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RECENT EARTHQUAKES LESSONS AND OPTIMAL DESIGN PROBLEM ANALYSIS AS BACKGROUNDS FOR SOME CONCEPTUAL DESIGN RULES AND FOR BUILDING CODES DEVELOPMENT

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SUMMARY

Seismic optimal design research studies were carried out in Moscow Earthquake Engineering Research Center, Russian State Construction Committee.

The optimization procedure is the minimax procedure for total seismic expenses is the sum of two parts: 1. The cost of the initial aseismic measures during the construction and 2. The losses caused by all probable (predicted) earthquakes during the life of the structure. The minimum of this sum corresponds to optimal expenses and optimal aseismic measures. The importance of structures, the occurrence probability of earthquakes are taken into account, as well as the human life cost (the cost the owner is ready to pay to protect the human life).

The optimal design analysis results could be considered as the background for the aseismic design main philosophy and for the PBD procedures. One of the main conclusions is that any damage, except total collapse, correspond to optimal design demands and could be considered as one of the design limit states. Very heavy damage are economically permissible for certain earthquake occurrence probability and intensity (for the rarest and the strongest earthquakes). Heavy damage during the strongest EQ are inevitable, from physical point of view, as well. In contradiction with these conclusions the calculation procedures in all seismic building codes are based practically on elastic linear models, on the ductility concept, on reduction factors, and static analysis. It means that no analytical procedures are used in any Code for life safety limit state. Development of such procedures is a difficult scientific problem and needs time.

The lessons of recent earthquakes have demonstrated that the main killers of people were buildings of different materials but having one common feature. All of these buildings bearings elements were overloaded by vertical static loads (dead loads vertical seismic loads, etc.). Among these buildings were reinforced concrete frame buildings (Armenia earthquake, 1988; Turkey, Greece, Taiwan earthquakes, 1999), concrete block wall buildings (Neftegorsk-Sakhalin earthquake, 1995), wooden buildings (Kobe earthquake, 1995).

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Some conceptual design rules, which being used in design increased sufficiently the structural safety and surviveability are formulated.

INTRODUCTION

The lessons of destructive earthquakes in different countries (Romania 1977, Armenia 1988, Japan, Turkey, Taiwan 1999) lead to conclusions that sometimes structures collapsed being designed more or less in accordance with current Seismic Building Codes, Eisenberg [3, 6, 7], Paulay [5]. The main reason of this is some contradiction, which exists between the main Seismic Building Codes analytical procedures, assumptions and mathematical models used in design practice and the actual seismic behavior of structures during earthquakes. The actual behavior of structures during a strong earthquake is sufficiently nonlinear, non-stationary, the structural elements could have very heavy damage. The traditional code calculation procedure is based as a rule on linear mathematical methods on spectral response approach. Some assumptions are used to smooth the contradiction, such as the assumption of linear and non-linear system response displacements or energy equality, as reduction factors and ductility factors. In some cases these simplifications work but in other cases they do not, Eisenberg [6].

An optimal seismic design investigation program was undertaken in Moscow Earthquake Engineering Center, beginning from the 1970-th. The minimal optimization procedure was used. The conclusion of the study is that many optimal limit states exist. Each limit state corresponds to a certain EQ occurrence probability and intensity. There are optimal pairs: physical limit state of the structure (including damage level) – earthquake intensity.

The performance-based design uses 2 or 3 limit states. The current Seismic Building Codes uses, as a rule, practically one limit state – the linear models without damage taken into account explicitly. Development of practical design methods for the structural design in state when the structure is heavily damaged meets difficulties because the mathematical formalization of a heavy damaged structure under strong seismic motions is a very complicated problem, which needs more investigations. Some conceptual design rules were formulated which implementation in design increased the survivability of structures. Such conceptual rules should be part of Seismic Building Codes. Some of them were included in the drafts of the Russian and of the CIS-countries Seismic Building Codes.

