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Plastic behavior particularities of structures subjected to seismic loads

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Abstract. For the majority of buildings and structures, the analysis of seismic effects is performed employing the linear-spectral method, and is included into the design regulations of different countries. The linear-spectral analytical method allows for estimating the inelastic deformations in structures by reducing (decreasing) the actual seismic load by means of the coefficient of reduction. The current method of the seismic load reduction corresponds to the elastic-plastic type of structural deformation, with the coefficient of reduction applied to the load-bearing system as a whole. Nonetheless, this deformation pattern is not the only one available. There are structures and structural materials that trigger the elastic-brittle mechanism of transition to the limit state. The constructed buildings and facilities normally contain the structural elements of various deformation patterns (combined structural schemes), and that requires consideration when choosing the calculation method. Employing a universal coefficient of reduction in the design calculations of the combined structural schemes leads to an inaccurate result. Opposite to this, the authors propose herein a solution to the problem of accounting for the joint activity of elastic-plastic and elastic-brittle elements being part of the entire structure based on the energy method. Studied is the combined design model with a single degree of freedom and consisting of elements with different mechanisms of inelastic deformation. Various scenarios of conditions for the joint deformation of heterogeneous elements are analyzed. The general solution to the problem of the coefficient of reduction value for the load-bearing systems made of the elements of different types of inelastic deformation depends on the ratio of stiffness values of the elastic-plastic and elastic-brittle subsystems in structures, as well as on the ratio of bearing capacity of such subsystems. General solutions are obtained to the problem of the maximum permissible value of the coefficient of plasticity for the combined load-bearing system that is responsible for safety of the elastic-brittle sections in structures, and for the system as a whole. When employing the linear-spectral method to calculate the seismic effects for individual parts in structures, it is suggested to use differentiated coefficients of reduction, which is, in fact, complies with the actual performance pattern of structures.

1. Introduction

The prediction of the seismic response of buildings and facilities is based upon the results of the design analysis for the stress-strain state of structures experiencing the seismic impact. In this case, as a general characteristic of the limit state, the concept assuming the local damages in structural elements and nodes occuring during the operation beyond the elastic limit is applied. This approach significantly complicates the techniques and design procedures when it comes to studying the pattern of performance of structures in event of earthquake.

Available nowadays are two main methods to proceed with the design analysis for structures under seismic effects:

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a) direct dynamic analysis based on the method of integrating the equations of motion taking into account the physically nonlinear behavior of structures/structural materials;

b) linear spectral analysis of structures.

Method a) is based on general principles of the structural dynamics [1, 2], and allows for obtaining an entirely accurate forecast for the behavior of structures in event of earthquake. Nonetheless, for for the purposes of a comprehensive analysis of seismic stability of a structural system, it is required to perform a set of calculations supported by the evaluation of the representative set of earthquake accelerograms, or to perform such evaluation based on the data of seismic movements and their parameters for any particular construction site. All contemporary problem-oriented computing software complexes are equipped with a built-in modules to perform the design analysis by the direct integration method of motion equations.

Another important condition for obtaining the correct result by Method a) is modeling the process of occurrence and development of damage in structures. Meeting this requirement is ensured by implementation of the special computation techniques which take into account the deformation in structures and structural materials beyond the point of elastic strain. It is noteworthy that the design analysis beyond the elastic phase of deformation requires considerable computational capacity.

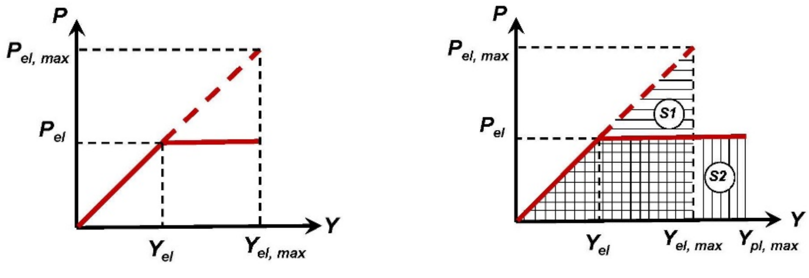
Thus, the desisng analysis as per Method a) is considered to be totally scientific-substantiated, yet still rather complicated in terms of its implementation, and requires the attention of high qualified specialists.

