PORTUGUESE STUDIES
ON EARTHQUAKE RESISTANT STRUCTURES

by

J. Ferry Borges*

1. INTRODUCTION

After the earthquake which destroyed a great part of Lisbon in 1755, reconstruction needs made it necessary to study a new type of building structure which could withstand, better than the plain masonry so far used, the destructive action of seisms.

Rough model tests were carried out in the open air at Lisbon main square (1), in which a platform, which replaced the present day shaking table, was struck by numerous soldiers armed with enormous hammers. From the experience thus achieved, it was prescribed that buildings should include a wooden frame consisting of horizontal and vertical members braced with diagonals. These frames were encased in masonry, the whole being sufficiently bonded to withstand seismic actions. These provisions formed what is believed to have been the first building code on earthquake resistant structures (2).

For more than a century and a half, building construction in Portugal complied with the rules laid down after 1755. It was only some decades ago that the generalized use of reinforced concrete made it possible to solve the problem in new bases.

Aware of the importance of the problem, Portuguese engineers decided to organize a symposium commemorating the 2nd centennial of the Lisbon earthquake of 1755, in which aseismic building problems were widely discussed (3). In 1956, the Portuguese Government appointed a committee to prepare a new code on earthquake-resisting structures which was issued in 1958 (4).

By means of a close co-operation between seismologists, geologists and engineers, a seismic map of the country was prepared. On plotting this map the following parameters were taken into account: most likely location of epicentres (between Azores and the Continent), seismic history in special as regards the two last centuries (the first informations on earthquakes in the Iberian Peninsula are about 2,400 years old), geological factors, particularly those concerning the nature of soils, and additionaly a global assessement in comparison with other

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areas, bearing in mind the seismic actions prescribed for those areas.

A translation of the above-mentioned Portuguese Code on Earthquake Resistant Structures as well as the map of seismic areas included therein, were sent under separate cover to the Organizing Committee of this Conference.

The basic design criteria for aseismic structures are discussed in this paper which also refers how such criteria were adopted in the Portuguese Code.

Some experimental studies on seismic actions on buildings, carried out or about to be undertaken at the Laboratório Nacional de Engenharia Civil, are also described.

2. QUANTIFICATION OF SAFETY

Among the forces acting on a structure, those due to earthquakes more than any other require that the basic notions which make possible a quantification of safety be carefully considered.

Design criteria will not be thoroughly scientific in all their stages unless a quite objective definition of safety can be achieved. For that, it is indispensable to think very carefully beforehand on the aims to be attained.

Political and social consequences of structural safety (5) being deemed outside the scope of the present paper, only economic criteria such as cost and utility shall be used as bases the considerations below.

We are thus led to think that a structure should be designed so as to minimize its generalized cost (in which all possible consequences of a collapse should be taken into account) during its anticipated life.

This cost will then consist, as a rule, of different items and while some of them can be considered to assume definite values, others particularly those concerning possible consequences of a collapse are obviously uncertain. Costs due to collapses resulting from earthquakes are particularly uncertain.

Notice that it does not by any means follow that, because a magnitude is uncertain, it can be considered with sufficient accuracy as random.

Let us then, first of all, discuss which scheme of knowledge is more adequate for studying the phenomena, the decision rules to be adopted depending on the scheme of knowledge selected. Due to their particular importance two main models are considered: random and strategic.

When the random model is adopted, the decision rule consists in minimizing the sum of the expected costs, each of which is the product of a cost by its probability.

When the strategic model is adopted the decision rule would consist e. g. in the minimax criterion in which it is tried to minimize the maximum value of the cost corresponding to the different possible situations.

The adoption of statistical models implies a knowledge of the probabilities of occurrence of earthquakes of different intensities. Unhappily our knowledge in this field is very limited as regards many areas of the world.

When the probability of ocurrence of earthquakes of different intensities is known (since what is required is the probability of collapse of a given type of building), this probability has to be carefully associated with the probability of the structure to undergo a collapse of a given type for a given earthquake intensity.

