IMPLICATIONS FOR DESIGN
OF THE SPATIAL NATURE OF SEISMIC ACTION
SİSMİK HAREKETİN DEĞİŞKENLİĞİNİN TASARIMA YANSIMASI

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ABSTRACT

The spatial nature of seismic action and structural response is generally recognized, yet its consideration is not implemented to date thoroughly, and this is true whether one considers here codes or engineering practice. The paper is aimed to deal with all main aspects connected with a consistent consideration of this fact: modelling of structures, modelling of action (and response), criteria of verification and capacity design. The presentation is intended to discuss primarily the basic, qualitative aspects involved. This discussion is followed by some considerations concerning the needs of research involved by the significant aspects referred to.

1. INTRODUCTION

The consideration of the spatial nature of seismic action and of its effects on structures is of obvious importance for a thorough verification and design. Several main aspects must be considered in a consistent way in this connection:

a) modelling of structures;
b) modelling of seismic action and, consequently, of structural response;
c) verification criteria for various components considered in design;
d) application of capacity design philosophy and techniques.

The consideration of the spatial nature of seismic action appears in codes (rather in qualitative terms) to various extents, but it is not yet fully implemented in operational provisions. Neglecting this problem involves significant shortcomings like: lack of invariance of results of analysis of structural behaviour with respect to the modifications of reference systems, sometimes inconsistent rules of superposition of effects of components of seismic action along different directions, lack of consistency of rules of definition of conventional eccentricities for various directions of seismic action, sometimes wrong outcome of the attempts to implement capacity design etc.

The paper is aimed to discuss the main aspects involved by the spatial nature of seismic action, referred to, and each of them is devoted a subsequent section. The

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aspects referred to should be considered in any case in a correlated way in order to provide a desired consistency to the approach as a whole. It turns out that an effort is necessary in this connection for a more consistent formulation of codes, both at the level of principles and at that of operational provisions.

2. MODELLING OF STRUCTURES

A 3D analysis of structural behaviour requires, of course, corresponding modelling from the viewpoints of both degrees of freedom and constitutive laws of components.

The degrees of freedom corresponding to the masses of the elevated parts (not in contact with the ground) do not raise special problems besides the standard task of being representative for the various significant possible categories of displacements and deformations.

The selection of degrees of freedom will be based practically in all cases on some kind of discretization. In cases of trusses or frames it is many times reasonable to consider only degrees of freedom defining the displacements of nodes. Some important additional simplifications may be brought for some storeyed structures (if this is realistic) by the assumption of in-plane ideally rigid floors. The validity of such an assumption must be carefully checked, especially for lower-rise, longer-in-plane, structures. More specific problems are raised by the degrees of freedom of the ground-structure interface. These must be selected in a way to make possible the representation of the relevant independent displacements and deformations, using at the same time a minimum of parameters.

The problems raised by the specification of constitutive laws for materials, sections, members or subassemblies of structures depend primarily on the stage of behaviour for which the analysis is to be carried out. As far as only the elastic stage is dealt with, there are few problems in specifying constitutive laws, and a small number of parameters will be involved. The analysis of post-elastic behaviour increases dramatically the complication of modelling. One must consider here two aspects with compound effects. One of them is the stress-strain or force-deflection relationship, for which non-linearity, hysteresis, cumulative strength and stiffness reduction etc. must be considered. The other is the multi-parameter nature of the states of stress and of deformation. The literature is little developed in this field. Parametric tests for various structural elements, subassemblies etc. are conducted as a rule for single-degree-of-freedom variation of stress or strain parameters, providing thus only partial direct information.

To close these remarks, it may be mentioned that, if a structure is characterized by dynamic symmetry and its behaviour is analyzed for the elastic stage only, it is possible to consider separately the motion along the degrees of freedom pertaining to sub-spaces that are orthogonal with respect to the properties of inertia, elastic stiffness, viscous stiffness, and to subsequently perform a superposition of effects. In case of non-linear behaviour this approach no longer works and it becomes necessary to consider unique structural models, to account for all degrees of freedom (and, of course, for corresponding, multi-parameter, constitutive laws). To keep such analyses in the range of the feasible, it is of course necessary to adopt a minimum acceptable number of dynamic degrees of freedom. A radical change in this situation cannot be expected for the near future, first of all due to the multi-parameter nature of the problem (different materials, different solutions, different features of the loading cycles). Using existing information and logical inference, combined, may help nevertheless.

