Earthquake Engineering, Tenth World Conference © 1994 Balkema, Rotterdam. ISBN 90 5410 060 5

Shaking table testing of structures

R.T. Duarte, M. Ritto-Corrêa, C.T. Vaz & A. Campos-Costa
National Laboratory for Civil Engineering, LNEC, Lisbon, Portugal

ABSTRACT: This paper presents, in the light of LNEC experience in Earthquake Engineering studies, the limitations and advantages of shaking table testing of reinforced concrete and masonry structures. It starts with a general assessment of the contribution of shaking table facilities to the mitigation of earthquake risks and proceeds with a discussion of some specific problems of shaking table performance and testing procedures, like shaking table design alternatives, self-tuning control and numerical evaluation of testing strategies.

1 INTRODUCTION

1.1 *Scope*

This paper discuss the present understanding in LNEC of the limitations, possibilities and purposes of shaking table testing in the field of earthquake engineering, with emphasis in the evaluation of the behaviour and safety of reinforced concrete and masonry structures.

Recent papers have dealt with shaking table testing either from a more general (Buland, 1972) or from a more technical (Clark, 1992) viewpoint.

1.2 *LNEC experience*

LNEC activity in the field of earthquake engineering started in the early fifties and is characterized by the development of analytical and experimental studies concerning fundamental research, the study of specific structures, and the elaboration of standards and codes. Analysis and evaluation of earthquake stricken zones have also been made in several occasions.

Experimental studies started in 1960 with an electrodynamic shaker (15 kN, 5-5000 Hz) which was used mainly for the tests of dams models (Ferry Borges et al., 1963). Presently the main experimental facilities comprise an uniaxial horizontal shaking table ($3.26 \times 2.26m^2$, in operation since 1972) and a vertical shaking table ($2.65 \times 1.60m^2$, in operation since 1977) powered by servocontrolled hydraulic actuators, hereafter referred to as servo-actuators; there are also testing rigs for beam column assemblages, masonry panels and dam models; specially develloped software is available for control of the equipment, and data acquisition and processing.

Those shaking tables have been used mainly in civil engineering studies, and in certification of electrical equipment, namely of control cabinets for nuclear power plants (Vieira Pinto et al., 1987). A large ($5.6 \times 4.6m^2$) triaxial shaking table, partially funded by the European Community Large Instalations Programme, is planed to start operating by the begining of 1993. Researchers specialized in mechanical systems, control systems, data acquisition and processing, experimental methods and computer science are available to support the testing activities.

In regard of analytical studies, the main computer codes perform linear and nonlinear analysis of structures; structure-water and structure-soil coupled problems are dealt with; stochastic and step-by-step integration methods are widely used; pre- and post-processing programs are available (Pedro et al., 1988).

Recent and on-going studies include the experimental investigation of the earthquake behaviour of beam-column assemblages and masonry panels, analytical and experimental analysis of arch-dams, basic research work on the quantification of behaviour factors through nonlinear computer analysis of buildings and bridge structures. LNEC is also actively collaborating with the National Civil Protection Agency and the City Council of Lisbon in earthquake risk mitigation programmes.

2 MITIGATION OF EARTHQUAKE RISKS

2.1 *Purposes of earthquake engineering*

From an appropriately inclusive viewpoint the purposes of earthquake engineering are:

(a) To design, build, inspect, strengthen and repair structures in conditions of economy and efficacy socially acceptable;

(b) To contribute to the formation, development and enforcement of policies aimed at the reduction of earthquake risks, in special those derived from damage or collapse of structures;

(c) To support the establishment of cultural values that facilitate the implementation of safety measures against earthquake losses.

The activities described in (a) are the traditional engineering activities. However, it is added that they should carried out in such a way that they do not unnecessarily interfere with other purposes of the structure, like functional needs and aesthetic requirements; and not only this should be achieved but also it should be shown to be so.

The activities described in (b) are not profissional activities of the earthquake engineer *qua* engineer but are his duty *qua* citizen of a given state. In effect, earthquake engineering should contribute to public education on earthquake hazards and should support the establishment and strengthening of risk mitigation policies (Press, 1984) at a national or international level. Simillarly the activities in (c) transcend those in (b) and suppose: i) politics are, at least partially, in service of cultural values; ii) cultural values are not imutable and can, and sometimes should, be changed. The importance of cultural values in the perception and acceptance of risks has been recently emphasized (Dake and Wildavsky, 1990).