If the intensity of the seismic force is measured e. g. by the maximum displacements undergone by a point of the structure, the problem may be reduced to determining the probability of occurrence of displacements above a given value during the life of the structure.

In a paper presented at the V Congress of the International Association of Bridge and Structural Engineering (6) it was shown that, assuming that the expected number of earthquakes $\lambda(K)$ is related with their magnitude K by the law suggested by Gutenberg and Richter (8)and that the maximum displacements have a Gaussian distribution — so that the probability of displacements above x for a seismic intensity K is $\phi(x,K)$ —, the expected number of times I that the maximum displacement of the structure would exceed x could be calculated by the expression

$$I = \int_0^\infty \phi(x,K) \, d_K \lambda(K)$$

By integrating this expression and neglecting some minor errors, the following result is obtained: the expected number of times that the displacements of a structure will exceed x equals the expected number of earthquakes more intense than the earthquake which on average causes the same displacement x.

Hence the practical conclusion: what is required is to know the mean value of the parameter defining the reponse of the structure to seismic actions of different intensities. From this and the probability of occurrence of earthquakes of different intensities, the probability of each seismic force during the life of the structure can be calculated.

If a strategic model is to be adopted, it is unnecessary to have so detailed an information and the decision can be based on the analysis of selected situations. Consequently decisions supplied by this model will be as a rule, less adequate. An example of application of the minimax criterion for chosing the most suitable structural type for a group of dwellings to be built in a seismic area was presented in a previous paper (5).

3. CRITERIA FOR DEFINING STRENGTH

The definition of seismic forces cannot be separated from the method of structural analysis adopted. This is possible for current static actions which can be considered as well defined forces,it being possible to determine the strength of a structure under their action by means of elastic or plastic criteria.

A preliminary discussion of the advantages of elastic and plastic criteria in current cases can serve as a guide for the particular case of seismic actions. The chief difference between these methods, as regards the definition of strength, can be summarized as follows.

The elastic method is adequate to study the structural behaviour in stages sufficiently remote from total collapse. It is thus particularly suited for studying the structural behaviour under the most likely actions. As a rule,displacements,the appearance of cracks and even early stages of rupture can be predict with satisfactory accuracy.

Plastic methods, on the other hand, make it possible to predict with accuracy the force inducing total collapse.They are thus more adequate for studying less probable actions. Nevertheless plastic methods are not yet sufficiently developed so far, for general application in dynamical or repeated phenomena.

It is considered that for seismic actions what matters above all, from an economic point of view, is to prevent a total collapse. Consequently the statements above show that limit design methods would be the most adequate. On the other hand, seismic actions have an essentially dynamic character which is difficult to take into account in a limit design method.

After all,the most adequate methods to assess the strength of a structure for seismic actions are possibly those based on its capacity to absorb energy (7). Nevertheless the investigation of this criterion is still in an early stage.While it is obviously advisable that further studies are undertaken in this field, there is no doubt that, from a practical point of view,design has yet to be based on elastic or plastic theories.

Such theories being adopted it is convenient to follow the traditional method of transforming seismic actions into equivalent static actions for which the structure is then designed by usual methods; the problem is thus decomposed and simplified.

There is no doubt tha ormations have been obtained assuming an elastic beh tion of static forces equivalent to seismic actions.I ess, that a design by means of these forces should not lastic but on a limit design criterion. This of course ermined by the elastic methods are duly corrected. Althou m solution, this duality of criteria is sufficiently c nstitutes the first step for a complete analysis of the iour by means of plastic criteria.

The simplest method to take seismic actions into account consists in defining seismic coefficients, safety being secured by a suitable choice of the safety factors.

4. CHOICE OF SEISMIC COEFFICIENTS AND OF SAFETY FACTORS

In order to make sure that the safety purposes in view will not fail to be achieved, the choice of seismic and safety coefficients has to be carefully considered and, as far as possible, turned into a quantitative determination.

