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NON-LINEAR SEISMIC ANALYSIS OF RC FRAMED BUILDING DESIGNED ACCORDING TO EC-8

Željana Nikolić[1*], Mijo Nikolić[1,2]

[1] University of Split, Faculty of Civil Engineering, Architecture and Geodesy
Matice hrvatske 15, 21000 Split, Croatia
e-mail: zeljana.nikolic@gradst.hr

[2] Ecole Normale Supérieure de Cachan, LMT-Cachan
61 Avenue du Président Wilson, 94235 Cachan, France
e-mail: nikolic@lmt.ens-cachan.fr

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Abstract. *One of the main aims of the design of earthquake resistant structures is to ensure that the design seismic action do not cause local or global collapse of the structure. Eurocode 8 includes prescriptions in order to guarantee ductile behaviour of the structure and its structural elements and adequate bearing capacity. Concrete buildings in high seismic area are classified in two ductility classes DCM (medium ductility) and DCH (high ductility) depending on their hysteretic dissipation capacity. To provide the appropriate amount of ductility, specific provisions for all structural elements shall be satisfied in each class. In this paper five-storey reinforced concrete frame building is studied using nonlinear static analysis and incremental dynamic analysis. The building was previously designed for DCM and DCH ductility class according to the prescriptions of EC-2 and EC-8, accepting the demands of the local ductility. The aim of this paper is the analysis of differences in the behaviour of the structure between these ductility classes. The mechanism of loosing the bearing capacity, collapse loads and behaviour factors obtained by non-linear static analysis and incremental dynamic analysis were analyzed and compared. A series of seven earthquakes taken from the European Strong-Motion Database, fully satisfying the EC-8 provisions, are used as input for incremental dynamic analysis. The results obtained by non-linear static analysis show higher yield ratio of base shear and building seismic weight for DCM in relation to DCH, while the target displacement and bearing capacity at the collapse is higher for DCH. Behaviour factors for both ductility classes obtained by incremental dynamic analysis and static non-linear analysis are larger than those demanded by EC-8.*

1 INTRODUCTION

Provisions of European norms EC-8 [1] are directed to design of structures which earthquake resistance is based on energy dissipation in provided critical zones. The design rules have to assure ductile behaviour of the structure and its structural elements and adequate bearing capacity.

Ductility class presents a level in which balance between the bearing capacity and capability of the energy deterioration is achieved. Ductility of the structures in linear analysis is based on reduced elastic spectrum of the ground acceleration. The reduction is performed by behaviour factor *q* which is equal for the whole group of the structures. This approach cannot give insight to the real behaviour of the structure and quantitative determination of the damage degree can be obtained only by non-linear analysis.

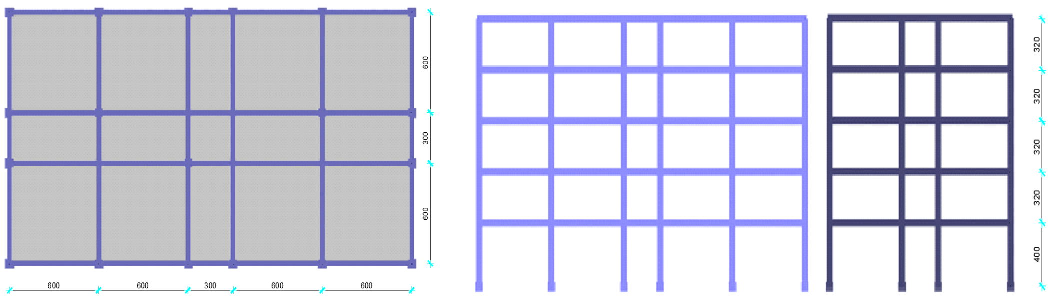
Concrete buildings in high seismic area are classified in two ductility classes, DCM (medium ductility) and DCH (high ductility), depending on their hysteretic dissipation capacity [1]. To provide the appropriate amount of ductility, specific provisions for all structural elements ought to be satisfied in each class.

In this paper five-storey reinforced concrete frame building is studied using nonlinear static analysis [2] and incremental dynamic analysis [3]. The building was previously designed for DCM and DCH ductility class according to the prescriptions of EC-2 and EC-8, accepting the demands of the local ductility. The aim of this paper is analysis of differences in the behaviour of the structure between these ductility classes. The mechanism of loosing the bearing capacity, collapse loads and behaviour factors obtained by non-linear static analysis and incremental dynamic analysis were analyzed and compared.