2.2 *Contribution of shaking table studies*

After each strong seismic event the knowledge on the earthquake response of structures is greatly increased by the observation and analysis of the behaviour of the different types of construction. The new knowledge is, in general, rapidly incorporated in the relevant codes through the revisions that are almost always carried out after a destructive earthquake. Even if very valuable, the information coming out of the observation of buildings that were subjected to a strong earthquake is not systematic, is not adequately documented and the response of the structures is the result of many unknown parameters: input motion, original structural characteristics, pre-earthquake damage (due to foundation settlements, previous earthquakes, absence of maintenance...), interaction with other structures, etc. The only method that can provide reliable results is the test of structures, or members of structures, on shaking tables. Furthermore, shaking table testing is the only way to evaluate directly the performance of some structural systems that are **very common in some earthquake zones (e.g. masonry** infilled reinforced concrete frames) which are much influenced by the dynamic and spatial character of the earthquake action.

In the case of natural disasters that have a large return period, like strong earthquakes, the perception of risk, of the need to take appropriate mitigation measures and of the efficacy of those measures, has a strong cultural component. The films and photographs obtained during shaking table testing are a good contribution to the support of the policies needed to mitigate earthquake risks. Attendance of shaking table tests by public officials is also important because they can have a direct perception of the intensity of possible earthquake vibrations and of the effective resistance of properly designed and constructed structural systems.

3 SHAKING TABLE DESIGN

3.1 *Some remarks about seismic testing*

The checking of safety against earthquake actions envolves, as pointed out by Ferry Borges (1980), some basic concepts: requirements, performance criteria, system behaviour, probabilistic reliability, hazard scenarios and quality assurance. All these concepts have some relevancy on the performance of seismic testing and, hence, on the design of shaking table facilities. Requirements specify the conditions that a system is expected to satisfy in accordance with its intended use; performance criteria are statements about the required properties of systems and components so that they will satisfy their intended functions. Probabilistic reliability may mean either the degree of rational belief or the antecipated frequency of occurrence that the system subjected to the actions due to its environment and to its operation will satisfy its performance criteria. Hazard scenarios are obtained from a reformulation of the probabilistic reliability assessment, this reformulation arising from the adoption of appropriate inference principles. Quality assurance refers to the "theory" justificating the operational procedures responsible for carrying out the safety checking.

The concepts underlying the safety checking procedures are all relevant to the design of shaking table facilities. In effect, it is not possible to separate the different components of a nonlinear problem without introducing errors. However for the design of the shaking table the most important concept is the hazard scenario one, because shaking table testing should be considered as the materialization of an hazard scenario (Jervis Pereira et al., 1985). It may be noted that the optimization of the quality assurance process itself requires that the specification of seismic test procedures should take into account the large uncertainties characteristic of our knowledge about future seismic actions; thus excessive precision should not be asked from a seismic testing facility; however this should not mean that it is not necessary to know accurately what happens during a seismic test.

The materialization of an hazard scenario envolves two types of problems: i) the assurance that the test specimen is supported during the test in **realist conditions**; ii) the imposition of the desired motion to the base of the test specimen. The first problem envolves the stiffness of the shaking table; the second the conception of the guiding and control systems. It is assumed that the models to be tested will always large enough to be near the performance limits of the shaking table, because the reliability of the results from reinforced concrete and masonry models do much increase when the scale factor approaches unity.

3.2 *General considerations*

The design of a three degrees of freedom shaking table may be considered as composed of a "testing platform", a "guiding system" and "actuators" (Emilio et al., 1986). The platform is a very stiff structure to which the test specimen is fastened. The guiding system task is to make sure that the platform moves only along the required degrees-of-freedom. The actuators are the active driving elements but, in some designs, they also fulfill guiding functions. Perhaps the major problem in an earthquake simulator is to ensure that the motion of the shaking table presents the desired characteristics despite the perturbating forces due to the test specimen base reaction; a good discussion of the capacities and limitations of modern actuators may be found in Kusner et al., 1992. This problem can be dealt with in two ways: i) by generating a time history of acceleration with the desired characteristics and then making the motion of the shaking table to following closely this time history; ii) by specificating the earthquake motion by a spectrum, start with a reasonable estimate of the signal input to the actuators and work out iteratively sucessive corrections, until sufficient approximation is achieved (section 4). This second way is, in principle, only applicable to linear systems; the first one must be resorted to when there is significant non-linear behaviour and it implies a real time adaptive control servosystem. Thus it is advisable that the guiding system should decouple the shaking table degrees of freedom (dofs) in order to facilitate the task of the actuators driving systems. In effect if the actuators responsible for the vertical vibration have also to cope with the overturning moments due to horizontal accelerations, they will be subjected to perturbating vertical forces (due to those overturning moments) that in general will be significantly larger than the vertical forces needed to produce the vertical motion, giving rise to difficult control problems. These control problems can be avoided if the translational and rotational dofs are decoupled by a mechanical system which is a very favourable situation from the viewpoint of the control. It is considered that presently the control aspects are the more delicate part of an earthquake simulator (Carvalhal, 1987) and that much effort should be dedicated to its minoration. In consequence, this paper only discusses shaking table designs with uncoupled dofs.