Let us see, in the first place, the possible policy to be followed in this choice. Two opposite criteria are possible. One consists in the adoption of small seismic coefficients and of safety factors approximately equal to the usual ones. In the other, seismic coefficients are high but safety factors low, about the unity.

In a first approximation it would seem that both criteria are to a certain extent equivalent. In fact they are not so. Adopting one or the other criterion has widely different consequences for the design. This is due to the fact that the total action to be considered is a sum of the actions due to gravity (permanent loads) with those due to the earthquakes.

Since, in seismic actions, what matters above all is that no collapse occurs, the behaviour of the structure under strong seismic forces has to be analysed, as the structure behaves quite differently in this case and under the action of small horizontal forces.

As an instance of the adoption of one or the other criterion, let us consider a reinforced concrete frame (fig. 1) made up of a beam and two columns each with a normal force N = 100 t. The initial moment at the top section of the columns can be made to vary within wide limits, according to the construction method adopted. Thus assuming that the beam is first built as hinged and then tied together to the columns, the moments at the top of the columns are null, $M = 0$. If both elements are initially tied together, M may be high.

For each initial value of $M = i\,N$ there corresponds a percentage of reinforcement which for usual reinforced concrete assumes the values shown in curve 1 of fig. 2. These percentages of reinforcement were computed assuming a permissible compressive stress for concrete of 75 kgcm-2.

Let us determine the percentages of reinforcement in function of the initial moments, when seismic actions are considered. The two referred criteria are applied, the action of an horizontal force at the beam, $F = 2\,c\,N$ being considered. The moments due to F have to be added to M in order to determine the final percentages of reinforcement.

First, a seismic coefficient $c = 0.06$ and an increase of the permissible stress in concrete of 1/3 are adopted. The percentages of reinforcement indicated by curve 2 are thus obtained. It is seen that for values of $i < 6$ cm, that is for small initial moments, no increase of reinforcement is obtained and one is limited by the minimum percentage of reinforcement indicated in the codes without considering seismic forces. As the initial eccentricity increases the corresponding percentage of reinforcement increases very fast and for $i = 10$ cm it exceeds by about 60% the percentage required to resist the initial moment. For the value of $i = 16$ cm the initial and final percentages become equal.

If a seismic coefficient $c = 0.20$ and a permissible stress double the usual one are adopted, curve 3 is obtained. In this case even for $i = 0$, a percentage of reinforcement of 1.7 % is obtained and the increase of this percentage in function of the initial eccentricity is much slower.

If instead of an elastic design we adopt a plastic design with the same value of $c = 0.20$, a horizontal line is obtained represented by 4 in the same fig. 2.

As the ultimate bending moments of the columns are approximately proportional to the percentage of reinforcement, this example shows that when small seismic coefficients and small increases of the permissible stresses are adopted a design is obtained that in some cases corresponds to insufficient strength to horizontal forces.

On the other hand, high seismic coefficients and high increases in the permissible stresses (leading to stresses near the ultimate point) yields a much more balanced design. If a limit design criterion is adopted, the initial moments can be neglected as in fact, due to the plasticity of the structures, they can have no influence on the value of the force F making the structure to collapse.

The preceding case is a typical instance of the following general statement. The most adequate design method, among the general criteria of adopting seismic coefficients, consists in using a limit design method with a safety factor near 1, and seismic coefficients high enough to ensure a sufficiently small probability of collapse.

Even if limit design is not adopted, it is necessary to admit high increases in the permissible stresses, the seismic coefficients being chosen in accordance with these increases.

This general design criterion adopted in some codes was also prescribed in the recently issued Portuguese code.

5. EXPERIMENTAL STUDIES

Some structural studies, static and dynamic, have been carried out in the later years at the Laboratório Nacional de Engenharia Civil with a view to determine the capacity of structures to withstand seismic actions.