RECENT EARTHQUAKES LESSONS: THE SEISMIC DESIGN CODES NEED IMPROVEMENTS

The recent strong earthquakes demonstrated that sometimes collapsed buildings, designed in accordance with current Seismic Codes. For example, after earthquakes in Bucharest, 1977, in Armenia, 1988, in Turkey, Taiwan and Greece, 1995, in Kobe, 1995 some heavily damaged or even collapsed reinforced concrete frame buildings have been observed which more or less answered the Seismic Design Codes demands. Some pictures of the collapsed buildings are given at the Figures 1 to 3.

The situations when the current Seismic Codes “do not work” or they “work” not very reliable were considered and discussed in some publications, Paulay, [5], Eisenberg [3, 6]. In these and other published works the conclusions were made, that some assumptions and approaches in Seismic Codes design loads calculations are not adequate to the actual seismic behavior of structures during strong earthquakes.

The ductility concept and the reduction factors approach used in practical design supposed kind of inelastic seismic structural behavior and the possibility of cracks and local damage of structural elements.

The same time the structural elements bearing capacity is usually determined for intact elements, in elastic deformation stage. And static type bearing capacity analysis is carried out in usual practical design.

a) b)

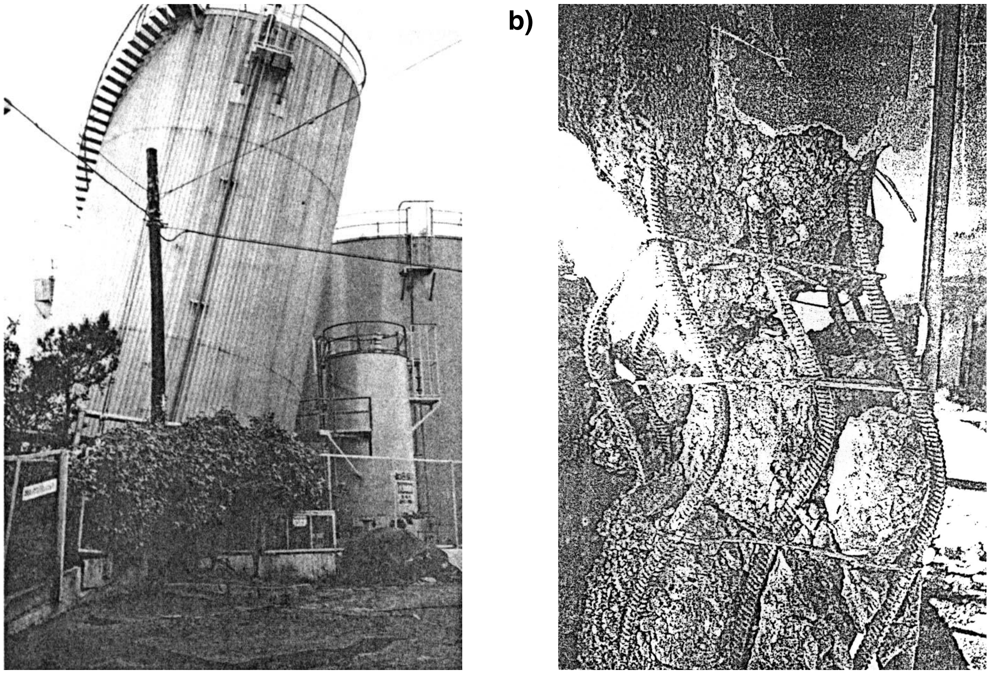

Figure 1. Kobe, 1995, EQ: a) Reservoir damage; b) RC frame building heavy damage

Figure 2. Turkey, Izmit, 1999, EQ: RC frame building collapse

Figure 3. Taiwan, 1999, EQ:
a) 12-story condominium in Tali; b) Collapsed condominium complex in Touliu

The main attention is paid to horizontal seismic loads calculation. Actually, the vertical, gravitational plus seismic, loads are the reasons of structural collapse. The main role of the horizontal seismic loads is that these loads cause some cracks, inelastic deformations and displacements. The structure in this damaged condition became vulnerable to vertical loads (dead loads and other gravitational loads plus seismic loads). This is the more often structural seismic collapse actual mechanism.

A principal difference exists between the elastic intact element and partly damaged element. For example, a reinforced concrete column with cracks in concrete sometimes doesn't more work as a reinforced concrete element. And the reinforcing bars only could not resist the whole vertical load. They lose their stability, often in form of steel flowers, which could be observed after strong earthquakes in RC frame buildings. Not only in RC frame buildings but also in other types of structures the vertical loads play often a decisive role in structural collapses.

