DESIGN PROCEDURE OF SEISMIC STRUCTURES WITH ASSIGNED CATEGORY OF PLASTICITY TAKING INTO ACCOUNT THE REQUIREMENTS OF EUROPEAN STANDARDS (EN 1998-1)

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SUMMARY:
The normative requirements from codes of different European countries as well as the USA, Japan, the CIS, Canada etc. related to safety ensuring of buildings and structures at earthquakes are analyzed. A procedure based on non-elastic response spectrum of buildings and considering non-linear behavior of structure is proposed in elaboration of the Eurocode 8 requirements. The report provides calculation examples of frequency and natural modes taking into account mass moment of inertia and non-linear displacements of framed and frameless concrete buildings with application of that methodology. When comparing maximum displacements of buildings with various structural layouts obtained in field dynamic test as well as in measuring vibration of buildings during earthquakes and the calculation results of the developed procedure, compliance has been reached. The procedure is recommended to be applied in seismic resistance assessment of existing buildings after main shock and next aftershocks taking into account damages and development of plastic deformations.

Keywords: earthquake engineering, plasticity, Eurocode 8

1. THE CONCEPTUAL REQUIREMENTS TO ENSURE THE FACILITIES EARTHQUAKE RESISTANCE

At design of structures for construction in seismic regions it is necessary to follow the main requirements to reduce the risk of damages at earthquake and to ensure the facilities earthquake resistance. These requirements are based on a long experience of catastrophic earthquake consequences analysis and improvement of anti-seismic measures given in Norms on design of different countries [1, 2, 3, 4].

Depending on degree of structures and facilities damage there are some fundamental principles to ensure the safety of facilities and structures which are designed and constructed in seismic regions [5]. They are based on the following provisions [6, 7, 8]:

1. At rare catastrophic earthquakes it is necessary to ensure the safety of human life, valuable equipment and infrastructure which is necessary to eliminate the earthquake consequences. In facilities it is possible to realize the limit states which are close to collapse. This principle is called as *The principle of structures safety*.

2. At moderate and strong earthquakes the significant damages and residual deformations in structures are allowed. In this case, the load-bearing structures should be able to resist to the further earthquake (aftershock) without violation of the overall stability – *The principle of allowable damages*.

3. At frequent weak earthquakes and limit damages the approved anti-seismic measures should insure the further normal operation of the construction – *The principle of no damages.*

In addition to the main principles to insure earthquake resistance at design it is necessary to do the following:

- to consider the secondary factors of collapse such as a fire, soil displacement and liquefaction and others;
- to assess the response spectra in places where equipment which is important for facility operation is installed;
- to develop the measures on human safety including fire safety, conditioning, water supply and other systems;
- to develop the measures on facility protection against progressive collapse which is a result of critical structures failure, terroristic aggression and other dangerous events.

2. THE MAIN PROVISIONS ON DESIGN OF STRUCTURES WHICH INSURE THE EARTHQUAKE RESISTANCE

The modern methods to design the earthquake resistant buildings are based on new approaches which are given in normative documents of foreign countries: the USA, Canada, Japan and Europe. The approved design approach "*Performance based on seismic engineering*" can be considered as "*Design of earthquake resistant structures with specified earthquake resistance parameters*" or "*Design based on performance characteristics*". The common calculation method of the given approach is "*Nonlinear pushover analysis*" [Nonlinear method based on analysis of process of structural elements destruction at transverse load]. The recommendations on design based on performance characteristics are given in Council instruction on USA applied technology (ATC-40) [6], Federal emergency management agency (FEMA) [7, 8, 9] and Structural engineers association of California (SEAOC) instructions [10].

In fig. 1 there is a base shear-displacement capacity curve graphics which shows a new approach to assess the performance characteristics of existing buildings and to design the buildings which are expected to be earthquake-resistant.