2 NON-LINEAR ANALYSIS OF RC FRAME BUILDING

2.1 Geometry of the building and modelling

Analyzed RC frame building (Figure 1) is a symmetrical five-storey building, regular in plan and elevation. The dimensions in plan are 27x15 m. The bottom storey height is equal to 4,0 m, while at the other levels it is equal to 3,2 m. The cross-section dimensions are 50x50 cm for all columns and 30x45 cm for all beams. The spans are 6 m and 3 m. The structure has reinforced plates with thickness equal to 16 cm. The concrete characteristic cubic strength is f_{ck}=30 N/mm^2 and steel characteristic yielding strength is f_{yk}=500 N/mm^2.



(a) plan (b) section

Figure 1: Geometry of the building.

The building loads are self-weight, additional dead load 2,8 kN/m^2 and imposed load 3,0 kN/m^2.

The building was designed according to EC-2 [4] and EC-8 [1] for ground type B, importance factor II (γ_I=1), type 1 response spectrum, damping ξ=5% and ductility classes DCM and DCH. Design ground acceleration is a_g=0.3g. The behaviour factors equal to q=3,9 for DCM and q=5,85 for DCH are adopted.

The columns are reinforced by longitudinal bars 24ϕ16 and stirrups 4ϕ10/10 cm in critical region and stirrups ϕ8/20 cm out of critical region for DCH, while the beams have longitudinal bars 7ϕ16 in upper and lower section and stirrups ϕ8/15 cm. The additional horizontal bars ϕ10/5 cm are placed in beam-column joints to ensure ductility behaviour.

The columns are reinforced by 20ϕ18, stirrups 4ϕ10/10 cm in critical region and stirrups ϕ8/20 cm out of critical region for DCM. The beams are reinforced by longitudinal bars 7ϕ18 in upper and lower section and stirrups ϕ8/15 cm.

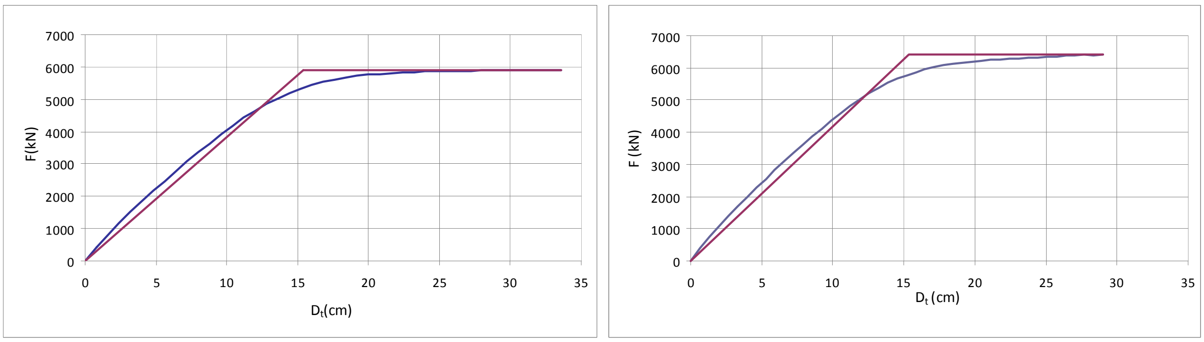
The non-linear static (pushover) analysis and incremental dynamic analysis are performed by computer program Seismosoft [5]. The behaviour of the reinforcing steel was modelled by bilinear model with kinematic hardening, while the concrete was modelled by Mander's non-linear model with possibility of including influence of stirrups.

The influence of the plate to flexural and torsional stiffness was taken by modelling the beams as T cross-section with effective width of 80 cm.

2.2 Non-linear static (pushover) analysis

Non-linear static (pushover) analysis according to EC-8 [1] was performed for presented RC frame building. Linear distribution of the lateral forces was taken. The mass matrix is diagonal with elements equal to storey masses (m_1=423 t i $m_{2,3,4,5}$=410 t). The equivalent mass m^* and transformation factor Γ have the values m^*=1274 t and Γ=1,36.

Pushover curves and their elasto-plastic idealizations for MDOF system and both ductility classes are shown in Figure 1.