So some contradictions which exist between the Seismic Design Codes procedures and the actual seismic structural behaviour lead to the situation when some structures designed in accordance with the Seismic Building Codes are not reliable enough. And some strong earthquake lessons illustrated this conclusion.

SEISMIC OPTIMAL DESIGN AS BACKGROUND FOR SEISMIC DESIGN CONCEPTS DEVELOPMENT

The seismic optimal design problem was investigated in Moscow EERC, Eisenberg [2]. The minimum of total expenses related to seismic risk was considered as optimum criterium. The optimal expences were defined by minimization of the function, which corresponds to this criterium:

$$R = R_a + R_s\left(I_s, T_p, R_a\right) = \min \qquad (1)$$

where

R – the total expences, related to seismic risk concerning a given object.

R_a – the initial expences on the aseismic reinforcing during the structure construction.

R_s – the total losses after all probable predicted earthquakes during the life time of the object (structure).

I_s – the intensity of the earthquake,

T_p – designed life time of the structure.

If R_{as} – is the mathematical expectance of losses during one S-intensity earthquake and the average yearly amount μ_s of such earthquakes are known, then average losses per year for S-intensity earthquakes is $\mu_s R_{as}$. For all earthquakes, probable for the are the loses per year will be equal to $\sum_{S_{\min}}^{S_{\max}} \mu_s R_{as}$.

If we will conditionally convert all expences to one basic year (the year of the construction finalizing), we could write

$$R_s(I_s, T_p, R_a) = \sum_{S_{\min}}^{S_{\max}} K_t T_p \mu_s R_{as} ,$$

where K_t is the factor converting all expences to one design year.

Let us present (1) in form

$$\rho = \rho_{\grave{a}} + \sum_{S_{\min}}^{S_{\max}} K_t T_p \mu_s \rho_{as} = \min \tag{2}$$

where $\rho = R/Q$; $\rho_a = R_a/Q$; $\rho_{as} = R_{as}/Q$

Here Q – is the cost of the same structure without aseismic reinforcement,
$S_{\min}$ – the minimal design EQ intensity at the given site,
$S_{\max}$ – the maximum design EQ intensity at the site.

Taking into account published data, Medvedev [1], we found the functional dependence between the economic losses and the damage level for structures having different levels of aseismic reinforcement. Substituting these data in (2) we receive the mathematical expectance of total expences related to a desirable (design) level of seismic risk.

The extremum – minimum of the mathematical expectance of the total expences we will found using the condition $\partial\rho/\partial\rho_a = 0$. Then we receive the equation for relative optimal expences calculation. Having optimal values ρ_a, we receive then the corresponding values of total optimal expences ρ and ρ_{as} – the values of optimal damage for a given seismic intensity S. Principally, taking into account these data we could define optimal physical states (or limit states) of the structure for given earthquake intensities.

The collapse probability of a structure during an S-intensity earthquake could be given by the expression

$$R\{x_{\Phi} > [x] = 3{,}2\} = \sum_{S=7}^{S_{\max}} \left[1 - F_{(x)}^{s}\right] \int_0^{T_p} \mu_s e^{-\mu_s t} dt, \tag{3}$$

where x_{Φ} – actual damage,
$[x]$= 3,2 – maximum permissible damage (according to MSK Seismic Intensity)
$F_{(x)}^{s} = R\{x_{\Phi} < [x] = 3{,}2\}$ – is the safety of the structure under S-intensity earthquake; the normal distribution law is used.

Poisson distribution was taken for the number of earthquakes for a given site. It is known that

$$F_{(x)}^{s} = \int_{-\infty}^{[x]} \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left\{ -\frac{[x(\rho_a) - m_{x(\rho_a)}]^2}{2\sigma_x^2} \right\} dx. \tag{4}$$

Substituting $F_{(x)}^{s}$ in (3), and integrating we will receive finally:

$$R\{x_\Phi > [x]\} = \sum_{S=7}^{S_{\max}} \left(1 - e^{-\mu_s T_p}\right) \cdot \left\{0{,}5 - 0{,}5 Erf \frac{[x] - m_{x(\rho_a)}}{\sqrt{2}\sigma_x}\right\} \tag{5}$$

where *Erf* – is the probability integral;

$m_{x(\rho_a)}$ – mathematical expectance of the structural damage level, depending of aseismic reinforcement ρ_a;

σ_x – is the standard deviation of x.