Fig. 3 shows the structural model of a building being tested to investigate its resistance to horizontal forces. This is a reinforced concrete model, to a scale 1/2, of a special type of structure without cross beams. It was investigated up to what extent the moments transmitted by the columns were taken up by the slab and how efficiently longitudinal beams subjected to torsion behaved. Different model tests were carried out with slabs of reinforced concrete and of prefabricated, prestressed elements. In the latter case it was also sought to study the behaviour of connections between the prefabricated and the in situ concreted elements.

The tests showed that this structural type, by means of which ceiling beams are not apparent, could present sufficient resistance to horizontal forces if the longitudinal beams are conveniently designed to withstand torsion, notably near the columns.

Dynamic tests are at present under way on models of dams and other structures. Vibrations in these tests are applied by means of an electro-dynamical shaker which can produce forces up to 1,300 kg (3,000 lb) for frequencies ranging between 10 and 1500 Hz. This shaker is operated by a 10 KVA amplifier in which sine waves or random pulses can be introduced. For low frequencies a mechanical vibrator of eccentric masses is also used. Sinusoidal vibration tests have, above all, the purpose of studying the behaviour of structures in the elastic stage and random pulses of horizontal velocity sepectrum, reproducing real earthquakes, are specially used for studying the ultimate dynamic strength. Spectral analysis of the records is made by electric and analytical methods, an electronic computer being used in the later case.

6. CONCLUSIONS

For the design of earthquake resistant structures, the adoption of limit design methods with safety factors near 1 is recommended and justified. The values of seismic coefficients have to be selected so as to obtain a conveniently small probability of collapse. Seismic coefficients should thus be selected by means of statistical criteria taking duly into account the behaviour of the structure, the characteristics of the soil and the seismicity of the area. Strategical criteria can also supply useful decision rules notably when the available information in scarce.

The observation of real structures during and after earthquakes and model studies in which vibrations similar to those actually occurring in earthquakes are used can give, in parallel with analytical studies, a very valuable contribution towards the improvement of design methods for aseismic structures.

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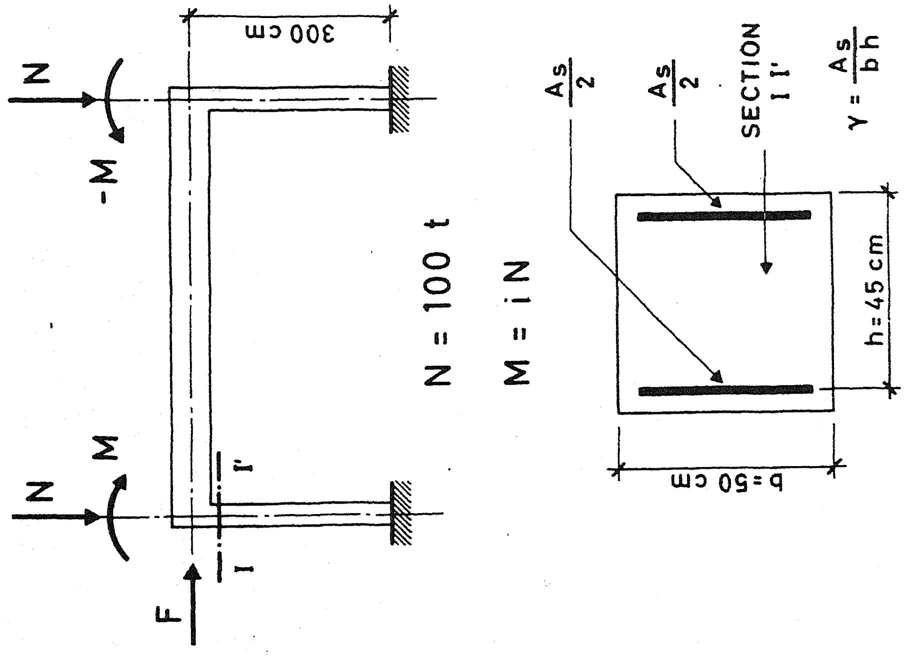
N
M
-M
N
F
I
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300 cm
N = 100 t
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As/2
As/2
SECTION I I'
Y = As/bh
h=45 cm
b=50 cm