(a) DCH (b) DCM

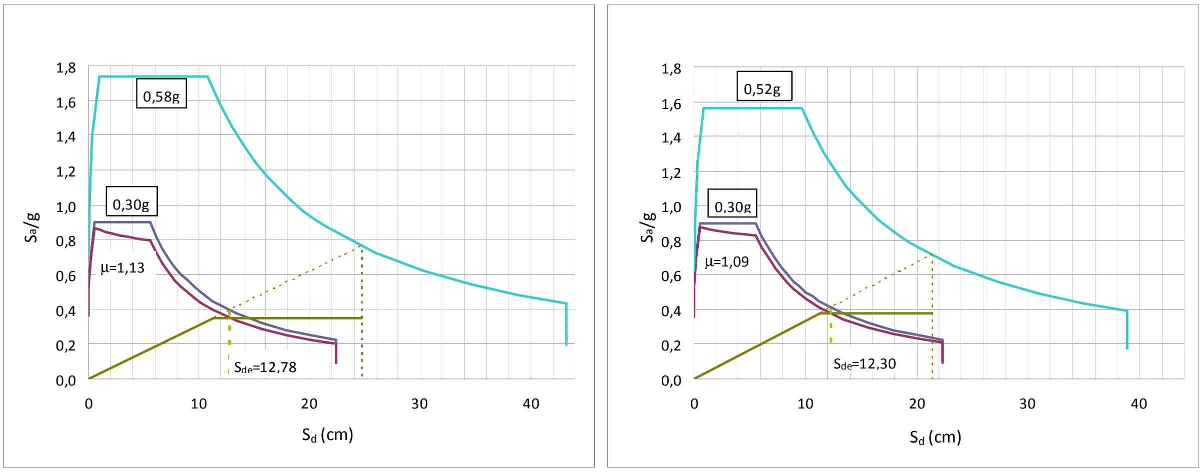
Figure 1. Pushover curves and their elasto-plastic idealization for MDOF system.

Table 1 shows characteristic values evaluated from the pushover curves for both ductility classes.

Figures 2a i 2b show elastic demand spectrum for ground acceleration a_g=0.3g, inelastic demand spectrum determined from the pushover analysis and elasto-plastic idealization of pushover curves for the equivalent SDOF system. Figures also show collapse curves which will be discuss hereafter.

Characteristic values	DCH	DCM
Yield strength (MDOF) F_y	5908 kN	6402 kN
Yield strength (SDOF) $F_y^* = F_y / \Gamma$	4343 kN	4706 kN
Yield displacement (SDOF) $D_y^* = D_y / \Gamma$	11,30 cm	11,32 cm
Elastic period (SDOF) $T^* = 2\pi\sqrt{m^* D_y^* / F_y^*}$	1,14 s	1,10 s
Acceleration on the yielding limit $S_{ay} = F_y^* / m^*$	0,348g	0,377g
Ductility factor $\mu = R_\mu = S_{ae}(T^*) / S_{ay}$	1,13	1,09
Displacemet demand (SDOF) D_t^*	12,78 cm	12,30 cm
Target displacement (MDOF) $D_t = D_t^* \Gamma$	17,4 cm	16,7 cm

Table 1: Characteristic values for ductility classes DCH and DCM.

