ESTIMATION OF DUCTILITY AT GLOBAL AND LOCAL LEVEL FOR ULTIMATE LIMIT STATES

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Summary: *Nonlinear behaviour due to earthquakes can be observed at the global level or at the local level through the estimation of ductility. Ensuring sufficient ductility in elements and the structure itself is quite important for structure collapse prevention. Criterion of structure ultimate (near collapse) limit state is not defined. At local level, ultimate limit state of element is when a deformation capacity is reached. The aim of this paper is estimation demanded and available ductility at the local and global level.*

Keywords: *ductility, top dispalcement, chord rotation, ultimate limit state*

1. INTRODUCTION

In seismic design by linear analysis through reduction of elastic forces, the concept of ductility is introduced which provides a nonlinear response of the structure. Ductility is one of the basic parameters of the structure and represents the ability of the structure or its elements to deform in an inelastic region. It can be defined as the ratio of nonlinear deformation and deformation at the yield limit state. The term ductility is often used for evaluation of seismic performance of structures, which indicates the amount of seismic energy that can dissipate through the plastic deformation. Ductility can be observed on a global and local level.
Collapse prevention is one of the objectives of a performance - based design and it is defined as the condition at which a structure, or a significant portion of it, is unable to support its gravity loads during a seismic excitation. Generally established criterion to identify when and how a structure collapses under the seismic action does not exists [1]. Two possible definitions of global ultimate (near collapse NC) limit states are: a 20 % drop of the lateral resistance of structure and NC limit state of the most exposed important vertical element [2].
In this paper, ductility was determined at a global level, through ductility of top displacement, and local level, as chord rotation ductility. Depending on the definition of the collapse of the structures, available ductility was determined and analysed. A

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nonlinear static analysis is applied which allows estimation of demands on a global and local level.

2. DUCTILITY ON GLOBAL LEVEL

The ductility on global level μ_δ is defined by the ratio of roof displacement demand to the yield displacement. When the displacement demand is maximally possible, i.e. represents displacement for the ultimate limit state, then the estimated ductility is the available ductility of the structure. The maximum available (ultimate) displacement can be estimated using several possible definitions of ultimate limit state. Generally accepted definition of structure ultimate (near collapse) limit state is missing. The most realistic definition of the maximum displacement is one of next two, whichever occurs first [3]: 1) the post - peak displacement when the load carrying capacity has undergone a small reduction; 2) the displacement when the material fractures or elements buckle, in case of reinforced concrete when the transverse or longitudinal reinforcing steel fractures or the longitudinal compression reinforcement buckles.

To determine ductility at the global level it is necessary to know the yield deformation. Definition of the yield deformation (displacement) often causes difficulties, since the load - deformation relation may not have a well-defined yield point. There are various alternative definitions, which have been used to estimate the yield displacement [3]. One of them, considered the most realistic, is the yield displacement of the equivalent elasto - plastic system with reduced stiffness found as the secant stiffness at either first yield or at 0.75 of the ultimate lateral load, whichever is less.

In this paper, yield displacement and maximum (ultimate) displacement (with a 20 % drop in maximum strength) are determined as shown in Fig. 1.

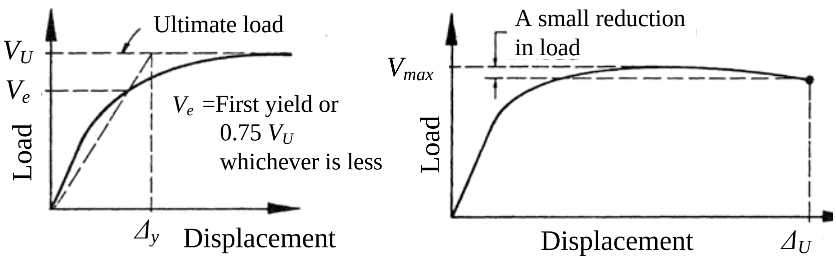

Figure 1. Definition of yield and ultimate deformations

3. DUCTILITY ON LOCAL LEVEL

At the local level appropriate deformation of elements according to EN 1998-3 [4] is a chord rotation at the end of members over the shear span. Chord rotation ductility μ_θ is defined by the ratio of the maximum and the yield chord rotation. The values of ultimate chord rotation can be calculated according to expression which was obtained on the basis of large database of test results, by Biskins (2007) and Biskins and Fardis (2004, 2007)