3. MODELLING OF SEISMIC ACTION

The modelling of seismic action must consider two complementary basic aspects: the features of ground motion during one event and the recurrence of the seismic action at various levels of severity (possibly also with different spectral contents etc.). The second aspect referred to is less significant for the scope of this paper, yet it is necessary to keep in mind, from this viewpoint, the need of considering for the input to the equations of motion various intensities and amplitudes and, eventually, different predominant frequencies, duration etc. Attention is given further on to the first aspect.

The main categories of representations of seismic action which are relevant for a predictive analysis of structural behaviour and are also currently usable, are:

R.1: stochastic representations (based mainly on second order correlation functions);

R.2: design accelerograms;

R.3: design spectra.

This sequence was chosen because the parameters of one kind of representation may be directly derived from those corresponding to a previous one, while going in the opposite sense raises problems (e.g. target spectrum techniques) for which there is not a satisfactory background. Considering now the representation R.3, which corresponds to the basic approach considered in codes and used in current practice, it must be strongly emphasized that this representation cannot basically account for the non-synchronousness of motion at different points, since all the information provided refers to one point and one component motion. On the contrary, the representations R.1 and R.2 are appropriate for the purpose referred to, in case they rely on appropriate modelling and calibration of corresponding parameters. The basic features of ground motion models can be examined in a convenient way in connection with the representations of the category R.1, due to their analytical character. Such developments may be converted directly into corresponding models or algorithms of generation of design accelerograms (representations R.2). Their use for the improvement of design code provisions, which rely on representation R.3, implies the need of specifications that are additional to the information provided by design spectra.

From a qualitative viewpoint, the seismic motion is three-dimensional for a ground point and it is non-synchronous for different directions at a point and for parallel directions at different points, when the distance between them is not negligible. Time-histories of ground motion could be generated artificially, such as to fit with actual records, in cases when data on source position and mechanism were at hand (such an example was provided by D. Enescu for the record of 1977 at INCERC [1]). Such a detailed analytical approach is nevertheless of limited significance from the view point of the need of predicting ground motions, due to the randomness of location of future earthquake sources and of the features of their detailed source mechanisms. At least, as far as problems of zonation of a territory are to be dealt with, a broader view is necessary.

An approach to be considered is as follows:

a) modelling of ground motion as a multi-component, non-stationary, random, function of time, based on the canonic expansion of non-stationary random functions;

b) postulation of a stochastic model for the stationary random factors of the expansion.

The ground motion along the relevant degrees of freedom of the interface between ground and a structure dealt with can be represented by means of a non-stationary random acceleration vector $W_g^{(n)}(t)$, expressed, according to the canonic expansion, as

$$W_g^{(n)}(t) = \sum_k a_k(t)\, W_k^{(s)}(t) \tag{3.1}$$

where $W_k^{(s)}(t)$ are stationary random vectors, while $a_k(t)$ are scalar envelopes, accounting for the non-stationary character of ground motion. It is assumed that different functions $W_k^{(s)}(t)$ are not cross-correlated.

The components of the vectors $W_g^{(n)}(t)$ and $W_k^{(s)}(t)$ (which are homologous for all off them) may correspond to translational or rotational degrees of freedom. In case one starts from the motion of a continuum, the characteristics of rotational components may be derived from those of translational components, using corresponding partial derivatives [6]. It appears to be reasonable to consider (in case of ground with practically flat, horizontal, free surface and with practically parallel surface layers):

a) homogeneity of the motion with respect to the horizontal coordinates, as well as some kind of isotropy in a horizontal plane, that is described more in detail further on;

b) for the translational components at a point, no correlation between the vertical component and any horizontal component, as well as no correlation between horizontal components along perpendicular directions;

c) for translational components at different points a non-zero cross-correlation, with a tendency of decreasing with increasing distance, which may be quantified in terms of corresponding coherence characteristics (i.e., in the frequency domain);

d) a dependence of the coherence characteristics on similitude criteria that are characteristic for the phenomenon of seismic wave propagation.

A fundamental similitude criterion for the phenomenon of wave propagation is the phase lag criterion,

$$s_\varphi = \omega \frac{d}{c} = \omega\, t_\varphi \tag{3.2}$$

where c is a wave propagation velocity, d is a distance between two points, ω is the circular frequency and t_φ is a phase lag time.

$$t_\varphi = \frac{d}{c} \qquad (3.3)$$

Of course, a more detailed approach will consider the type of waves, the relationship between the relative position of points dealt with and the directions of propagation and oscillation etc.