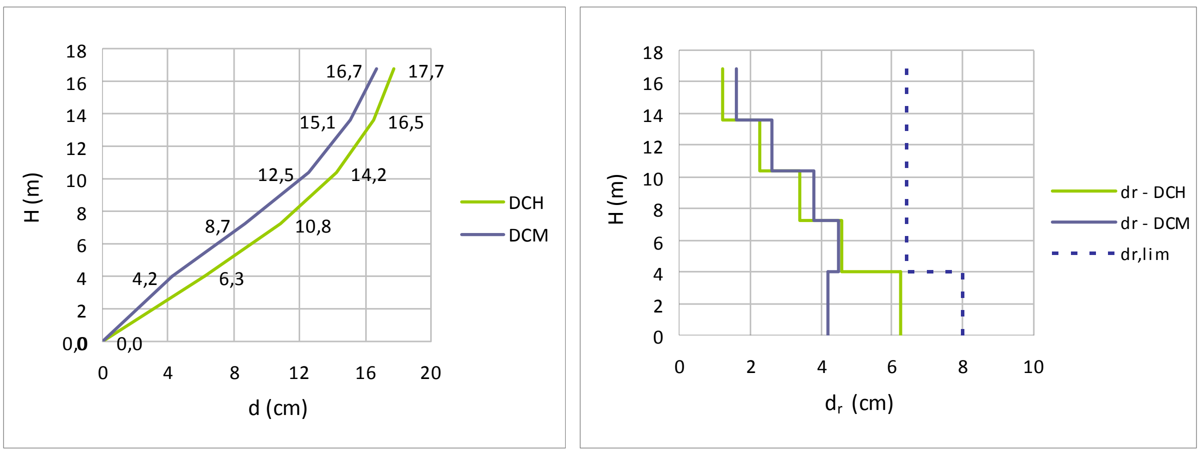


(a) DCH (b) DCM

Figure 2. Elastic demand spectrum, inelastic demand spectrum, elasto-plastic idealization of pushover curves and collapse curves for equivalent SDOF system.

Displacements of MDOF model and damage control

Displacements d and interstorey drifts d_r for target displacement are shown in Figure 3.



(a) (b)

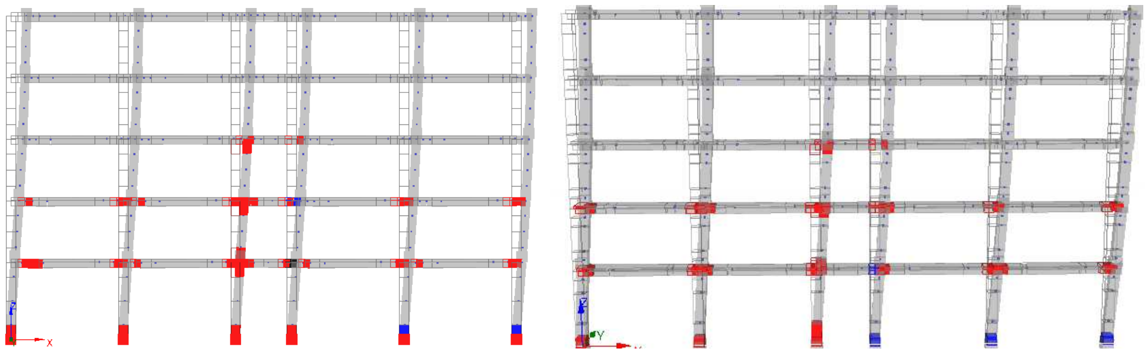
Figure 3. (a) Storey displacements d, (b) Interstorey drifts d_r.

Interstorey drifts d_r are compared with limited interstorey drifts $d_{r,lim}$ according to EC-8 [1] which, for the buildings having non-structural elements fixed in a way so as not to interfere with structural deformations, can be calculated as $d_r \nu \le 0{,}010h$. The damage limitation requirement is satisfied (see Figure 3).

The response of the structure for target displacement is shown in Figure 4. The response is non-linear for both ductility classes. Reinforcement yielding (red colour in Figure 4) is achieved for deformation 0,25%, reinforcement failure (green) for deformation 6%, crushing of the concrete protective layer (blue) for deformation 0,35% and crushing of the concrete core (black) for deformation 0,8%.

The yielding of the reinforcing bars for DCM ductility class occurs in the beams critical regions of the first and second floors as well as in the columns lower critical regions of the first floor and in the columns of the second and third floors.

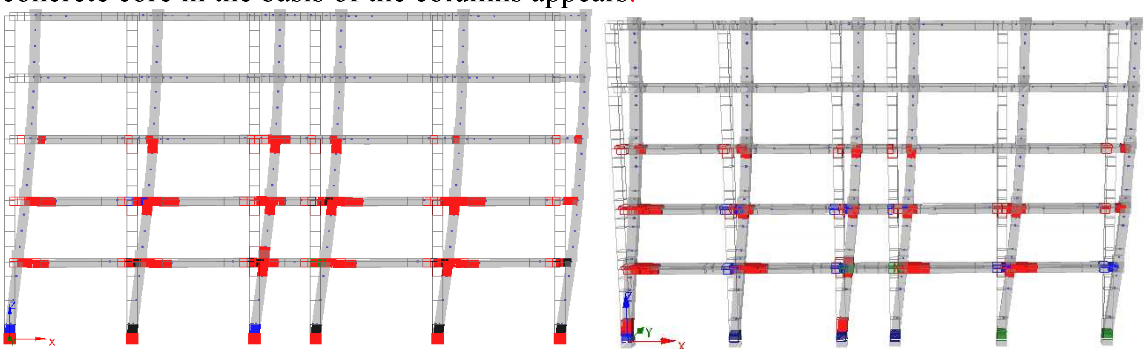
The behaviour of the structure for DCM ductility class is similar.