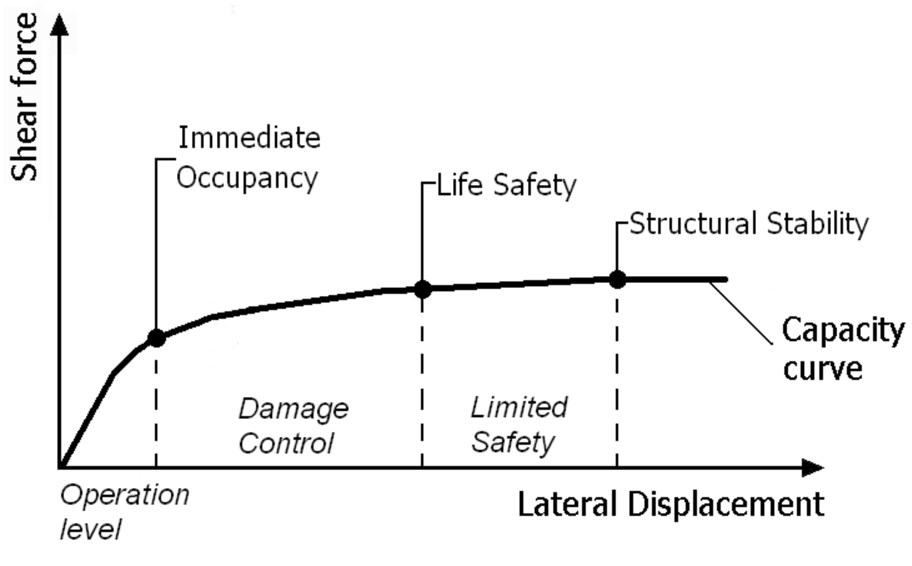


Figure 1. Relations between summarized forces and displacements for different operation levels corresponding to base shear-displacement capacity curve

In this case the base shear-displacement capacity curve is intrinsic (skeleton) for hysteresis curves at cyclic load. In many foreign publications and Instructions on design [7, 8, 10] there are three variants to idealize the skeleton curve characterizing the dependence between summarized forces and summarized displacements. The variant of the curves correspond to plastic, partially-plastic and fragile behavior of structures destruction. The points on the curves show the levels of plastic state and deformations values. In Instructions [6, 8] there are recommendations on selection of skeleton curves parameters corresponding to work of metal, reinforced concrete, stone and wood structures.

The given documents represent the first generation of procedures on assessment of seismic hazard and purpose of building state performance characteristics. They regulate the use of the following safety insurance levels determined for structural and non-structural buildings elements:

- the further safe building operation after earthquake [*Operation level*];
- the opportunity for immediate occupancy [*Immediate Occupancy*];
- the level where the damage control is allowed [*Damage Control*];
- the level which is characterized by life safety [*Life Safety*];
- the level of limited safety [*Limited Safety*];
- appearance of facility structural instability (collapse) [*Structural Stability*];
- the level which is not considered (nonconstructive assessments) [*Not Considered*].

For practical application it is possible to use a number of "*performance characteristics*" which corresponds to information on seismicity of certain regions and their correspondence to seismic zoning maps with determined levels of impacts and possible earthquakes. Taking into account this thesis having seismic knowledge on earthquakes effects in Ukraine at buildings and facilities design for practical purposes it is enough to take three levels of seismic resistance which should correspondent to structures damages which are given in fig. 1 and characterize the following:

- no damages and opportunity to continue the building operation after earthquake [*Immediate Occupancy*] - weak earthquake (WE);
- life safety and opportunity to realize the damage control after moderate earthquake [*Life Safety*] - design-basis earthquake (DBE);
- facility stability, safety of people, valuable equipment and infrastructure which are necessary to eliminate the consequences of earthquake [*Structural Stability*] – maximum design earthquake (MDE).