A type of function that appears to be reasonable in order to characterize the coherence of motion along parallel directions at different points is

$$\rho(\omega,\gamma,t_\varphi) = \exp(-\gamma|\omega|t_\varphi)(\cos|\omega|t_\varphi + \gamma \ \sin|\omega|t_\varphi) \qquad (3.4)$$

$(0 < \gamma < 1)$. This expression is consistent with the model of a wave propagation process, for which the auto-correlation function at a point (of Kanai-Tajimi type) is converted into a coherence characteristic (the role of time coordinate being taken by space coordinates). The partial derivates with respect to space coordinates, that are required in order to derive from the correlation (coherence) characteristics of translational components the corresponding characteristics for rotational components (cross-correlation between a translational component and a rotational one, or between two rotational components) will be derived on the basis of the detailed expressions developed for the distance d (more precisely of its components) and for the various propagation velocities c of (5.3), considered.

This model is, of course, heuristic, but it can account in an acceptable way for some coherence features. It was used in order to derive expressions of participation factors for a 3D analysis in the Romanian code, since 1981 [12]. It was used also for some applied parametric analyses, like that carried out for the new trans-Danube bridges [4], and for generating of multi-component artificial accelerograms [2]. In the latter case an alternative approach was considered too, using a model for which, due to reflection-refraction phenomena, the apparent propagation direction of the spectral components of seismic waves is random (frequency-related random number generator for azimuth directions). This introduced, of course, random phase lags for each spectral component between the motions at different points.

4. VERIFICATION OF STRUCTURAL COMPONENTS.

A consistent verification of structural components subjected to earthquake loading raises highest difficulties, first of all because of the limited knowledge concerning realistic verification criteria. There are two main aspects to be combined:

a) the effect of time dependence, keeping in view the superposition of effects due to repeated stress-strain cycles;

b) the effect of combined stresses-strains (normal force and bending moments etc.), as common for most structural components.

The literature is yet far from providing a satisfactory collection of constitutive laws for the various categories of structural components, so the background of verification rules is quite limited.

The assumption that is implicitly accepted by various engineering approaches, among which the concept of (linear or non-linear) response spectra, is that verification criteria can be related to the instantaneous (extreme) values of some parameters of the state of stress.

In this case the domain for which failure does not occur can be represented in a relatively simple way in the space of parameters describing the state of stress. The condition of no failure means in this representation the non-exceedance of a boundary correspondingly defined by the extremity of a vector varying randomly in time during an earthquake, representing the instantaneous state of stress at a point, for a section, for a structural member etc. The verification under such conditions will rely on an appropriate representation of the vector referred to.

An appropriate representation will be consistent with the category R.1 referred to in section 3 and it should lead to the determination of domains of the states of stress for which the probability of exceedance by the vector of states of stress is limited. In case one accepts the normal distribution of instantaneous values of parameters varying randomly, a good reference is given by their instantaneous root mean square values, which can be defined on the basis of the corresponding variance matrix. In case of linear analysis this can be easily determined starting from the states of stress corresponding to the normal modes. The matrices of instantaneous variance can be represented in this connection by means of ellipses, ellipsoids or hyper-ellipsoids. After determining on this basis r.m.s values in various directions, it must be checked that the figures determined by multiplying the r.m.s values by a convenient factor, leading to a desired non-exceedance probability, do not exceed the boundaries of domains of acceptable loading. Some analytical developments in this connection were given in [8].

This approach can be related to different probabilistic approaches to structural safety (semi-probabilistic, or consistently probabilistic). On the other hand, the definition of variance matrices, r.m.s. values etc. as previously referred to, is consistent with a fixed intensity of ground motion (e.g. with a return period of 200 years),and has consequently a conditional character. In order to define homologous parameters with a specified non-exceedance probability for a definite lifetime of a structure, it is necessary to conduct appropriate convolutions between the conditional characteristics referred to and the characteristics of recurrence of various earthquake intensities.

Another aspect to be considered is that of the possible presence of a significant (random) variation in time of some masses (associated with retained fluids, with live loads etc.) and, also, of some non-seismic loads. In case the distribution in time of these variable quantities is characterized in probabilistic terms, a convolution is to be performed in this direction too [8].