(a) DCH, D_t=17,4 cm (b) DCM, D_t=16,7 cm

Figure 4. Damage of the structure for target displacement D_t.

The damage of the building is also analyzed for 150%D_t. For DCH ductility class, several types of damages occur including the crushing of the concrete protective layer in the columns of the first floor, expanding of the plastic zones in the beams and further propagating of the plastification in the columns of the third floor. For DCM ductility class, the crushing of the concrete core in the basis of the columns appears.



(a) DCH, 150%D_t=26,1 cm (b) DCM, 150%D_t =25,1 cm

Figure 5. Damage of the structure for displacement 150%D_t.

Collapse of the structure

The collapse point of the structure can be obtained from idealized elasto-plastic curve on the basis of the ultimate displacement. In the analyzed example D_t is less from $3D_y$ for both ductility classes and collapse point is determined from the calculated ultimate displacement.

The intersection of the vertical axis placed in the point of ultimate displacement and radial line corresponding to the elastic part of the idealized elasto-plastic curve, gives the point of the collapse curve of the structure. Figure 2 shows graphical procedure for determining the structural collapse capacity. The same results can be also obtained analytically. The collapse point of the SDOF system corresponds to the acceleration value of 0,58g for DCH and 0,52g for DCM.

Behaviour factor

Non-linear static procedure based on pushover curves can be used for obtaining the values of the behaviour factor. The procedure is based on EC-8 which indicates that the ultimate displacement may not exceed the value $3D_y$. The behaviour factor depends on elastic force F_e, design force F_d and yield force F_y. In this example ultimate displacement is less than the value $3D_y$, so the value of the ultimate displacement is applied for obtaining the value of the behaviour factor.

The behaviour factor can be calculated from the pushover curve and it is presented as a product of two components [6]:

$$q = R_\mu R_S = \frac{F_e}{F_y}\frac{F_y}{F_d} = \frac{F_e}{F_d} \tag{1}$$

where R_μ and R_S are ductility reduction factor and overstrength factor respectively.

Table 2 shows a calculation of the behaviour factor for ductility classes DCH and DCM.

Characteristic values	DCH	DCM
S_{ae}	0,76g	0,71g
$V_e^* = S_{ae} m^* g$	9493 kN	8880 kN
F_d	2112 kN	2782 kN
$F_d^* = \frac{F_d}{\Gamma}$	1553 kN	2045 kN
F_y^*	4343 kN	4706 kN
$q = F_e / F_d$	6,11	4,34
q (EC-8)	5,85	3,90

Table 2: The calculation of the behaviour factor based on non-linear static (pushover) analysis.

2.3 Incremental dynamic analysis

In order to evaluate the dynamic response of the buildings, the incremental dynamic analysis (IDA) [3] was performed for seven accelerograms chosen from the European Strong-motion Database [7] for soil type B. The chosen accelerograms were scaled taking into account that maximum value of the acceleration ought to be $a_g S$, where a_g was design ground acceleration and S was the soil parameter according to EC-8 [1]. The acceleration spectra of the selected earthquakes for damping ξ=5%, their mean value and elastic spectrum for a_g=0,3g according to EC-8 are shown on Figure 6.