For the purposes of carring out the mass estimation and forecast of seismic resistance, the less complicated approach, i.e. Method b), was elaborated and substantiated. This method is based on the research studies completed in the 40s of the XXth century by M.A. Biot [3, 4], and A.S. Veletsos, N.M. Newmark [5].

The research by M.A. Biot made it possible to obtain the spectra of dynamic response for the single-mass models, which served grounds for development of the design analysis techniques based on the modal analysis of multi-mass systems. The theoretical foundations for the analysis based on the modal calculation are well worked out [1]. Nonetheless, it is noteworthy that the modal calculation approach allows for obtaining the accurate results only within the framework of the elastic performance of structures.

In his research papers, Newmark came forth with the idea of carrying out calculations for inelastic systems assuming the seismic actions as elastic, but employing the lower (reduced) loads. The method of N.M. Newmark is supported by the following concept:

- for the systems demonstrating the natural vibration frequency range at t > 0.5 sec, the displacement of elastic and ideally elastic-plastic systems is equal. This assumption is graphically represented in Fig. 1, a);
- for the systems demonstrating the natural vibration frequency range 0.1÷0.5 sec, the energy of elastic (S1) and elastic-plastic (S2) systems is equal. This assumption is graphically represented in Fig. 1, b).



a b

Figure 1. Graphic representation of the assumption made by N. Newmark [3] as regards the compatibility of characteristic parameters of elastic and elastic-plastic systems.

The assumption introduced by N.M. Newmark makes it possible to carry out static calculations within the framework of the elastic performance in structures, but with consideration of the possible occurrence of a certain amount of inelastic deformations taking place when the load-bearing system experiences the seismic loads of an actual level. The important aspect of using the assumption by N.M. Newmark is the opportunity to employ the modal calculation of structures taking into account the dynamic response spectra of load-bearing systems following the approach of M.A. Biot. The linear-spectral method for the design calculations of seismic effects is incorporated into the regulations of the majority of countries [6, 8–12].

The reduction in the seismic load level is ensured by multiplying its initial value by a certain coefficient which in the Russian norms [6] is known as the coefficient comprising the capacity of buildings and facilities to withstand the inelastic strains (K_1) 6In Eurocode-8 [8] the ‘behavior factor’ for structures *r* is mentioned accounting for the similar physical meaning but a reciprocal value ($r = 1/K_1$). Comparable methods of the seismic load reduction are referred to in the design norms of India [9], Turkey [10], Algeria [11], Ukraine [12], and many other countries.

Multiple sources [13–19, etc.] cover the problems of the coefficient of reduction In different research papers.The attempt at assessing the accuracy of this technique was made, as well as defining more precisely the conditions of its use [20–30]. In research studies [31, 32] it is proved that the elements of the bearing system with the pronounced shear deformation pattern have significant impact upon the generalized parameter of the load reduction. Nonetheless, it should be highlighted that the entire scope of the carried out research activities pertained to the structures made of one material (either steel or reinforced concrete), the elastic-plastic response of which resulted in no loss in rigidity. At the outcome, it was concluded that the response spectral technique together with the reduction employed can be feasible while making design calculations for framed buildings of a simple geometric pattern the rigidity parameters of the bearing elements of which do not manifest a wide scatter.

With the reference to the above, the following should be stated. The reduction in seismic loading as it is represents a simulated approach based on the idea of evaluating the behavior of an elastic-plastic system through the results of calculating its elastic analogue. Indeed, the strains in elements of the system and the corresponding internal forces are limited by the yield point of the material, i.e. reduced if compared to those generated elastically. However, when shown in the way of the load reduction instead of limiting the response of the system, the idea of reduction looks as if during the vibrations of the elastic-plastic system the inertial forces decrease being the seismic loads impacting the structure, and that does not correspond to the physical side of the phenomenon.

At that, all available ways to estimate the coefficients of reduction are associated with the design model of a dynamic system with a single degree of freedom, which in fact has a single structural element the plastic behavior of which is taken into account. In fact, almost any actual structure represents a complex system, and if its dynamic deformation can still be approximated by a certain geometric shape determined with an accuracy to one parameter variable in time (the system with a single degree of freedom), then the actual content of the structure can hardly be so easily reduced to one element experiencing deformation. This is particularly true in cases when the plastic properties of various parts of the structure differ significantly one from another and, moreover, when the plasticity bears no impact whatsoever upon the load-bearing resistance of certain parts of the structure.

