Seismic risk assessment earthquake resistant construction

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Abstract At present, earthquake-resistant design of buildings is based on force-based analysis and on representing the effect of an earthquake by static equivalent forces, which are calculated using elastic response spectra that relate the law of ground motion to the absolute acceleration of a model in the form of a nonlinear oscillator.

Such an approach does not directly take into account either the influence of the duration of strong motions or the plastic behavior of the structure. The frequency content and duration of ground vibrations directly affect the energy entering the structure and causing damage to its elements. Unlike force-based or kinematic analysis, the seismic action on a structure can be interpreted without considering forces or displacements separately; it may be represented as the product of both quantities, that is, as work or input energy (the maximum energy that a structure can acquire as a result of an earthquake). In an energy-based approach to seismic design, it is necessary to estimate the seismic input energy entering the structure and its distribution among the various structural components.

The article provides a justification for the energy-based approach in the design of earthquake-resistant buildings and structures as an alternative to the currently used method, which is based on force analysis and on the representation of earthquake effects by static equivalent forces calculated using response spectra. It is noted that interest in the use of energy concepts in earthquake-resistant design began with the works of Housner, who represented seismic forces in the form of seismic input energy using the velocity spectrum and proposed that damage in an elastoplastic system, as in an elastic system, is caused by the same seismic input energy. The paper presents indices for determining the input energy of an earthquake. It is shown that modern approaches to ensuring the seismic resistance of structures, based on representing the earthquake effect as a static equivalent force, do not describe the behavior of the system during an earthquake adequately enough.

The article proposes a new approach to seismic risk assessment that makes it possible to formalize the decision-making process concerning anti-seismic measures. The developed document represents a step forward with respect to the optimal design of earthquake-resistant structures.

Keywords: seismic resistance of structures, energy method, earthquake-resistant construction, response spectra, earthquake input energy, earthquake recurrence period, seismic risk, anti-seismic measures, seismic-resistance criteria, nonlinear static and nonlinear dynamic calculation method.

Introduction

In terms of destructive consequences, number of casualties, material losses, and destructive impact on the human environment, earthquakes occupy one of the first places among hazardous natural phenomena and determine the conditions of human life and engineering activity over a significant part of the globe.

Strong earthquakes threaten the countries of Transcaucasia and many countries located in active seismic zones. Since earthquake threats are realized in accordance with stochastic laws, this means that damage and losses from earthquakes can be managed by minimizing seismic risk. However, this possibility can be realized only when seismic risk is adequately assessed. The centuries-long experience accumulated by humanity in combating the consequences of earthquakes shows that the most effective way to minimize them is to carry out large-scale anti-seismic measures already during construction in seismic-hazard areas. Anti-seismic measures require additional costs compared with construction in non-seismic regions. From the standpoint of the effectiveness of such costs, they must be justified by a reduction in probable earthquake losses. In this case, the reduction of probable earthquake losses can be considered as a future effect, while additional costs for anti-seismic measures can be interpreted as components of seismic risk. In our opinion, the solution to this problem is seen primarily in the need to clarify the concept of seismic risk and its assessment in the context of decision-making.

Main Part

At present, earthquake-resistant design of buildings is based on force-based analysis and on representing the effect of an earthquake by static equivalent forces, which are calculated using elastic response spectra (the linear-spectral method) that relate the law of ground motion to the absolute acceleration of a model in the form of a linear oscillator (Fig. 1):

$$m\ddot{u} + c\dot{u} + F(u, \dot{u}) = -m\ddot{u}_g \qquad (1)$$

where $F(u, \dot{u}) = ku$ for a linear oscillator; m, c, k - mass, damping coefficient, and stiffness of the oscillator; ξ - damping parameter.

Such an approach does not directly take into account either the influence of the duration of strong motions or the plastic behavior of the structure.

