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THE DUCTILE DESIGN CONCEPT FOR SEISMIC ACTIONS IN MISCELLANEOUS DESIGN CODES

BY

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Abstract. The concept of ductility estimates the capacity of the structural system and its components to deform *prior* to collapse, without a substantial loss of strength, but with an important energy amount dissipated.

Consistent with the „Applied Technology Council” (ATC-34), from 1995, it was agreed that the reduction seismic response factor to decrease the design force. The purpose of this factor is to transpose the nonlinear behaviour of the structure and the energy dissipation capacity in a simplified form that can be used in the design stage. Depending on the particular structural model and the design standard the used values are different.

The paper presents the characteristics of the ductility concept for the structural system. Along with this the general way of computing the reserve factor with the necessary explanations for the parameters that determine the behaviour factor are described. The purpose of this paper is to make a comparison between different international norms for the values and the distribution of the behaviour factor. The norms from the following countries are taken into consideration: the United States of America, New Zealand, Japan, Romania and the European general seismic code.

Key words: ductility; reduction factor; reinforced concrete frames.

1. General Considerations about the Ductility Concept

The seismic forces are complex actions that depend on several factors, difficult to anticipate and to appreciate. Between 1950 and 1960 technical discoveries were made which lead to the improvement of the design codes for the seismic action, introducing new concepts, as the concept of ductile design, determining the review of the way that the joints between columns and girders are designed in seismic areas [2].

The design of reinforced concrete (rc) structures to seismic action should provide sufficient information about the energy dissipation capacity of the structure without reducing substantially the strength in favour of horizontal and vertical loads. An adequate strength should be provided from the seismic combination for the structural elements and the non-linear deformations in critical areas should permit to obtain the total ductility considered in the design.

The ductility is the structures', elements' and constituent materials' property to deform beyond the elastic limit without any strength loss and energy accumulation during the loading cycles. Ductility can be expressed, for the material, as a function of the characteristic stress–strain curve, for the structural element with the moment–curvature relation and for the structural assembly with the relation between force and displacement.

The columns in a frame structure are considered nondissipative elements, hence the seismic codes have previsions which assure the fulfilment of these requirements. The lower areas of the columns represent the exception; here the plastic hinges are allowed in order for the global plastic mechanism to form.

Even though the structural elements are designed as ductile, the overall structural behaviour may not be adequate if the inelastic deformations are concentrated in a limited number of elements, forming a partial plastic mechanism. The ductility level of a structure may be assured by designing the structural elements so that to form a global plastic mechanism.

The ductile behaviour of a structure is ensured when a large number of elements are considered to behave ductile. The ductile failure modes should precede the brittle ones with a certain safety limit [3].

The meaning of ductility for reinforced concrete structures can be summarized as follows:

a) re-distribution of internal forces at hyperstatic structures (slabs, beams);

b) reduction of internal forces due to restraint of hyperstatic structures (extreme settlement on bridges);

c) indication of failure (all structures);

d) mobilization of capacity reserves for partial failure of pre-stressing (robustness of bridges);

e) dissipation of energy for impact like earthquake, dynamic impact, or explosion (buildings and bridges).

Considering the energy dissipation capacity of the reinforced concrete structures, in Eurocode 8 (EC8), are presented three ductility classes

a) ductility class „L"(low), corresponds to structures designed and dimensioned according to EC2, completed by the specific rules to enhance ductility;

b) ductility class „M”(medium), corresponds to structures designed, dimensioned and detailed according to previous recorded earthquakes, allowing the structure to work in the inelastic domain under cyclic actions, without brittle failures;

c) ductility class „H”(high), corresponds to structures designed, dimensioned and detailed so that the structural response to seismic action is according to the considered failure mechanism, with a large amount of energy dissipated.

2. Reduction Factor – General Considerations

In design codes the considered seismic force used to dimensioning the structural elements is multiplied by several coefficients, in order to simplify the design process. One of them is the reduction factor. In the following are presented different ways to evaluate the seismic force, as well as the values for the behaviour factor in some seismic design codes.

The behaviour factor of the response is computed as a product of three factors

$$R = R_S R_\mu R_\xi , \tag{1}$$

where: R_S is the strength reduction factor; R_μ – the ductility reduction factor; R_ξ – the damping reduction factor.

In the ATC-19 meeting from 1995 the damping reduction factor was not taken into consideration, being replaced by the redundancy reduction factor, R_R [1]

$$R = \left(R_S R_\mu \right) R_R . \tag{2}$$

The strength reduction factor, R_S , is computed as the difference between the seismic force at the bottom, V_b , and the ultimate shear force at the bottom, V_u . The values of this factor, depending on the height of the structure, are presented in Table 1.