The purpose of this research paper is to improve the reduction approach in order to study the possibility of the combined resistance in structures in which only one part of there elements is elastic-plastic, while the other part performs elastically and breaks down in a brittle way (e.g. it loses stability). It is noteworthy that the international standard ISO 3010 [33] explicitly points to the dependency between the coefficient of reduction value and the destruction mechanism type, as well as implying a very descreet approach to the problem of assigning the value to the coefficient in question.

2. Method

In the course of this research, a nonlinear model with a single degree of freedom is mentioned as well in order to assess the behavior of the structure, but with one significant difference, i.e. the model is made of two constituents resisting the motion. The first constituent has the elastic-plastic behavior and the second one has the elastic-brittle behavior. Approximation of the use of the model with a single degree of freedom was substantiated by many authors, together alongside the corresponding reference herein [35].

The grounds of analysis lie in comparison of the deformation energy in an ideally elastic and studied systems. The assumption is made about the ideally plastic behavior of the corresponding part of the structure (Prandtl diagram) and about the instant (brittle) failure of parts showing no performance in an elastic-plastic way.

As illustrated above, as early as the classical works by Newmark [5, 34] and down to the recent times [35–43], the problem of seismic impact reduction by the plastic response of the structure proved to be a good solution for the system all elements of which functioned in the elastic-plastic mode. The solution to this problem was forming up on the assumption about the equality of the utmost displacements in plastic and elastic-plastic structures under the same seismic impact and equal initial natural frequencies. In conformity with the assumption, the design model was developed for the system of a single degree of freedom to demonstrate the reduction scenario. However, the load-bearing systems comprise the structures for which the transition to the limit state is associated with significant difference if compared to the mechanism of plasticity, i.e. the mechanism of brittle failure, rigidity loss, etc.

Is it reasonable to employ the generalized reduction coefficient supported by the elastic-plastic performance for such systems? In what way the reduction coefficient value itself depends on correlation between the rigidity of elastic-plastic and elastic-brittle subsystems?

The problem of taking into account the collaborative performance of subsystems of various mechanisms of inelastic deformation appear to be rather complicated and has not been previously considered. In order to analyze and demonstrate the distinctive features of the problem, a simplified scenario with a single degree of freedom is studied (Fig. 2) where the resistance against transition is achieved through simultaneous operation of two subsystems: marked in red is the elastic-plastic system with the idealized Prandtl diagram and rigidity of its elastic part C_1, and marked in blue is the elastic-brittle system with its rigidity C_2.

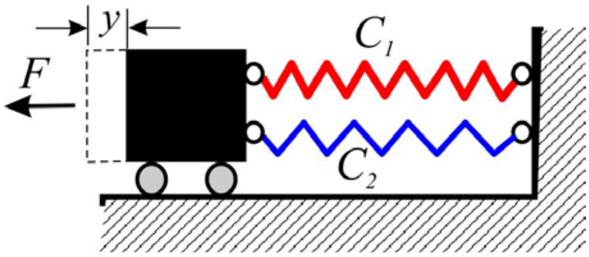


Figure 2. Design model with simultaneous performance of elastic-plastic and elastic-brittle subsystems.

3. Results and Discussion

3.1. Mechanisms of transition into limit state and impact thereof on structures

Fig. 3 introduces four possible scenarios of physical and mechanical properties correlation for these subsystems by means of the displacement-response grid coordinates. As indicated, F_T shows the tolerable limit load state for elastic-plastic subsystem; y_T depicts transition corresponding to the baseline of yield for elastic-plastic subsystem, and by y_d the displacement is introduced which is compatible with the greatest probable overlap with the zone of plasticity. Value F_{cr} stands for the tolerable limit load for elastic-brittle subsystem; y_{cr} depicts transition at which the elastic-brittle subsystem gets crumbled. Owing to the simultaneous performance of the system in general, no system failure occurs upon malfunction of one of its components. Here it should be stated that the tolerable limit state is aligned with the transition y_d for scenarios *a*) and *c*) whilst the transition y_{cr} goes along with the scenarios *b*) and *d*). At that, we shall discuss whether the defective system can function for a long period of time in the event of only one of its subsystems functioning properly. It is of paramount importance that in this state the transition shall be increasing till the moment of complete failure.