The calculations show that earthquakes of small intensity (for example, MSK 7- Intensity degree) in areas where 8 or 9 – Intensity earthquakes are expected more rarely, add relatively small values to the total collapse probability. Therefore in (5) only one component could be retain instead of the sum:

$$R\{x_\Phi > [x]\} = \left(1 - e^{-\mu_s T_p}\right) \cdot \left\{0{,}5 - 0{,}5 Erf \frac{[x] - m_{x(\rho_a)}}{\sqrt{2}\sigma_x}\right\} \tag{6}$$

Using (2) and (6), optimal values ρ_a could be defined for given (desirable) damage probabilities [R] and damage levels [x]; or comparative collapse probabilities of the structure $R_s\{x_\Phi > [x]\}$ for definite ρ_a and [x] values.

At the Figure 4 (above) the dependences are presented between ρ_a (relative initial expences of aseismic reinforcement) and relative total expences, including losses due to earthquakes. Three curves are presented for three different areas. At the Figure 4 (below) the curves are presented, of the dependence between ρ_a and the damage level values ρ_{as}. Different curves correspond to different earthquake intensities. Here discreete values of intensities have been used. But any amount of intensity values could be considered. To the minimum values of ρ (above) correspond optimum values of damage for any intensity S (below) at a given area.

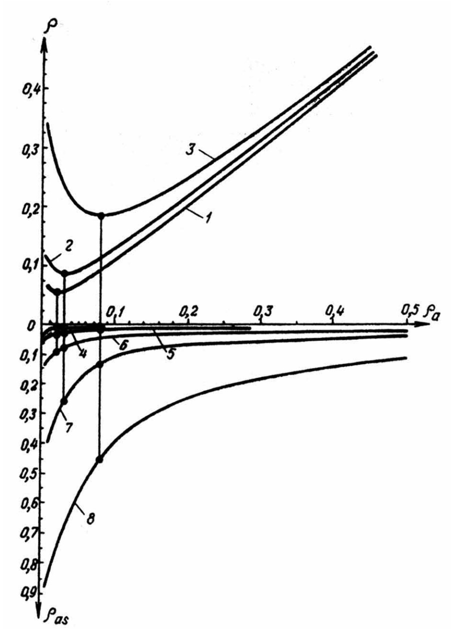

Figure 4. The dependens between initial expences ρ_a and a) total expenses; b) losses due to EQ

So, the following conclusion could be done. A set of pairs exists corresponding to the optimal value of total seismic expenses. Each of the optimal pairs includes:

1) earthquake intensity;
2) structural damage level, which is the background for the mathematical model of the structure under seismic load.

The more of such pairs would be used in design the closer is the design to the optimum. Naturally, too much pairs using is unrealistic. In the current design practice only one pair is usually used. And the mathematical models of the structures are, as a rule, linear elastic systems, without taking into account sufficient damage in structural elements. The seismic design intensities correspond to the relatively, low occurrence period (approximately 50 to 100 years). These calculations have a definite sense, at least, from economical point of view.

But to guarantee the desirable seismic collapse probability and desirable seismic risk level this seismic analysis is definitely not enough. The seismic analysis taking into account the maximum probable earthquake intensities at the given site and mathematical models which describe the condition of a strongly damaged structure are not provided at all. The safety limitations, type (3) or (6), do not taken into account in actual design practice. Such analyses, for a strongly damaged system, are very complicated even for more simple elements than an actual 3D non-linear structure. Now many research laboratories and universities in different countries provide research programs to solve the problem of seismic analysis of neavily damaged structures.

Some suggestions were presented to take into account 2 or 3 limit states in seismic analysis. Such suggestion are reflected, for example, in the “Performance Based Design” approach, SEAOC [4]. In view of proposals presented in this paper the following conclusion is important.