In norms of Ukraine [1] the level of DBE action is determined by general seismic zoning map OCP-2004 "A". There is a 10% probability that calculated seismic intensity will be increased for 50 years, and average period of such intensity repeatability is once for 500 years. The level of MDE action is determined by general seismic zoning map OCP-2004 "C". There is a 1% probability that calculated seismic intensity will be increased for 50 years, and average period of such intensity repeatability is once for 5000 years. The level of WE action is determined in [1] at low-responsible facilities design using map OCP-2004 "A". There is a 39% probability that calculated seismic intensity will be increased for 50 years, and average period of such intensity repeatability is once for 100 years. At present this level is determined only for Odessa region and Autonomous Republic of Crimea; their seismic zones are considered to be the most researched.

The specific values of seismic hazard and load parameters for each country are given in National Annexes in accordance with the general provisions of EN 1998-1 [4]. Thus, at present it is actual to determine the reference values which correspond to approved "*performance characteristics*" for harmonization of Ukrainian normative documents requirements with European norms provisions [11].

3. THE METHODOLOGY TO DESIGN THE SEISMIC STRUCTURES OF GIVEN PLASTICITY CATEGORY TAKING INTO ACCOUNT EUROCODE-8 RECOMMENDATIONS AND UKRAINIAN NORMS REQUIREMENTS

The another actual task [11, 12] is development of methods to calculate the buildings and facilities structures for earthquake of different intensity to determine the dependence between level of earthquake action and degree of building structures damage up to collapse. In order to solute these tasks it is necessary to have calculation methods which consider the structures material nonlinearity and actual data on appearance and development of damages at dynamic testing and past earthquakes.
To use the strict mathematical approaches due which it is possible to realize the nonlinear dynamic calculation of multidegree-of-freedom system is extremely time-taking. For objects of mass construction it is better to use simplified methods based on the capacity spectrum method (CSM) [13]. The use of such methods shows a good correspondence of full-scale dynamic testing results with nonlinear dynamic calculation results [14, 20, 22].

One of the ways to have nonlinear response of single degree-of-freedom system is to build up the inelastic response spectra at fixed damping values. The inelastic response spectra can be obtained by the following way:

1. The calculation of the nonlinear single degree-of-freedom system for earthquakes accelerograms influence.
2. The updating of the elastic normative spectrum by the use of reduction R_μ and ductility μ coefficients.

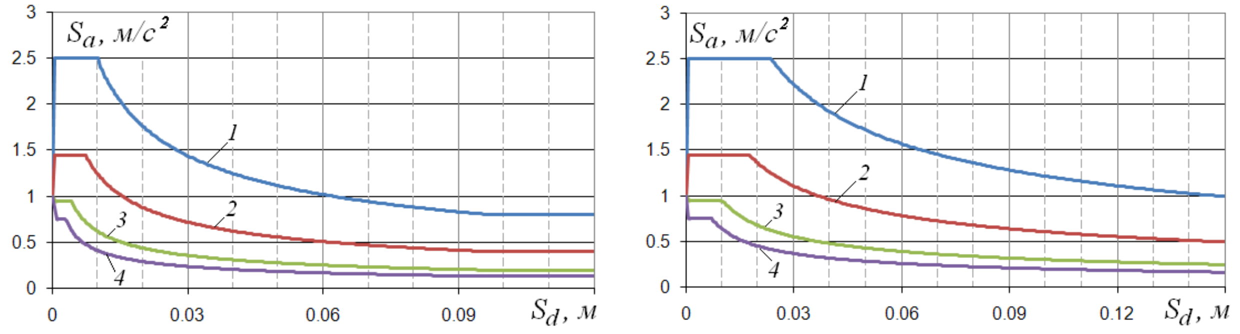
The results of experiments and analysis of earthquakes consequences showed [12, 15] that inelastic response spectrum depends on vibrations characteristics which are expected on the site and nonlinear materials characteristics and buildings and facilities constructive schemes. Thus, inelastic response spectrum for determined influence should consider hysteresis characteristics which correspond to expected state of the used materials and structures.