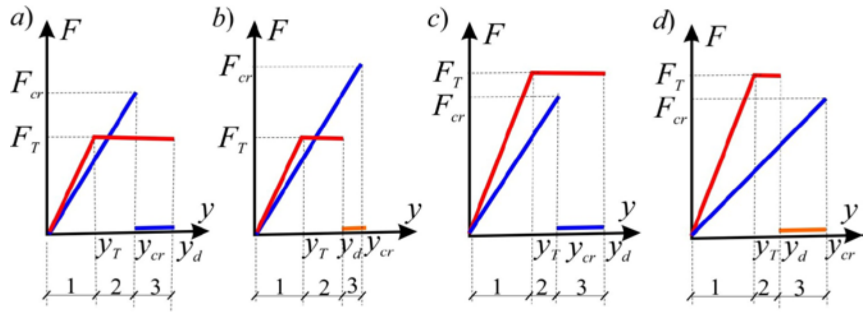


Figure 3. Possible physical and mechanical properties representation scenarios.

The value of potential cumulative energy of the system for all scenarios of physical and mechanical properties at the point when the system reaches its limit state can be estimated as follows:

$$W_d = \frac{Py}{2} = F_T\left[\frac{y_T}{2} + \left(y_d - y_T\right)\right] + \frac{F_{cr}y_{cr}}{2} = = C_1\left(y_T y_d - \frac{y_T^2}{2}\right) + C_2\frac{y_{cr}^2}{2} \quad (1)$$

It is possible to work out at which value of the coefficient of reduction λ the force F would work at its elastic stage in order to enable the system with the original rigidity of C_1+C_2 to accumulate the same value of energy. The assumpton of the energy balance is represented as follows:

$$\frac{(C_1+C_2)(\lambda y_d)^2}{2}=C_1\left(y_T y_d-\frac{y_T^2}{2}\right)+C_2\frac{y_{cr}^2}{2} \tag{2}$$

or

$$\lambda=\sqrt{\frac{2C_1\left[y_T y_d-\frac{y_T^2}{2}\right]+C_2 y_{cr}^2}{2(C_1+C_2)y_d^2}}=\sqrt{\frac{(2\mu-1)}{2(C_2/C_1)}+\frac{(y_{cr}/y_T)^2}{2}}\,. \tag{3}$$

The value of $\mu=y_d/y_T$ represents here the coefficient of plasticity which defines the depth of deformation progress along the yield line. If compared to just elastic-plastic system with the value of the coefficient of seismic load reduction equal to $K_1=1/\lambda=1/\sqrt{2\mu-1}$ (for reference see [5, 34]), the adjustment was obtained as regards two relative measures for the elastic-plastic part of the system and contributing to its overall performance: rigidity values ratio $\alpha=C_2/C_1$ and bearing capacity values ratio $\beta=y_{cr}/y_T$.

The design model with the simultaneous performance of elastic and elastic-plastic subsystems as discussed above is not the only possible example. Another example worth considering is when the subsystems perform sequentially (Fig. 4).

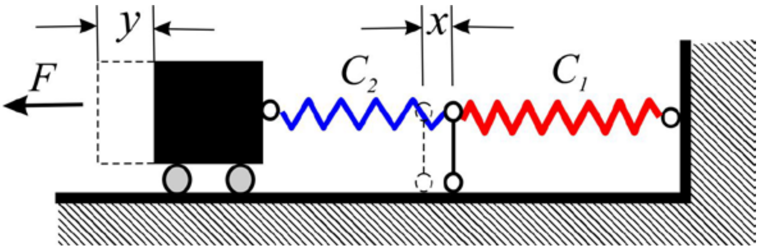


Figure 4. Design model with sequential performance of elastic-plastic and elastic-brittle subsystems. In this model the force F corresponds to the transition as follows:

$$y=F\left(\frac{1}{C_1}+\frac{1}{C_2}\right),\quad x=\frac{F}{C_1} \tag{4}$$

and besides, the values of F_{cr} and F_T are the limit values of force. In as much as for the system of this type the complete failure corresponds to the failure of the weakest element, the limit state is reached upon obtaining the lowest value of these forces., and prior to that moment both subsystems perform symultaneously at the elastic stage. Therefore, for the structure shown in Fig. 3 the coefficient of reduction is at K_1 = 1.