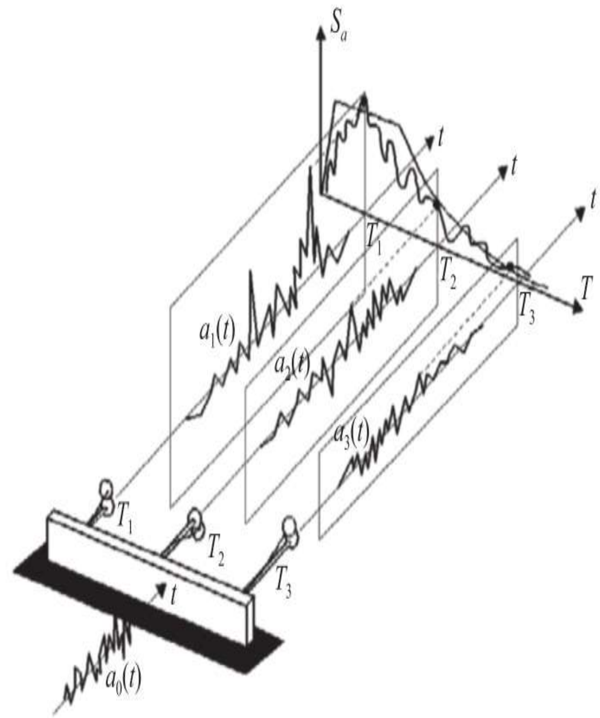

Fig. 1. Diagram of seismic ground vibrations and the response spectrum

The frequency content and duration of ground vibrations directly affect the energy entering the structure and causing damage to its elements. However, the elastic response spectra obtained in 2016 for these earthquakes, as shown in Fig. 2, cannot reflect these differences in the records. Unlike force-based or kinematic analysis, the seismic action on a structure can be interpreted without considering forces or displacements separately; it may be represented as the product of both quantities, that is, as work or input energy (the maximum energy that a structure can acquire as a result of an earthquake).

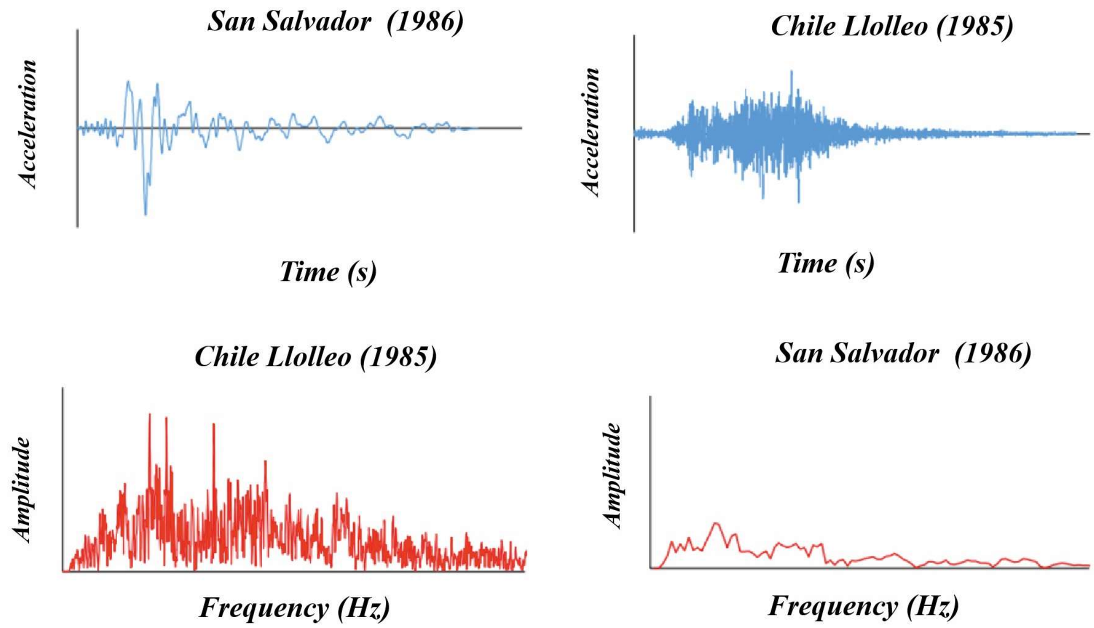

Fig. 2. Acceleration and amplitude Fourier spectra of two different earthquake recordings