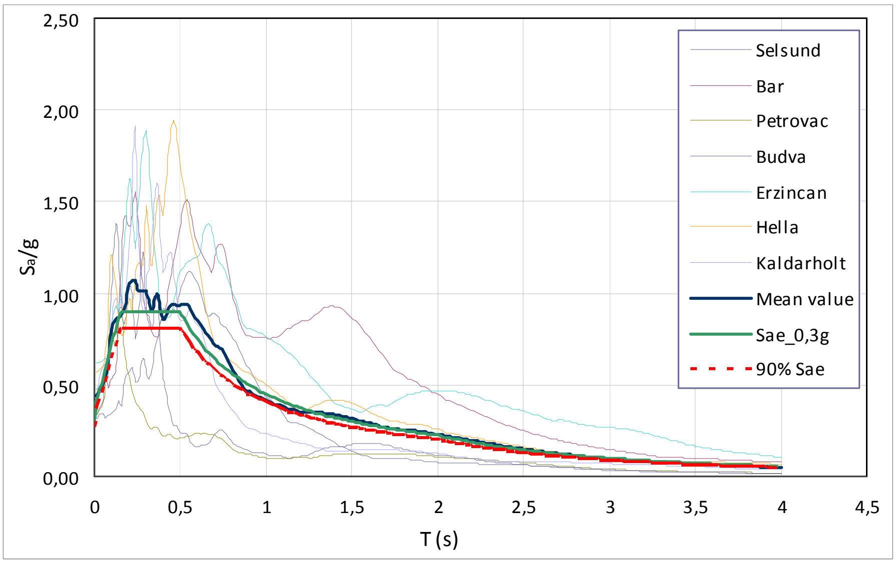
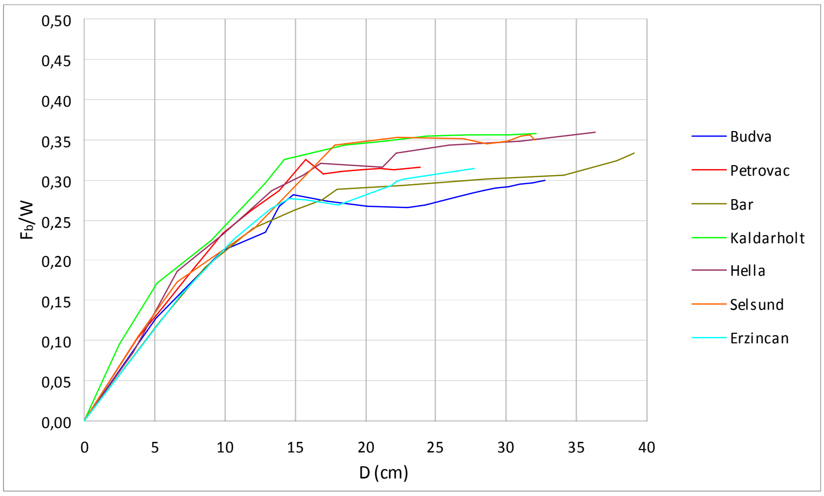
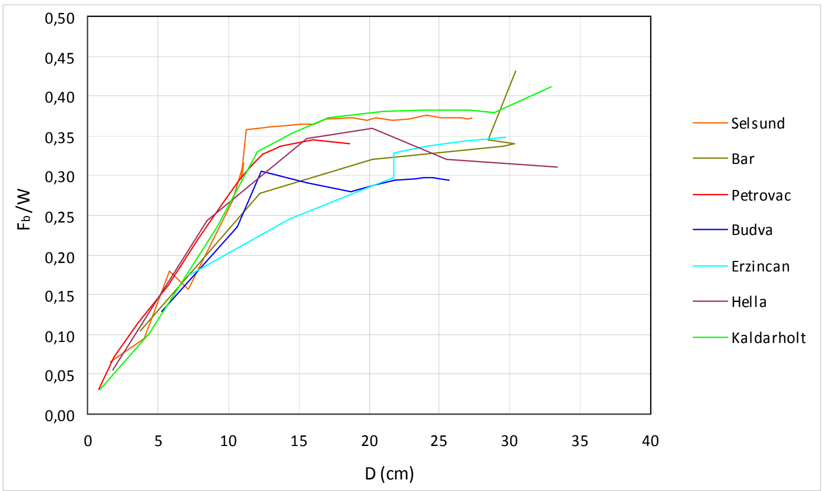


Figure 6: Spectra of the records used in incremental dynamic analysis, their mean value and EC-8 spectrum.



(a) DCH



(b) DCM

Figure 7: IDA curves.

The RC frame was analyzed by incremental dynamic analysis with gradual increasing of the acceleration spectrum ordinate to the collapse. Numerical instability is taken as indicator of the collapse. Figure 7 shows IDA response curves where the roof drift *D* between the top and base of the structure is presented on the x-axis, while the base shear force F_b/W is presented on the y-axis.

