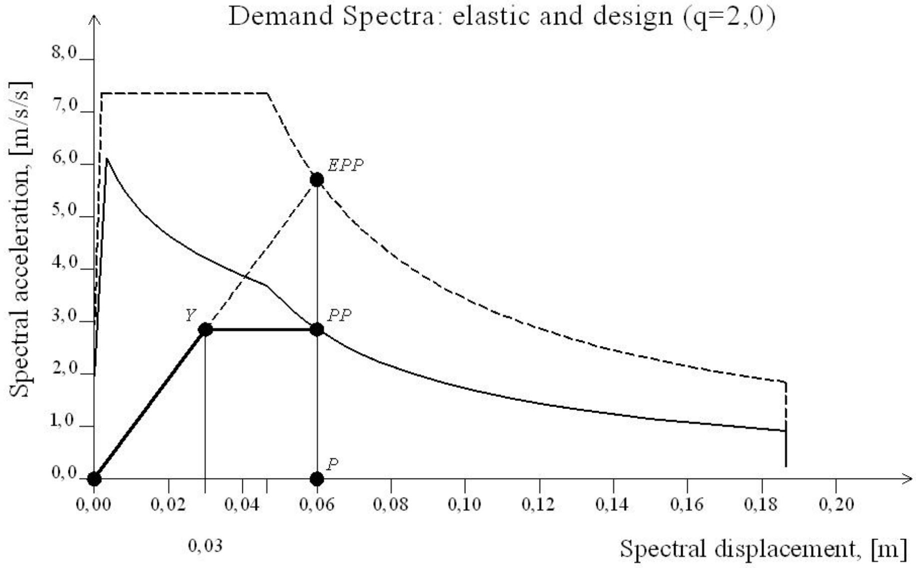


**Fig. 4. Determination of target capacity spectrum using base shear force – roof displacement relationship**

At first we supply the amount of the yielding displacement, equal to 0.03 m. We draw the vertical line passing through 0.03 m. Than we determine the design displacement demand value of 0.06 m (note than for long period structures displacement ductility and the behavior factor are equal according to Newmark principle). Using the vertical line passing through 0.06 m displacement we discover the location of EPP as intersection point between elastic demand curve and vertical line. Connecting the point EPP with the origin of the reference frame we obtain the initial (elastic) stiffness of ESDOF system. The intersection point between design demand spectrum and last vertical line and initial stiffness line both define the yielding point Y. Doing all these geometric steps we have TCS already determined and denoted by solid line. Note that the vertical line passing through 0.06 m contains the points EPP and PP on it.

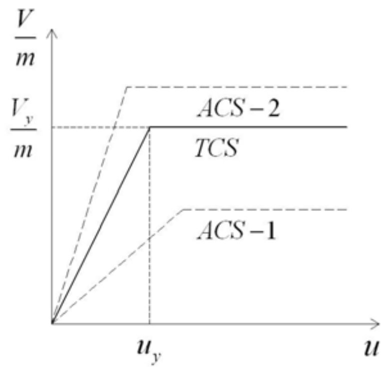


**Fig. 5. Comparison between TCS and ACS capacity spectra:**
**ACS–1 represents the actual capacity spectrum of existing structure before strengthening;**
**ACS–2 is the actual capacity spectrum after strengthening the existing structure**

The assessment procedure developed in the paper implies comparison between ACS (see Fig. 2) and TCS (see Fig. 4). Fig. 5 incorporates both ACS and TCS capacity spectra in format convenient to carry out comparison. Capacity spectrum ACS–1 is determined for structure which is not strengthened. Comparison with TCS shows that it has insufficient yield strength and insufficient elastic stiffness. In contrast with this the comparison between ACS–2 (structure after strengthening) and TCS shows that ACS–2 spectrum has an excessive yield strength and initial stiffness. The benefit of strengthening is confirmed. Ref. [1] shows some of the most frequently used methods for strengthening.

## 3. Conclusions

The following conclusions are made as a result of proposed study:

1. Comparable analysis between target capacity spectrum (TCS) and actual capacity spectrum of existing structure before strengthening (ACS–1) is capable of indicating whether strengthening is necessary or not.

2. Comparable analysis between target capacity spectrum (TCS) and actual capacity spectrum (ACS–2) of strengthened structure can be used to prove the benefit and efficiency of strengthening.

3. Target capacity spectrum (TCS) is the spectrum which satisfies the Eurocode 8 provisions considering the deformation issues. The scatter between TCS and ACS–1 shows how the paramaters of existing structure should be changed. The scatter between TCS and ACS–2 can be used for prediction of level of safety after strengthening.

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# СЕИЗМИЧНО УСИЛВАНЕ НА СТОМАНОБЕТОННИ РАМКОВИ КОНСТРУКЦИИ ЧРЕЗ ИЗПОЛЗВАНЕ НА ПОДХОД ЗА ОТЧИТАНЕ НА РЕАЛНОТО ИМ ПОВЕДЕНИЕ

**З. Бонев[1], Ст. Доспевски[2]**

***Ключови думи***: *оценка на поведението чрез отчитане на реалната работа, целеви капацитивен спектър, сеизмично усилване*

***Научна област***: *сеизмично усилване на конструкции: необходимост, приблизителни методи за оценка*

## РЕЗЮМЕ

Разработена е процедура за оценяване на необходимостта от сеизмично усилване на сгради, както и за доказване на ползата и ефективността на усилването. За целта са използвани два съвременни и приблизителни метода – метода на капацитивния спектър и N2 метода. Отчита се нелинейното поведение на конструкцията, а натоварването ѝ се реализира по две схеми – с еластичен спектър и с изчислителен спектър на реагиране. Изчислителната процедура за целевия капацитивен спектър е подробно обяснена, използван е и сравнителен анализ между актуалния и целевия спектър. Направени са необходимите заключения.

[1] Здравко Бонев, проф. д-р, кат. ”Строителна механика”, УАСГ, бул. ”Хр. Смирненски” № 1, 1046 София, e-mail: zbp_uacg@abv.bg
[2] Станислав Доспевски, д-р, кат. ”Строителна механика”, УАСГ, бул. ”Хр. Смирненски” № 1, 1046 София, e-mail: stdospevsky@abv.bg