These designs may be classified as "additive designs", i.e. those in which the desired number of dofs are built sucessively through linear motion mechanisms, or as "subtractive designs", i.e. those in which the unwanted dofs are eliminated through suitable mechanisms. The designs will also be evaluated in regard to the possibility of eliminating the vertical dof for the testing of very heavy models, and will assume that the shaking table is to be driven by four 400 mm stroke actuators, three with a force capacity of 300 kN and one with a force capacity of 1000 kN. Those actuators were a donation to LNEC from the British Government, under a Technical Cooperation Program and their characteristics were selected taking into consideration that they also would be used for static (repeated loading) and pseudo-dynamic testing.

3.3 *The "additive designs"*

Two "additive designs" were considered. In design A the platform moves vertically with respect to a structure which can move in the horizontal directions. In design B the platform moves horizontally with respect to a structure which can move in the vertical direction. In this section only the guiding systems will be discussed; the platform design will be discussed in the next section.

Figure 1 presents the mechanical layout of design A. It consists of a very stiff square grid structure suspended at the vertices by four 4.1 m long connecting rods. From near the vertices four stiff rods rise like the edges of a pyramid having at the vertex a massive structure housing the outer part of a journal bearing. The inner part of this bearing is part of the rod connecting the piston rod of the vertical actuator to the platform. The vertical actuator is supported by the square grid structure through the inner part of another journal bearing, whose outer part is the vertex of an inverted pyramid-like structure of four rods rigidly connected to the platform. Thus vertical movement of the platform is achieved. Platform rotation around the vertical axis defined by these two journal bearings is restrained by a small system (not shown in the figure) comprising two cranks and a connecting rod. A similar system is used to eliminate rotation of the square grid structure. The horizontal motion actuators are directly connected to the platform.

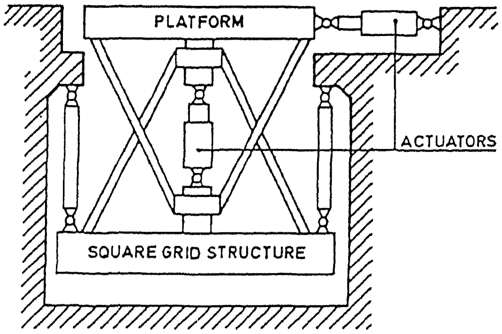

Fig. 1 - Schematic representation of design A.

The main difficulty found in this design is how to provide sufficient stiffness under the vertical actuator, which actuates at the center of the square grid structure. It was not sufficient to have its members as truss girders, so four suspending rods (not shown in the figure for the sake of clarity) coming from near the higher journal bearing to near the base of the actuator were considered. However this solution would cause a very difficult access to the vertical actuator. It should also be pointed out that since the overturning moments due to horizontal accelerations give rise to horizontal forces acting on the journal bearings, this bearings have to be very large. On the other hand, this kind of bearings involves expensive technology manufacturing, and delicate and time-consuming mounting and alignment procedures.

When testing very heavy models the outer part of the lower journal bearing could be fastened to the square grid structure, to eliminate the vertical motion; when testing includes vertical movement, it is possible to introduce air springs between the bearing and the structure to support the dead weight of the model and platform, thus facilitating the function of the vertical actuator driving system.

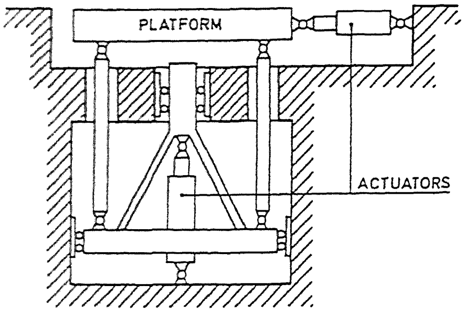

Fig. 2 - Schematic representation of design B.

Figure 2 presents the mechanical layout of design B, which is not so heavier as design A. It consists of a pyramid-like tubular structure moving along the vertical direction and guided by hydrostatic pad (plane) bearings at the base and the vertex, where it is acted on by the vertical actuator.