[5]. This expression refers to chord rotation of members with rectangular compression zone and detailing for earthquake resistance, in case of flexure controlled failure:

$$\theta_{um} = a_{st}\left(1-0.43a_{cy}\right)\left(1+\frac{a_{sl}}{2}\right)\left(1-0.42a_{w,r}\right)\left(1-\frac{2}{7}a_{w,nr}\right)\cdot \\ \cdot 0{,}3^{\nu}\cdot\left[\frac{\max\left(0{,}01;\omega'\right)}{\max\left(0{,}01;\omega\right)}\cdot f_c\right]^{0{,}225}\cdot\left(\min\left(9;\frac{L_v}{h}\right)\right)^{0{,}35}\cdot 25^{\left(\alpha\cdot\rho_{sx}\cdot\frac{f_{yw}}{f_c}\right)}\cdot 1{,}25^{100\cdot\rho_d} \tag{1}$$

where: a_{st} is the coefficient dependent on the steel type, 0.0185 for ductile hot rolled or heat-treated steel and 0.015 for cold-worked steel, a_{cy} is the zero-one variable for the type of loading, 0 for monotonic and 1 for cyclic loading, $a_{w,r}$ is the zero-one variable for rectangular walls, 1 for rectangular walls and 0 otherwise, $a_{w,nr}$ is the zero-one variable for non-rectangular walls, 1 for walls with T, H, U or hollow rectangular section and 0 for other members, $\nu = N/bhf_c$ where b is width of compression zone and N is the axial force, ω, ω' are mechanical reinforcement ratios of tension and compression longitudinal reinforcement, respectively, L_v is shear span, α is effectiveness factor for confinement by transverse reinforcement, ρ_{sx} is ratio of transverse steel parallel to the loading direction, and ρ_d is steel ratio of diagonal reinforcement in each diagonal direction.
Depending on the type of steel, slipping of longitudinal bars and in case of cyclic loading, this expression was adopted in EN 1998-3 as the total ultimate chord rotation capacity.
The values of yield chord rotation can be calculated according to expression which was developed using a large database of test results, by Biskins (2007). For RC rectangular beams and columns having purely flexural behaviour:

$$\theta_y = \varphi_y\frac{L_v + a_v z}{3} + 0.0014\left(1+1.5\frac{h}{L_v}\right) + a_{sl}\frac{\varphi_y d_b f_y}{8\sqrt{f_c}} \tag{2}$$

where: φ_y is the section curvature at yielding, a_v is the zero-one variable for diagonal cracking before flexural yielding of the end section, z is internal lever arm, a_{sl} is the zero–one variable for slip of longitudinal bars from their anchorage zone beyond end section, d_b is diameter of longitudinal reinforcement and f_y is yield stress of longitudinal reinforcement. In EN 1998-3 has adopted an earlier version of this equation.

4. NUMERICAL EXAMPLES

In this paper, 4 RC frame structures with four storeys, designed according to EN 1992-1-1 and EN 1998-1 for two ductility classes (DCM and DCH, with the behaviour factors $q = 3.9$ and $q = 5.85$, respectively) and two cases of seismic action ($a_g = 0.2g$ and $a_g = 0.3g$) were analyzed. RC frames structures are with regular configurations with 3 bays of 5 m. First storey is 3.5m height, and for others storeys heights are 3.0 m. Beams of all RC frames have the same section, 30×45 cm, modeled as T section, with effective width 170 cm and a slab thickness is 15 cm. Cross section dimensions of columns of all RC frames are 45×45 cm. Concrete class C30/37 and steel S500 class C were used in the design of frames.

Nonlinear static analysis is carried out under constant gravity loads and monotonically increasing lateral loads applied on the masses of the structural model. According to EN 1998, at least two vertical distributions of lateral loads should be applied: a modal pattern, the inverse triangular distribution (L), and a uniform distribution (U). Pushover analysis were conducted using the OpenSees [6]. Beams and columns were modelled using force-based non-linear beam column element and cross sections were presented with fiber model, which was defined with three kinds of fiber: unconfined concrete (cover), confined concrete (core) and reinforcement. The concrete was modelled by the uniaxial material Concrete01, steel was modelled by the uniaxial material Steel02.

Pushover curves, in terms of top displacement and base shear, were determined for two patterns of lateral load: with linear distribution (L) and uniform distribution (U), for all frame structures and are shown in Fig. 2. On the curves are marked displacements for ultimate limit states on global level (triangle) and on local level (square). Ultimate limit states at the local level were determined by reaching the cord rotation capacity of the most exposed vertical element.