Fig. 1

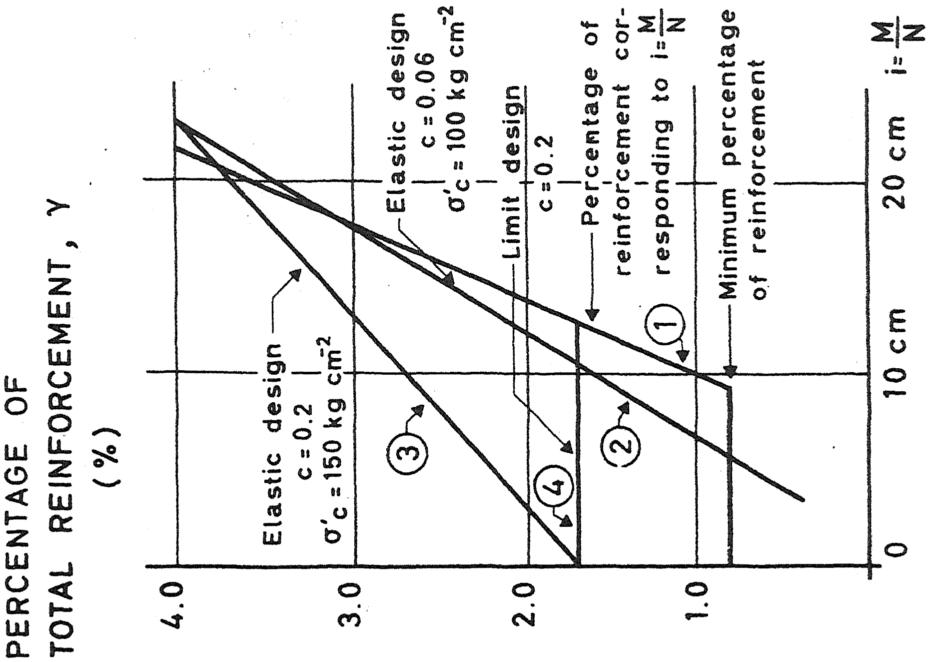
PERCENTAGE OF TOTAL REINFORCEMENT, Y (%)
4.0
3.0
2.0
1.0
0
10 cm
20 cm
i = M/N
Elastic design c = 0.2 σ'c = 150 kg cm^-2
Elastic design c = 0.06 σ'c = 100 kg cm^-2
Limit design c = 0.2
Percentage of reinforcement corresponding to i = M/N
Minimum percentage of reinforcement
①
②
③
④