Table 1

The Strength Reduction Factor for Reinforced Concrete Structures

Structural type	R_S
R_c structures medium and high in elevation	1.6…4.6
R_c structures with irregularities in elevation	2.0…3.0

The values of the strength reduction factor are determined by:

a) the strength characteristics of the materials;

b) the use of the response spectrum in the seismic computations;

c) column design to the seismic action on two directions; along one is applied 100% of the seismic force, and along the orthogonal one only 30% of the seismic force.

3. Reduction Factor in Different Design Codes

The assessment of the seismic force in both – current Romanian standard and the European one – is similar. The following relations are used: (P100-2006, Eurocode 8, 2002)

$$F_b = \gamma_I S_d(T) m\lambda, \tag{3}$$

$$S_d(T) = \frac{a_g \beta(T)}{q}. \tag{4}$$

In Table 2 are presented the values of the behaviour factor, q, considered in the actual Romanian design norm.

Table 2

Behaviour Factor for Structures Regular in Elevation

Structural type	q	
	High class ductility (DCH)	Medium class ductility (DCM)
Frame system, dual system, coupled wall system	$5\alpha_u/\alpha_1$	$3.5\alpha_u/\alpha_1$
Uncoupled wall system	$4\alpha_u/\alpha_1$	3.0
Torsionally flexible system	3.0	2.0
Inverted pendulum system	3.0	2.0

α_1 represents the value by which the horizontal seismic design action is multiplied in order to first reach the flexural resistance in any number in the structure, while all other design actions remain constant; α_u – the value by which the horizontal seismic design action is multiplied in order to form plastic hinges in a number of sections sufficient for the development of overall structural instability, while all other design actions remain constant.

The α_u/α_1 ratio describes the redundancy effect on the response reduction factor. This factor is the ratio between the structure capable lateral force and the lateral force corresponding to the moment when the first element of the structure reaches its bearing capacity. The values of the multiplication factor are presented in Tables 3 and 4.

Table 3

Multiplication Factor α_u/α_1 According to Eurocode 8 and P100-2006

Frame or frame-equivalent dual systems	α_u/α_1	
	P100	EC8
One-storey buildings	1.15	1.10
Multi-storey, one-bay frames	1.25	1.20
Multi-storey, multi-bay frames or frame-equivalent dual structures	1.35	1.30

Table 4

Multiplication Factor α_u/α_1 According to Eurocode 8 and P100-2006

Wall or wall-equivalent dual systems	α_u/α_1	
	P100	EC8
Wall systems with only two uncoupled walls per direction	1.00	1.00
Other uncoupled wall systems	1.15	1.10
Wall-equivalent dual or coupled wall system	1.25	1.20

In the European norm, EC8, the response reduction factor value, is computed with relation

$$q = q_0 k_w \geq 1.5, \tag{5}$$

where: q_0 is the basic value of the behaviour factor, depending on the type of the structural system and on its regularity in elevation (s. Table 5), and k_w – the factor reflecting the prevailing failure mode in structural systems with walls. The values of this coefficient are: 1.0 for frame and frame-equivalent dual systems, respectively $0.5 \leq (1+\alpha_0)/3 \leq 1.0$ for wall, wall-equivalent and torsionally flexible systems. α_0 is the prevailing aspect ratio of the walls of the structural system.

Table 5

Basic Value of the Behaviour Factor, q_0, for Systems Regular in Elevation

Structural type	DCM	DCH
Frame system, dual system, coupled wall system	$3\alpha_u/\alpha_1$	$4.5\alpha_u/\alpha_1$
Uncoupled wall system	3.00	$4\alpha_u/\alpha_1$
Torsionally flexible system	2.00	3.00
Inverted pendulum system	1.50	2.00

The EC 8 “Design Orovision for Earthquake Resistance of Structures” was prepared by the European Committee for Standardisation (CEN) on behalf of the EU. The application of the EC 8 in the EU member countries is possible only in connection with a national code. The EC 8 must represent the basis for the development of national building codes. Therefore it was stringently required to change the seismic code in all EU countries. This is a process which is assumed to take until 2014, meanwhile some countries have already modified their codes.

The seismic force at the bottom of the building, according to the American design code, is computed with the following relationship (IBC, 2003):

$$V = \frac{1.2 S_{DS}}{R} W\,. \tag{6}$$

In Table 8 are presented the values for the reduction coefficient used for reinforced concrete structures.

Table 8

Reduction Factors According to IBC 2003

Structural type	*R*
Special rc frames	8.0
Intermediate rc frames	5.0
Ordinary rc frames	3.0

According to the New Zeeland design norm, the coefficient C_μ from the seismic force relation is determined by taking into consideration the fundamental oscillation period, T_1, the ductility displacement, μ_Δ , and the soil type,

$$F_{\text{tot}} = C_\mu RZW_t . \tag{7}$$

The value of C_μ coefficient ranges between 0.4 and 0.04, for ductile rc structures with the ductility displacement, μ, between 4 and 6. The values of the ductility displacement, μ_Δ, are listed in Table 9.