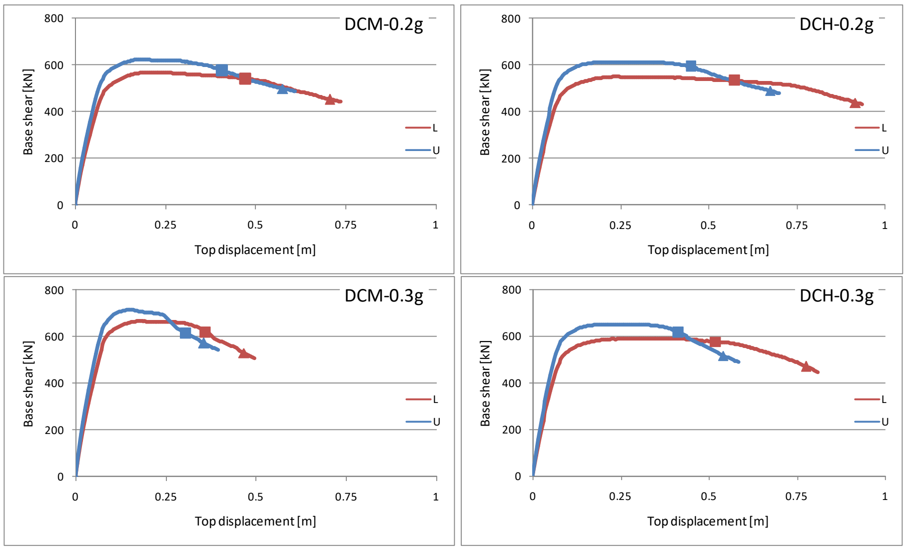

Figure 2. Pushover curves

Table 1 shows the available ductility of the chord rotations and demand ductility of the top displacement for the ultimate limit state at the local level. Available ductility of the chord rotations, i.e. chord rotations capacity depends on the geometrical and mechanical characteristics of the element and the cross section and axial load ratio, and are independent of patterns of lateral load.

Table 1 – Chord rotations and top displacements ductility for ultimate limit states on local level

	$\mu_{\theta,L}$	$\mu_{\theta,U}$	$\mu_{\delta,L}$	$\mu_{\delta,U}$
DCM-0.2g	7.101	7.101	5.74	5.34
DCH-0.2g	7.471	7.47	6.83	5.89
DCM-0.3g	6.941	6.941	4.40	4.13
DCH-0.3g	7.375	7.375	6.11	5.32

Table 2 shows the available ductility of the top displacement and demand ductility of the chord rotations for the ultimate limit state at the global level. Demand ductility of the chord rotations for the ultimate limit state at the global level are greater than their available ductility, i.e. the demand chord rotations are greater than the capacity chord rotations calculated according to Eq.1.

Table 2 – Chord rotations and top displacements ductility for ultimate limit states on global level

	$\mu_{\theta,L}$	$\mu_{\theta,U}$	$\mu_{\delta,L}$	$\mu_{\delta,U}$
DCM-0.2g	12.23	11.28	8.63	7.63
DCH-0.2g	14.15	12.66	10.85	8.81
DCM-0.3g	10.28	8.33	5.61	4.73
DCH-0.3g	13.75	11.61	9.07	6.97

The ultimate limit state at the local level was reached before ultimate limit state at the the global level. The element demanded ductility is always greater than the corresponding structural demanded ductility. In addition, the available ductility of the DCH frames are higher than the DCM frames.

5. CONCLUSION

Nonlinear behaviour due to earthquakes can be observed at the global level in form of pushover curve (top displacement-base shear) or at the local level through appropriate deformation of elements (the chord rotation in EN 1998-3). Structure collapse prevention under the strong rare earthquake is most affected by ductility. Ductility is one of the basic parameters of the structure and represents the ability of the structure or its elements to deform in an inelastic region. Ensuring sufficient ductility in elements and the structure itself is quite important for their seismic performance. The global, structural ductility significantly depends on available local ductility. Inelastic deformations at the global level require high ductility at the local level.

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ПРОЦЕНА ГЛОБАЛНЕ И ЛОКАЛНЕ ДУКТИЛНОСТИ ЗА КРАЈЊЕ ГРАНИЧНО СТАЊЕ

Резиме: *Нелинеарно понашање услед дејства земљотреса може се посматрати на глобалном и локалном нивоу кроз процену дуктилности. Осигурање адекватне дуктилности елемената и саме конструкције је веома важно за превенцију конструкцијског колапса. Критеријум крајњег (близу колапса) граничног стања конструкције није дефинисан. На локалном нивоу, крајње гранично стање елемента је када се достигне капацитет деформације. Циљ овог рада је процена захтеване и расположиве дуктилност на локалном и глобалном нивоу.*

Кључнеречи: *дуктилност,померање врха, ротација тетиве, крајње гранично стање*