3.2. Limit values of the coefficient of plasticity

As regards the value of the coefficient of plasticity μ, its value cannot be arbitrary. Moreover, it cannot be assigned based on the conditions of the equilibrium limits in the structure [35], as the structure is not entirely elastoplastic.

At this point it would seem possible to reason as follows: the strain in the elastic part of the system should not exceed the critical value of F_{cr} as the elastic part may be completely destroyed. Still, as per Fig. 1, the system can indeed exist in this form, if in such a case the plastic strains remain within tolerable limits. It is possible to suppose that this limit is set by way of the maximum permissible value of the coefficient of plasticity μ_{max}, and in this case the elastic part transitions to the limit state and the entire load is solely born by the plastic part of the structure.

The corresponding maximum displacement $y_{max} \le y_T \mu_{max}$ is representative of the force acting on the elastic system $F_{max} \le C_2 y_T \mu_{max}$. The energy balance equation shall generate the value of the coefficient of reduction that corresponds to this scenario, i.e. $\lambda^* = \sqrt{2(\mu_{max} - 1)}$.

When setting the equation equal to the value defined by the equation (3), generated will be the value of μ_{max} limited by the condition as follows:

$$\sqrt{2(\mu_{max} - 1)} = \sqrt{\frac{(2\mu_{max} - 1)}{2\alpha} + \frac{\beta^2}{2}}, \quad (5)$$

which is reduced to the following:

$$\mu_{max} = \frac{\alpha\beta^2 + 4\alpha - 1}{4\alpha - 2}. \quad (6)$$

In the case of equal scores of the elastic-plastic and elastic-brittle parts of the system, when $\alpha = 1$ and $\beta = 1$, there will be $\mu_{max} = 1/2$.

Limiting the values of the coefficient of plasticity was also suggested previously. Thus, in the research papers [42–43], instead of the value of μ corresponding to the ultimate breaking load, it was advised to use some smaller value corresponding to the load resulting in 'tolerable' value of deformation (damage) of the structure. For this reason, naturally, it is required to be aware of the ability of the structure to exhibit the plastic stage of deformation to the extent sufficient for the operation of the damaged structure in the aftermath of seismic action. Obviously, the structures made of different materials (masonry, concrete, reinforced concrete) are capable of exhibiting significantly different values at the plastic deformation stage, within which the values of the tolerable plastic strain differ accordingly.

The actually built structures represent much more complex systems than those simplified models studied herein, the purpose of which being only the demonstration of the effects under analysis. Various structures deforming, in fact, beyond the elastic limit, may comprise the elements that do not exhibit plastic strain (brittle fracture, loss of stability, etc.). In addition, there may be critical elements integrated into the system for which the transition to the plastic stage of performance is undesirable (e.g., embedded parts). For the elements as such, the concept of a bearing capacity margin triggering the reduction in seismic loads, is improper.

The question arises whether coefficient of reduction should be attributed not to the seismic load when it affects the structure in its entiriety, but to the internal strains supposing that it may have different values for different elements, as it is introduced, for instance, by means of Eurocode or in the regulations of Uzbekistan?

4. Conclusion

The outcome of the performed research studies deduce the statements as follows:

1. The linear spectral technique to model the buildings and facilities for their seismic effects using the coefficients of reduction corresponding solely to the elastic-plastic mechanism of inelastic deformation, is not of the generalised nature. When building the earthquake-resistant projects, widely used are the structures exhibiting the elastic-brittle mechanism of transition to the limit state, or the mechanism of loss of stability. Cases of collaboration in structures with different modes of deformation can take place. In such cases, implementation of the existing technique with the coefficient of reduction universal for the entire load-bearing system and considering only the elastic-plastic strain mechanism shall inevitably result in incorrect values.

2. Different scenarios for the combined pattern of structures performing the elastic-plastic and elastic-brittle deformation mechanisms are studied. On the basis of the energy balance approach, more accurate values of the coefficient of reduction are obtained taking into account various deformation mechanisms contributing to the overall inelastic performance of the load-bearing system.

3. As regards the load-bearing system comprising the set of structures with different deformation mechanisms, the restrictions in view of the coefficient of plasticity values are proposed.

4. Approaches to use differentiated coefficients of reduction while calculating the seismic impacts following the linear spectral technique are introduced. Using the coefficients of reduction corresponding to

the inelastic deformation in structures under study shall ensure reliability of the complex systems performance with parallel or sequential operation of heterogeneous parts of the structures.

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