The dynamics of an elastoplastic system with one degree of freedom is also described by differential equation (1), in which F(u, u̇) is the nonlinear specific restoring force. Writing the terms in equation (1) as functions of time, we obtain

$$\int_0^t \dot{u}\ddot{u}\,dt + 2\xi\omega\int_0^t u^2\,dt + \int_0^t f(u,\dot{u})\dot{u}\,dt = -\int_0^t \ddot{u}_g\dot{u}\,dt \qquad (2)$$

In the energy-based approach to seismic design, it is necessary to estimate the seismic input energy entering the structure and its distribution among the various structural components. Fig. 3. Elastic response spectra for earthquake records in Chile (1985) and San Salvador (1986). Equation (2) corresponds to the energy relationship (energy-balance equation)

$$E_I = E_K + E_\xi + E_A \qquad (3)$$

E_i is the seismic input energy, E_k is the kinetic energy, $E\xi$ is the damping energy, and $E_a = E_s + E_h$ consists of the sum of E_s, the potential energy of elastic deformation, and E_h, the energy dissipated through plastic deformations.

The calculated input energy depends on the structural model being considered. The input energy determined as a result of dynamic analysis of the selected model, or obtained on the basis of theoretical estimates, is compared with the energy capacity, that is, with the maximum energy that can be imparted to the structure before its failure. Thus, seismic input energy serves as an alternative response-parameter index and takes into account the effect of seismic damage associated with the duration of base motion, the frequency content of the earthquake, and plastic deformation.

The behavior of a structure during an earthquake is determined by the amount of energy entering the structural elements of the system. This energy is in a complex dependence on the intensity, frequency content, and duration of ground motion, as well as on the structural parameters of the system. Thus, determining the energy entering the structure is the most important task in the energy-based approach to ensuring seismic resistance, because it makes it possible to establish a relationship between the energy entering the system and the possible damage to the structure. Seismic input energy is the amount of energy entering the system as a result of ground motion during an earthquake. In seismic analysis, the main problem is to establish an effective relationship between energy and the actual damage to the structure. The damage capacity during an earthquake can be expressed by the degree of structural damage, which, in turn, is determined by the response of the structure, including maximum deformation and the dissipation of plastic hysteretic energy. In an energy-based design approach, it is necessary to quantify the input energy entering the structure during an earthquake for the purpose of distributing it among various structural components.

The maximum seismic acceleration a max of ground-particle vibrations at the earth's surface is used as the main design characteristic describing the level of seismic hazard. A graph is given for maximum acceleration, establishing a complex probabilistic dependence (Fig. 1), which was obtained by statistical processing of earthquake accelerograms recorded in different parts of the world.

Concept of a New-Generation Regulatory Document for Earthquake-Resistant Construction seismic risk is determined by the probability of occurrence of an earthquake, taking into account design criteria and boundary conditions. For this purpose, in Europe [Eurocode 8, 2003; European Standard, 2002] and in many other countries [ATC-40, 1996; ATC-55, 2005; FEMA-273, 1997; FEMA-274, 1997; FEMA-356, 2000; NEHRP, 1997], it is accepted practice to design earthquake-resistant structures for an earthquake that may occur with a probability of 10% over 50 years.

On the basis of the Poisson distribution in time (the approximation concerns small probabilities of event occurrence), an earthquake recurrence period of T = 475 years follows. During this time, the design earthquake will occur with a probability of 63%. In the general case, when estimating the total probability of structural failure, the following may be taken into account: the response of the object to seismic events of different intensity, the spectral composition of different earthquakes, and the sequence of different characteristics of seismic activity. All these factors can also be expressed through conditional probabilities. The foundations of such an approach to seismic-risk assessment, taking into account the action of earthquakes of different intensity and total probability, were laid in the 1960s. Nevertheless, despite the prospects opened by quantitative seismic-risk assessment within the framework of a probabilistic approach, the question of the usefulness of such assessments for solving practical problems of minimizing seismic hazard still remains unanswered.