Four of them are located at the vertex and eight at the base, this last number being needed for eliminating rotations around the vertical axis. On the four vertices of the base of the pyramid-like structure are linked four vertical connecting rods that allow the horizontal motion of the platform, which is driven directly by the horizontal actuators, as in design A. The weight of the shaking table plus model may be supported by air springs located at the four vertices of the pyramid-like structure, directly below the connecting rods. Those springs may be substituted by stiff blocks, to fasten the pyramid-like structure to the foundation, eliminating vertical motion when testing heavy models. The main problem with this design stems from the high precision alignment of the twelve hydrostatic pad bearings and also from the cost of the bearings themselves.

3.4 *The "subtractive design"*

It was found that the subtractive design constitutes a preferable alternative to the additive designs. In the subtractive design, the rotational dofs are eliminated by torque tube systems (figure 3), one for each dof. This system is composed by a torsionally very stiff torque tube (1200 mm diameter and 20 mm thickness for the torque tubes restraining rotations caused by the overturning moments) which can rotate around its center line and is supported at both ends by two vertical supports (so called because they have mainly to resist vertical forces); at each end, a crank links the torque tube to a stiff connecting rod, which is also linked to the platform. The two spherical swivels at each end of the connecting rod allow horizontal motion of the platform. When the platform moves vertically, it either pulls or pushes the connecting rods, then both cranks rotate the same angular amount and so does the torque tube; thus, no forces whatsoever arise. But if there is an overturning moment and the platform starts to rotate, then vertical movement in opposed directions appears at the upper end of the connecting rods, which cause opposed rotation of the cranks, only possible through torsional deformation of the torque tube. Since the torque tube is very stiff, a very large reaction force opposes a very small platform rotation. To illustrate the efficiency of these systems it may be mentioned that a 20 ton model with a natural frequency of 10 Hz on an undeformable base will have a natural frequency of 7.4 Hz when supported by the shaking table. Furthermore all the main "flexibilities" that contribute to test specimen base rotation about horizontal axis are of the same order of magnitude. These flexibilities are (Emilio et al. 1989):

1) the platform deformation (10 - 35%);
2) the axial deformation of the connecting rods (20 - 30%);
3) the bending and shear deformation of the crancks (13 - 20%);
4) the torsional deformation of the torque tube (31 - 38%).

It should be mentioned that when control actuator technology will be developed enough, it is possible to insert a short stroke actuator (i.e. a very stiff actuator) in one connecting rod (or in the two connecting rods to preserve symmetry) to eliminate the flexibilities of the torque tube system.

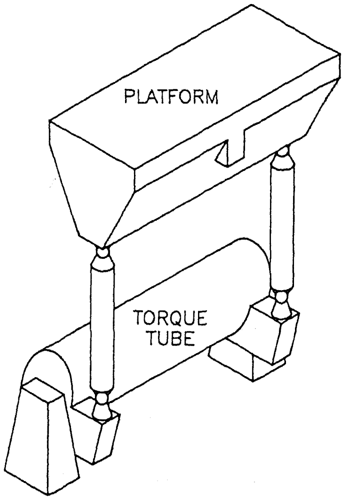

Fig. 3 - Schematic representation of a torque tube system.

It also shall be pointed out that the overall flexibility of a torque tube system is smaller than the flexibility of a pair of vertical actuators, unless the actuators have a small stroke and a large piston area; a small stroke poses obvious restrictions on displacement requirements, which are unacceptable in a shaking table for testing reinforced concrete structures up to collapse, and a large piston area implies huge oil flow, regarding velocity requirements, and thus quite expensive hydraulic power supply.

On of the advantages of the torque tube system is that it only involves articulated mechanisms, as opposed to the other designs which have sliding mechanisms. Experience have shown that sliding mechanisms should be realigned after each heavy test, which needs difficult and lengthy procedures.

Obviously a torque tube system only eliminates rotations around an axis orthogonal to the torque tube axis and paralel to the cranks direction; so, two horizontal torque tube systems with horizontal cranks are set under the platform, in mutually orthogonal directions, to eliminate rotations about horizontal axes. A third horizontal torque tube system, with vertical cranks, is located on the side of the platform to eliminate rotations about the vertical axis and since the torsional moments are much smaller than the overturning moments, this last tube system is not so large as the other two. The arrangement of the three torque tube systems is shown in figure 4. Between the underside of the cranks and the base, can be mounted either passive hydraulic actuators to cope with the weight of the shaking table and of the test specimen, or rigid blocks to fasten the cranks to the base, thus eliminating vertical motion of the table; the purpose of this last option is to enable performing the testing of heavy models (>400 kN).