5. CONDUCTING THE POST-ELASTIC BEHAVIOUR.

The impossibility of avoiding post-elastic deformation of usual structures during strong earthquakes and the importance of providing in this event a ductile behaviour are generally recognized at present. Providing ductile post-elastic behaviour implies a design strategy to be thoroughly implemented, such as to provide appropriate ductility to zones pre-established to perform in the post-elastic stage and to protect the other zones from exceedance of the elastic stage. This strategy is referred to as capacity design. The strategy was explicitly adopted in some codes, like [11] or [12], introducing rules of layout, detailing, checking that post-elastic deformation develops in a suitable way etc.

The code provisions developed to date, as in the two cases referred to, [11], [12], are expressed in a way that corresponds to the consideration of a plane structure (e.g. a plane frame), loaded exclusively in its plane. Conditions like those of avoiding the occurrence of plastic hinges in columns, or of limiting the stresses in beam-column joints, are expressed in corresponding terms.

Neglecting of the 3D nature of seismic oscillations and loading may make design rules like those referred to, inefficient, since it is easily possible that beams oriented along the longitudinal and transverse directions of a structure are loaded simultaneously up to their ultimate loading capacity. In this case a column adjacent to a 3D joint will be loaded (if it resists) to the maximum possible bending moments in both planes and, besides this, it is possible that the variation of the normal force (in any sense), due to the linear sum of effects of oscillations in both planes brings the column into a very unfavourable situation, with considerable decrease of bearing capacity to bending, and/or of ductility. The conclusion is that codes must explicitly specify the need of checking columns, for the simultaneous action of oscillations in both planes, in order to avoid the development of unwanted plastic hinges. The same holds, of course, for tangential stresses developed inside the joints in order to transmit the jumps of bending moments between beams and columns adjacent to a given joint. In case one accepts a simplified model assuming uniform distribution of tangential stresses inside the joint, the consideration of seismic oscillations in both main directions leads to the need of determining the quadratic sum of stresses acting in the longitudinal and transverse planes respectively.

6. FINAL CONSIDERATIONS.

The main aspects connected with the spatial nature of seismic action and with its consequences upon design were discussed. The aspects referred to were enumerated in the introduction. The examination of the problems raised puts to evidence the fact that some aspects can be solved without major difficulties, thus leading to an obvious improvement of code provisions, while other ones require yet research. The main directions for which research is necessary are:

a) development of constitutive models for materials, elements or other structural components, to account simultaneously for the behaviour under cyclic loading (seismic type) and, also, for the multi-parameter nature of the states of stress and deformation of components referred to;

b) development and calibration of stochastic models of seismic action, to account in a more thorough way for the coherence characteristics of ground motion;

c) techniques of practical verification of structural components, considering the random walk of the points representing the instantaneous states of stress, of internal forces etc.;

d) criteria of resistance of columns, column-beam joints etc. in cases of combined loading due to oscillations along various directions, such as required for a thorough approach to capacity design.

It is obvious that all directions of research referred to require considerable efforts, in most cases of a cooperative nature.

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SİSMİK HAREKETİN DEĞİŞKENLİĞİNİN TASARIMA YANSIMASI

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Genelde sismik hareketin uzaysal yapısı anlaşılmasına rağmen bunun şartname ve mühendislik uygulamalarına yansıması çok sınırlı kalmaktadır. Bu ise deprem hareketinin yapı üzerinde oluşturacağı etkinin gerçek anlamda incelenmemesine neden olmaktadır. Bu nedenle ayrıntılara gidilebilmesi için yapının ve sismik hareketin modellenmesi, yapıyı oluşturan elemanların tanımı, projelendirme ve uygulama sırasında kullanılan tekniklerin iyi seçilmesi gerekir. Her bir faktörün iyi incelenmesi deprem şartnamelerinde olan eksikliklerin giderilmesine olanak verecektir.

Bu nedenle araştırmaların iyi yönlendirilmesi gerekir. Özellikle araştırmalarda yapı elemanları için çok parametreli, lineer olmayan bünye denklemlerinin geliştirilmesi, farklı noktalarda olmayan yer hareketinin kalibrasyon parametrelerinin belirlenmesi, karşılıklı etkileşim sınırlarında çok parametreli gerilme durumlarının kontrolü için tekniklerin geliştirilmesi, uzaysal yüklemelerde kiriş - kolon birleşim yerlerinde ve kolonlarda kapasitenin incelenmesi gerekmektedir.