Different damage levels correspond to the optimal conditions of a structure during probable ievery structure should be analysed using several different mathematical models corresponding to the amount of limit states and seismic intensities. The optimal mathematical model of a structure under the strongest rare earthquake should be sufficienly non-linear, inelastic, non-stationary. But development of such models and methodolojies needs more research efforts and they need time, perhaps, a long time.

Some investigations lead to formulation of some simple but effective conceptual design rules, which being used in design permits to increase sufficiently the seismic surviveability and seismic safety of structures.

RESULTS AND DISCUSSION

The values of linear and non-linear seismic displacements response spectra ordinates are equal. This is Prof. N.Newmark assumption. This assumption is the background for reduction factor values definition in Seismic Building Codes. But sometimes, depending of the earthquake spectral and other parameters, the response displacement of linear and non-linear, of elastic and inelastic systems are drastically different Eisenberg [6]. The difference between linear and non-linear response spectra could be seen at the Figure 5.

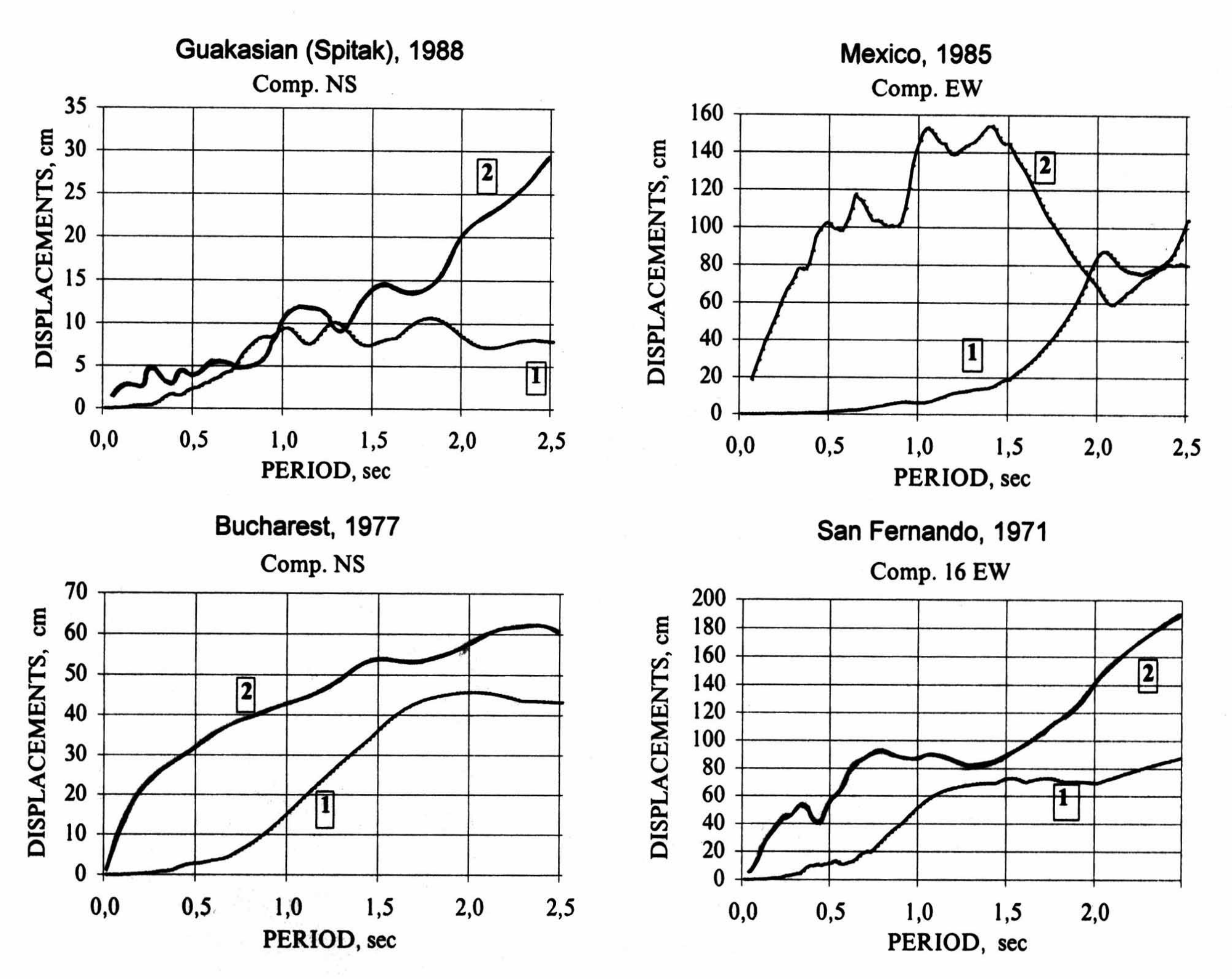

Figure 5. The displacement response spectra of:
1. elastic (C=1.0) systems;
2. inelastic (C=0.1) systems

Ductility concept, response spectra and reduction factor approach is not always adequate for seismic structural analysis. Direct dynamic structural analysis is to be carried out in these cases. The result of optimal design investigation is that for rare and strong earthquakes sufficiently large damage and inelastic deformation are permissible from economical point of view. And they should be incorporated in the mathematical models which are used for seismic analysis of structures. This structural condition corresponds approximately the Life Safety Limit State in terms of Performance Based Design, SEAOC Vision [4].

The mathematical models formulation and seismic analysis of a structure which is strongly damaged, with developed cracks and inelastic deformations, is now possible for only comparatively simple structures. For a 3D structure with probabilistic distribution of physical parameters, as strength, rigidity and other parameters under 3D seismic loads such analysis is now a research problem, but it meets difficulties in design practice.
The gravitational collapse model was investigated for frame buildings and wall buildings, Eisenberg [6]. Some parameters and approaches were formulated which influence sufficiently the seismic surviveability of structures, as the relation between gravitational loads to the vertical bearing capacity of the structural