The generally accepted calculation of structures for seismic resistance is based on comparing the forces (or stresses) caused by external loading with the maximum permissible values of internal forces (or stresses) that can be resisted in the corresponding sections of the structure. Depending on whether only the elastic behavior of the material is considered or whether its plastic deformations are also taken into account, the values of the maximum permissible internal forces in the sections of the structure change. In general, it is not possible to say anything definite about the seismic resistance of a structural system designed in this way. Consequently, we obtain a structure with an unknown level of seismic resistance. Calculation of structures with allowance for plastic and nonlinear behavior, and even with allowance for the failure of individual structural elements of buildings and structures, requires the use of more complex mechanical-mathematical models and theories, that is, the assumption of controlled damage. It is also necessary to take into account the redistribution of forces through the structure associated with the appearance of zones of plastic deformation in it. However, in all cases, the criterion for assessing the bearing capacity of a structure is the principle of comparing external and internal forces. In our opinion, the solution to this problem is seen primarily in the need to develop new-generation regulatory documents and to introduce into practice design methods with a specified level of seismic resistance.

Experience in the design of earthquake-resistant buildings shows that the property of regularity of the building and of the structural solution, which includes the following, contributes most to ensuring seismic resistance:

– regularity of the structure in plan and in height;
– regularity of the structural solution.

When assigning zones of plastic deformation and local failure, structural solutions should be adopted that reduce the risk of progressive collapse of the structure or its parts and ensure the survivability of structures under seismic actions. Structural solutions that allow the collapse of a structure in the event of failure or unacceptable deformation of one load-bearing element should not be used. According to Eurocode 8 [Eurocode 8, 2003], design is carried out in such a way that certain elements of the structural system are selected, appropriately designed, and detailed with the expectation of dissipating energy under the action of large deformations, while sufficient strength is provided for all other structural elements to ensure the possibility of using the selected energy-dissipation means. Preference is given to dissipative structures, that is, structures capable of dissipating energy on the basis of plastic hysteresis and/or other mechanisms. In the structural system, dissipation zones are assigned: predetermined parts of the dissipative structure in which the main part of the dissipation capacity is concentrated. These zones are also called critical regions. At the same time, a non-dissipative structure is a structure designed for a specific design seismic situation without taking into account the nonlinearity of material behavior.

Conclusion

1. Analysis of modern approaches to ensuring the seismic resistance of structures has shown that existing methods are based on representing the effect of an earthquake as a static equivalent force calculated from elastic response spectra that relate peak ground acceleration (PGA) to the absolute acceleration of an elastic system. These methods do not describe the behavior of the system during an earthquake adequately enough.
2. Because of the complexity and randomness of base motion during an earthquake, it is difficult to accurately assess the applicability of existing energy-based proposals for estimating the seismic energy entering the system during an earthquake. In addition, there is no objective quantitative method for assessing the applicability of such indicators. However, it is appropriate to note the advantage of energy-based approaches, which make it possible to take into account the dependence of system behavior on the intensity, duration of base motion, and its frequency content.
3. On the basis of an analysis of research on methods of earthquake-resistant design of

structures, it can be concluded that at present the theory and practice of construction in seismic regions have reached a high level of development. However, there are a number of issues that require more detailed study. This concerns, first of all, issues related to the behavior of building structures under conditions of elastoplastic deformation: which method should be used to estimate the input energy entering the system, and how to optimally correlate the input energy entering the system with the damage sustained by the structure.

4. A quantitative seismic-risk assessment approach has been proposed, making it possible to formalize the decision-making process concerning anti-seismic measures.
5. A concept of new-generation seismic construction standards has been developed, making it possible to design buildings and structures with a specified level of seismic resistance.

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