The approach to update the elastic normative spectrum using the reduction coefficient Rμ is based on works of N.Newmark and W.Hall [16], A.Chopra [15] and at present it is used in different seismic codes: EN 1998-1 [4], ATC 40 [6], FEMA-273 [7], FEMA-356 [8]. According to [15, 17] the dependence between structure reduction coefficient R_μ, ductility coefficient μ and period of natural vibrations T_n is as follows:

$$R_\mu = \begin{cases} 1 & T_n < T_a \\ \sqrt{2\mu - 1} & T_b < T_n < T_c \\ \mu & T_n > T_c \end{cases} . \quad (1)$$

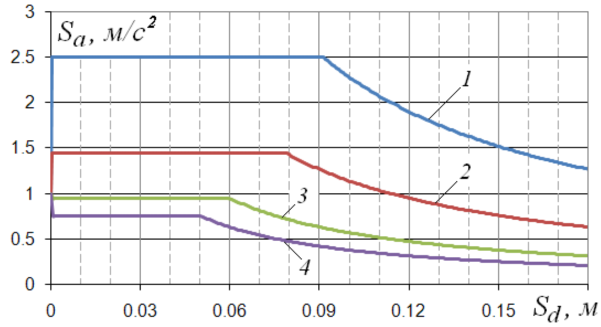
in which T_a, T_b и T_c are bonders of zones which correspond to the dynamic system response to accelerations, velocity and displacements at earthquake.

Dependences (1) were used to build up the graphs of dynamic response factors and inelastic response spectra which help to determine the seismic loading on buildings and facilities and their nonlinear displacements [23] on the basis of DBN B.1.1-12:2006 [1] spectral method. Fig. 2 shows an example of the dependences of spectral accelerations S_a on spectral displacements S_d which are built up taking into account the DBN B.1.1-12:2006 [1] spectral dynamic response factors graphs for soils of the first, second and third categories using seismic characteristics and earthquake intensity of 7 points on scale of seismic intensity in Ukraine [18].



a)

b)



c)

1, 2, 3, 4 – respectively, at μ=1, 2, 4, 6

Figure 2. Dependence “spectral acceleration S_a – displacements S_d” at different ductility coefficients μ for soils of the 1-st (a), 2-nd (b) and 3-rd (c) categories using seismic characteristics and earthquake intensity of 7 points on scale [18]

Fig. 3 shows an example to determine the nonlinear displacements of three buildings (different constructive schemes) where the values of natural vibrations period (the first form T_1) and ductility coefficient μ are the following:

1. 6-storey reinforced concrete monolithic building (period T_1 = 0,37 s, μ = 1,28);
2. 9-storey large panel building (period T_1 = 0,7 s, μ = 4);
3. 7-storey frame building (period T_1 = 1,0 s, μ = 1,7).