Table 9

Ductility Displacement Values, μ_Δ, According to NZS 4203

	R_c	Prestress concrete
Structures with elastic behaviour	1.25	1.00
Structures with limited ductility		
Frames	3.00	2.00
Walls	3.00	
Coupled walls	2.00	
Ductile structures		
Moment resisting frames	6.00	5.00
Walls	5.00	

According to the Japanese design code the seismic force at the bottom of the structure is computed using the following relation (Building Standard Law of Japan, 2004):

$$V_{un,i} = D_{S,i} F_{es,i} V_i . \tag{8}$$

The coefficient $D_{S,i}$ depends on the structural type and it represents the inverted value of the behaviour factor from the European norm. This factor is influenced by the material used. In Table 10 are presented only the values for reinforced concrete structures depending on the structural type and the ductility class.

Table 10
Response Reduction Factors According to BSLJ 2004

Ductility	Moment-resisting frames	Other frames	Frames with bracing
Excellent	0.30	0.35	0.40
Good	0.35	0.40	0.45
Normal	0.40	0.45	0.50
Low	0.45	0.50	0.55

The Japanese design code accounts for the case of rigid structures having low ductility in the design process, instead of the more flexible ones with higher behaviour factors.

4. Conclusions

The structural design taking into account the ductility concept leads to an increase of the strength and the quantity of dissipated energy. It also ensures a global plastic mechanism of the structure before collapse.

The design of structures located in seismic areas uses the dissipative behaviour principle. According to this substantially reduced seismic loads are used instead of those corresponding to the elastic response of the structures through the behaviour factor. The reduction of the seismic design forces is realized based on the ductility, redundancy and the strength excess of the structure. Among these, the most significant reduction of the design forces is based on the ductility of the structure that depends on the chosen structural type and the material characteristics.

Thus, the rigid structures are characterized by lower behaviour factors (in EC8 and P100 between 0.2 and 0.5; in IBC between 0.125 and 0.333; in BSLJ between 0.3 and 0.55), while the flexible ones are characterized by higher behaviour factors.

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REFERENCES

1. * * * *An Evaluation of a Response Spectrum Approach to the Seismic Design of Buildings*. ATC (Applied Technology Council), 1995.
2. Paulay T., Bachmann H., Moser K., *Proiectarea structurilor de beton armat la acțiuni seismice* (transl. from German). Edit. Tehnică, Bucureşti, 1997.
3. Barbat A.H., Vielma J.C., Oller S., *Confinamiento y ductilidad de los edificios de hormigon armado*. Edit. Gráficos Almudena S.L., Madrid, Espana, 2007.

4. * * * *Building Standard Law Enforcement Order*. Ministry of Construction, Building Center of Japan, Tokyo, Japan, 2004.
5. * * * *Design of Structures for Earthquake Resistance.* EUROCODE 8, Brussels, 2002.
6. * * * *International Building Code*. Internat. Building Conf. of Building Officials, Whittier, USA, 2003.
7. * * * *Cod de proiectare seismică*. Partea **I**, P 100-1/2006, Bucureşti, 2006.
8. * * * *Structural Design Actions*. Ministry Department of Building and Housing, Wellington, New Zealand, 2003.

CONCEPTIA DE PROIECTARE DUCTILA LA ACTIUNEA SEISMICA IN DIVERSE NORME

(Rezumat)

Conceptul de ductilitate estimează capacitatea unui sistem structural şi a componentelor acestuia de a se deforma înainte de cedare, fără o pierdere substanţială a rezistenţei, dar disipând o cantitate importantă de energie.

În concordanţă cu „Applied Technology Council” (ATC-34), din 1995, s-a convenit ca factorul de reducere al răspunsului seismic, să diminueze forţa de proiectare. Rolul acestui factor este de a transpune comportamentul neliniar al structurii cât şi capacitatea acesteia de disipare a energiei într-o formă simplificată, care să poată fi folosită în calcul. În funcţie de modelul structural ales şi de norma după care se realizează proiectarea, valorile utilizate diferă.

Se prezintă caracteristicile conceptului de ductilitate pentru structură. De asemenea se prezintă modul general de calcul al factorului de reducere, cu explicaţii suplimentare referitoare la parametrii care determină acest factor. Autorii îşi propun să realizeze o comparaţie a normelor actuale la nivel mondial cu privire la valorile şi la modul în care este repartizat factorul de comportare. Se iau în considerare normele din următoarele ţări: Statele Unite ale Americii, Noua Zeelandă, Japonia, România precum şi cea Europeană.