Fig. 2

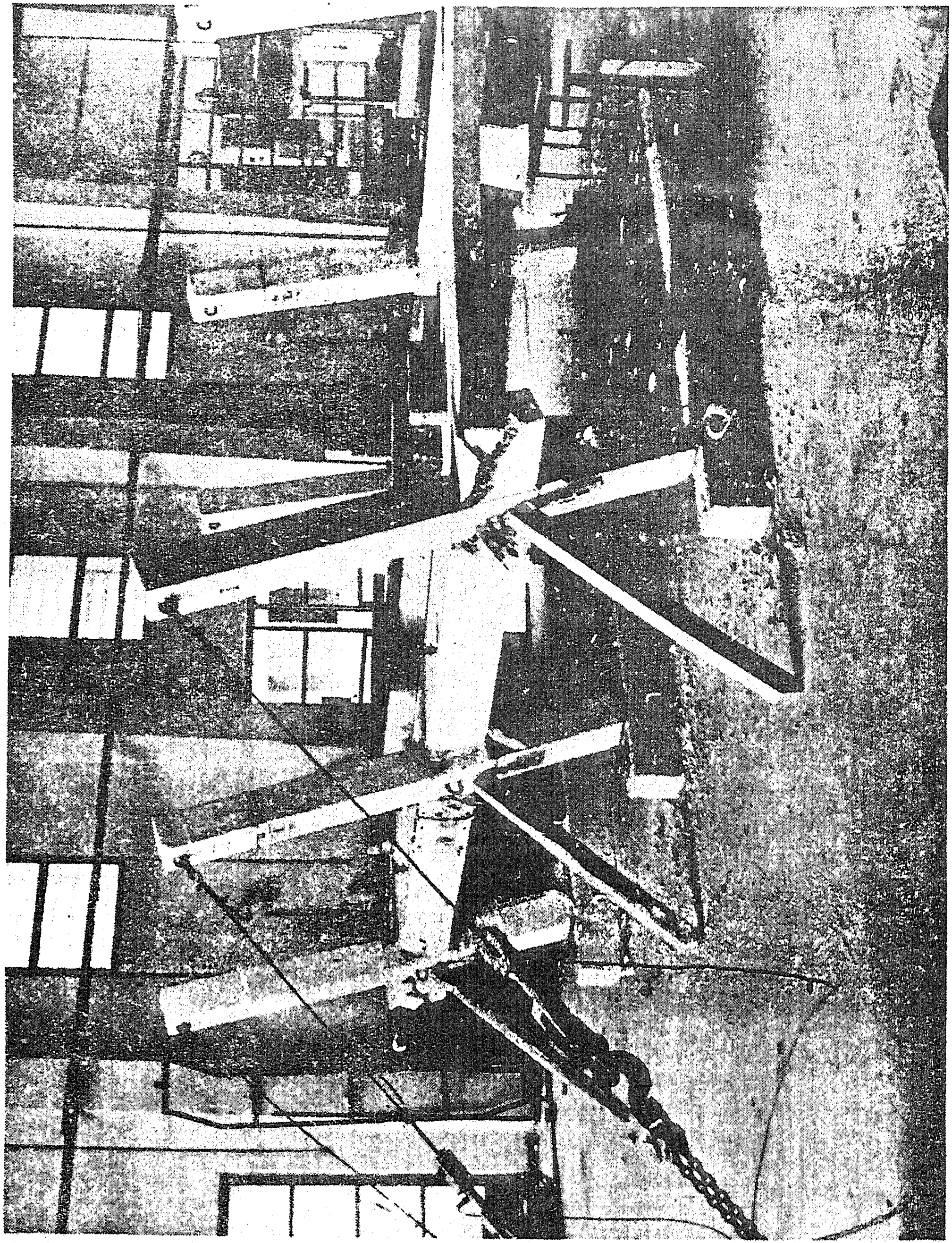

Fig. 3

DISCUSSION

G. W. Housner, California Institute of Technology, U. S. A.:

The calculated seismic coefficients for damaged buildings in Agadir are very interesting and I should like to inquire as to the method of determining the ultimate stresses used in the calculations?

J. F. Borges:

The buildings have been computed in accordance with the Portuguese code, that is, adapting for the steel and the concrete ultimate stresses corresponding to the minimum value of the yielding and compressive ultimate stress usually used. To judge the mechanical properties some samples were taken and also some measurements with a sclerometer were made. The ultimate moments were computed in accordance with the real dimensions of the elements.

It was so possible to obtain seismic coefficients for different buildings and simple structures, and these coefficients can be directly compared with those indicated in the codes.

As the slides show the behaviour of these reinforced concrete structures was very similar. At the final stage, at one storey, the curtain wall is completely destroyed and only the structure remains. Plastic hinges are formed at the top and at the bottom of the column. This shows that limit design really applies.

In most cases the seismic coefficients of the structures that did not fail range between 0.10 and 0.20, but, even so, these structures were much damaged.