elements. Some conceptual design rules are proposed to increase sufficiently the surviveability of structures under strong earthquakes to be included in Seismic Building Code, Eisenberg, 2002. One of these rules is the limitation of the vertical (gravitational plus seismic) loads related the elements bearing capacity. In the Drafts of the Russian and of the CIS-countries Seismic Building Code the values γ_s of this relation were included

$$\gamma_S = \frac{W}{R} \tag{7}$$

where W – is the value of vertical static load (dead load, live load etc) for the most loaded bearing elements, in the critical cross-section. R – the generalized bearing capacity for the same section. The γ_s values are given in Table 1.

Table 1. Structural Seismic Surviveability Parameter γ_s

Parameter γ_s values	Seismic surviveability
$\gamma_s \leq 0{,}2$	Very high
$0{,}2 < \gamma_s \leq 0{,}4$	High
$0{,}4 < \gamma_s \leq 0{,}6$	Medium
$0{,}6 < \gamma_s \leq 0{,}8$	Low
$\gamma_s > 0{,}8$	Very low

This rule results from, the gravitational collapse model investigation, J.M.Eisenberg [6]. The other important conceptual design rule that also is included in the Drafts of above mentioned SBC is the refusal of the equal bearing capacity of all structural elements and the damage sequence control using different important factors for different structural elements.

CONCLUSIONS

1. The optimal design analysis result is that for any designed structure for a given site a set of optimal pairs "design earthquake-mathematical model of the structure" exists. Each element of the set corresponds to a given EQ probability occurrence and intensity. The mathematical models of the structure are different. For rare and very intensive earthquakes optimal are limit states of the structure with sufficiently heavy damage. The earthquakes lesson is that during a strong earthquake more or less damage of a structure are inevitable.

2. The analysis procedure in current Seismic Building Codes are simplified, they do not take into account explicitly the life safety limit states. The development of adequate analytical methods for damaged structures is a research problem and need time, perhaps, a relatively long time.

3. The gravitational collapse mechanism understanding permits to formulate some important and simple conceptual design rules. Using these rules in design permits to increase the seismic survivability and the safety of structures. Some of these design rules, as relative vertical static loads limitation, as control of the damage sequences and collapse mechanisms, were incorporated in the Drafts of the Russian and CIS – countries Seismic Building Codes.

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