Incremental dynamic analysis is useful in assessing the collapse point of the structure and for obtaining the values of the behaviour factor *q* which is presented by following equation [6,8]:

$$q = \frac{a_{g(collapse)}}{a_{g(design\ yield)}} \tag{2}$$

where $a_{g(collapse)}$ and $a_{g(desing\ yield)}$ are the collapse and yield design peak ground acceleration respectively. The acceleration $a_{g(collapse)}$ is obtained from the IDA curves, while $a_{g(design\ yield)}$ is the yield acceleration assumed in the design.

Behaviour factor	q (DCH)	q (DCM)
Bar	6,49	5,60
Petrovac	6,33	4,49
Budva	5,84	4,10
Erzincan	6,11	4,58
Selsund	6,93	4,94
Hella	7,01	4,99
Kaldarhollt	6,96	5,35
Mean value obtained by IDA	6,53	4,86
Behaviour factor prescribed by EC-8	5,85	3,90

Table 3: Behaviour factors of the structure obtained by IDA.

The values of the behaviour factors for seven earthquakes and mean value of the computed factors are shown in Table 3. These values correspond to the dynamic response of the building subjected to the chosen accelelograms and are compared with the behaviour factors prescribed by EC-8. The mean value of the behaviour factor obtaining by IDA is higher than the behaviour factor according to EC-8.

3 CONCLUSIONS

- In this paper the behaviour of the five-storey reinforced concrete frame building, previously designed for DCM and DCH ductility class according to the prescriptions of EC-8, was studied using nonlinear static analysis and incremental dynamic analysis. The aim of the paper was analysis of the differences in the behaviour of the structure between these ductility classes, especially the mechanism of loosing the bearing capacity, displacements and storey drifts, collapse loads and behaviour factors.

- The longintudinal reinforcemet of the beams in critical region is 27% higher for ductility class DCM in comparison to DCH. The longintudinal reinforcemet of the columns is 6% higher for DCM. The additional horizontal bars ϕ10/5 cm are placed in beam-column joints.

- Non-linear static (pushover) analysis shows that the structural yielding for DCH arises for the lower value of the acceleration 0,348g in relation to DCM ductility class where it is 0,377g. The values of the target displacements for the structure are 17,4 cm for DCH and 16,7 cm for DCM. These values for the equivalent SDOF are 12,78 cm and 12,30 cm for DCH and DCM respectively. The interstorey drifts for both ductility classes are less than the allowed value according to EC-8. They are significantly higher for DCH at the first storey, while they have similar values for both ductility classes for the other storeys. The value of the behaviour factors are 6,11 for DCH and 4,34 for DCM. The mechanisms of loosing the bearing capacity are very similar for the both classes. After the yielding of the reinforcement in the beam-column joint, the collapse for both ductility classes results due to the crushing of the concrete and reinforcement failure in the columns basis.

- The behaviour factors evaluated by incremental dynamic analysis as a mean value for seven accelerograms are 6,53 cm and 4,86 cm for DCH and DCM, respectively, and they are higher in relation to the values obtaining by non-linear static analysis.
- The bearing capacity of the frame for DCH is 12% higher in relation to DCM, although the acceleration corresponding to the yielding of the structure is less than for DCM.

REFERENCES

[1] CEN, Eurocode 8: *Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings. EN 1998-1*. Brussels, 2004.

[2] P. Fajfar, A non-linear analysis method for performance-based seismic design. *Earthquake Spectra*, **16**(3), 573-592, 2000.

[3] D. Vamvatsikos, C.A. Cornell, Incremental dynamic analysis. *Earthquake Engineering and Structural Dynamics*, **31**, 491-514, 2002.

[4] CEN, Eurocode 2: *Design of concrete structures – Part 1-1: General rules and rules for buildings, EN 1992-1-1*. Brussels, 2004.

[5] *SeismoStruct – A computer program for static and dynamic nonlinear analysis of framed structures*, http://www.seismosoft.com

[6] A.M. Mwafy, A.S. Elnashai, Calibration of force reduction factors of RC buildings. *Journal of Earthquake Engineering*, **6**(2), 239-273, 2002.

[7] European Strong-Motion Database, http://www.isesd.hi.is.

[8] A.H. Barbat, J.C. Vielma, S.Oller, Seismic safety of reinforced concrete framed buildings designed according to EC-2 and EC-8. *COMPDYN 2009, ECCOMAS Thematic Conf. on Comp. Meth. in Struct. Dynamic and Earth. Engineering*, Eds. M. Papadrakakis, N.D. Lagaros, M. Fragiadakis, Rodes, Greece, 2009.