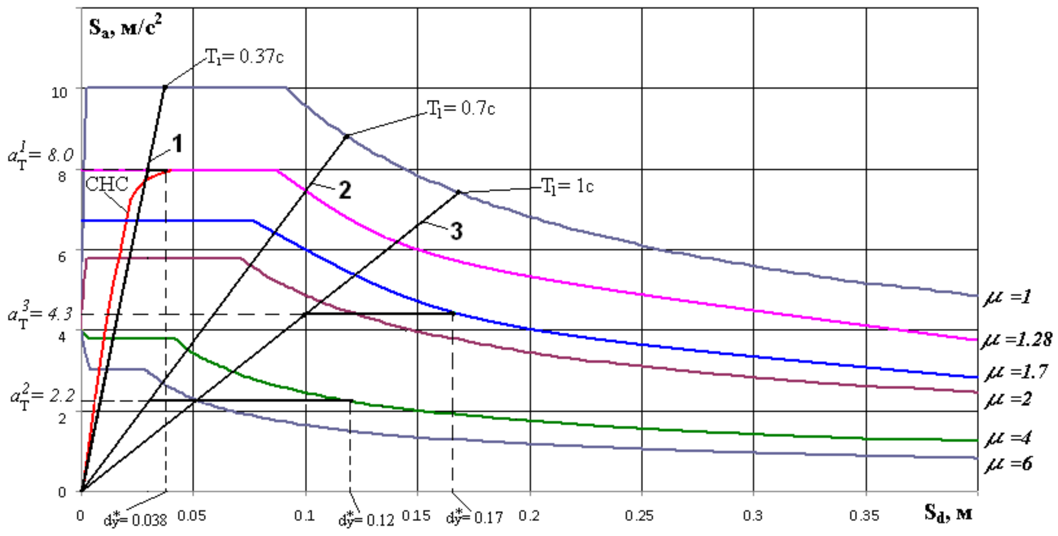


Figure 3. Examples to determine the nonlinear displacements d of three buildings (1, 2 and 3) with different values of period T_1 , yield limit and ductility coefficient for soils of the 2-nd category using seismic characteristics at earthquake intensity of 9 points on scale [18]

The nonlinear displacements for buildings 1, 2 and 3 are d_1=0,038 m, d_2=0,12 m and d_3=0,16 m, respectively.
The nonlinear displacements can be determined by the following dependence:

$$d = \mu \cdot a_T / \omega^2 , \quad (2),$$

in which ω is the equivalent single-mass building model frequency (oscillator, rad/s).

For example we determine the nonlinear displacement for building with ductility coefficient μ=1,7, yield acceleration a_T = 4,3 m/s^2 (ordinate in fig. 3) and period T_1 = 1 s (ω^2 = 39 rad/s^2). According to (2) we have value of nonlinear displacement d=0,019 m which is close to 0,017 m determined by graphs for μ=1,7.

Table 1 shows the results of calculation on maximal displacements of buildings (different constructive schemes) obtained on the basis of inelastic response spectra which are given in this report and their comparison with the results of full-scale dynamic testing by powerful vibration machines [19, 20] and records made at past earthquakes [21].

Table 1. Comparison of actual and calculated values of maximal reinforced concrete buildings top displacements

Constructive scheme, number of stories in the building, reference	Period of vibrations, s	Amplitude of horizontal displacements, mm		Error, %
		at testing	by calculation	
Block building, 5 stories [19]	0,2	9,0	8,0	11
Fragment of monolithic 16-storey building, 6 stories [20]	0,37	41,0	38,0	7,3
Monolithic building, 9 stories [21]	0,71	75,0	72,0	4

Table 2 shows the results of calculation on maximal displacements of buildings (different constructive schemes) obtained by EN 1998-1 [4] methodology and inelastic response spectra given in this report.

Table 2. Comparison of calculated values of maximal reinforced concrete buildings top displacements

Constructive scheme, number of stories in the building, reference	Amplitude of horizontal displacements, mm		Error, %
	By EN 1998-1 procedure	by proposed methodology	
Frame building, 7 stories	19,0	17,0	10
Fragment of monolithic 16-storey building, 6 stories [20]	39,0	38,0	2,5
Block building, 9 stories [22]	51,0	52,0	2

CONCLUSIONS

On the basis of researches the following conclusions are made:

1. We got the inelastic response spectra in coordinates “β – T” based on spectral dynamic response factors graphs of DBN B.1.1-12:2006 norms of Ukraine and in coordinates “S_a - S_d” developed to realize the nonlinear calculations of buildings structures at design and assessment of used buildings earthquake resistance using the nonlinear static methods of calculation.

2. Comparison of the values of maximal displacements of buildings (different constructive schemes) obtained at realization of full-scale dynamic testing and measuring of buildings vibrations at earthquakes with the results of calculation using the developed methodology on

the basis of proposed inelastic dynamic response spectra showed a good correspondence. The maximal error is 11%.

3. The values of maximal top displacements of buildings (different constructive schemes) given in this report are obtained by calculation using the procedure of Attachment B EN 1998-1 and the proposed methodology on the basis of inelastic dynamic response spectra are different by 10%.

4. The developed methodology is recommended to be used in works on existing buildings dynamic certification and earthquake resistance assessment after the main shock and further aftershocks (considering the existing damages and developing plastic deformations) and at design of responsible facilities and buildings using new constructive decisions which are not checked at strong earthquakes.

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