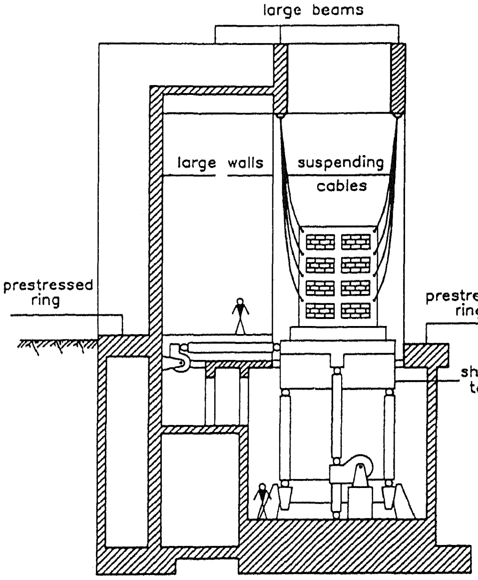

Fig. 4 - The shaking table building

3.5 *The shaking table building*

The effective capacities of an earthquake simulator do not depend only of the type of shaking table but are also dependent from the characteristics of the building where it is installed. In the case of the LNEC triaxial shaking table the building and the table were conceived as a single integrated system to test up to collapse heavy models (200-300 kN). This system was designed to optimize the "test cycle" which comprises the construction of the model, its colocation over the shaking table and instrumentation, its vibration test and its removal.

The special structure around the shaking table is composed by a multi-cellular reinforced concrete structure (figure 4) connecting a 2m-thick prestressed reinforced concrete slab (which supports the vertical actuator and the two torque tube systems that eliminate rotations around horixontal axis) with the prestressed ring which supports all the horizontal actuators and the small torque tube systems that eliminate rotations around a vertical axis. Over the prestressed ring there are three reinforced concrete walls with a shallow U-section, which will be used as support for measuring displacements; they can also be used as "reaction walls" for small forces (up to 50 kN). Those walls are continued over the roof by 3.30 m high 0.6 m thick beams which meet over the shaking table; there are 8 fixation points with an individual capacity of 200 kN and a total capacity of 800 kN. From those fixation points will hang the suspending cables that will sustain the more heavy elements of the model after the collapse.

The removal of a collapsed model from the shaking table a critical phase of the testing cycle. For that purpose the overhead travelling crane will be stationed over the model during the test and a second set of suspending cables will connect the heavy parts of the model to the crane hooks; those cables will be more loose than those going from the model to the roof beams. After the collapse of the model, the hoisting of the hooks will transfer the weight of the broken model from the roof suspending cables to the crane suspending cables. At that point, the roof cables will be disconnected from their fixation points; for that purpose there is a special work platform on the crane. To protect that platform from the roof cables if the collapse of the model is associated to large horizontal displacements, twelve 200 kN fixation points are disposed on the three large walls and another four points are provided in the floor of the testing hall in the direction where there is no wall.

4 THE ADAPTIVE CONTROL SYSTEM

4.1 *General characteristics*

A self-tuning control system (e.g. Wellstead and Zarrop, 1991) as been developed for the uniaxial horizontal and vertical shaking tables (Carvalhal, 1979; Jervis Pereira and Carvalhal, 1984). Because of the decoupling of the dof in the triaxial platform, this control system, in triplicate, will also be used in that platform. The system output to the shaking table is a voltage signal which is fed into the servo-actuator and the usual input is the acceleration time history of the shaking table. The main task of the control system is to generate an adequate output in order that the shaking table response has the required characteristics, regardless of the perturbation due to the reaction forces of the specimen being tested. The control system works in an iterative manner on a "performance index" which is evaluated from the shaking table accelerations, that may be either the response spectrum or an estimate of the power spectrum.

The control algorithm has three stages: estimator, decision and test signal synthesizer. In the estimator stage either the response spectrum or the power spectrum are computed. In the decision stage the computed spectrum is compared with the desired spectrum and the necessary corrections are evaluated. In the synthesizer stage a new output to the servo-actuator is constructed. However, before the control algorithm can operate, the actual motion (of duration T) of the shaking table must be discretized with a Δt sampling interval by an analog-digital converter into a time series of acceleration a_{mi} $(m = 0, ... N-1; N = T/\Delta t)$ and the index i indicates iteration cycle. At the end of operation of the control algorithm a digital-analog converter transforms a time series of displacements u_{mi+1} $(m = 0, ... N-1)$ into the voltage signal for the servo actuator.

Only a sketchy description of this control system is appropriate for the present paper; full details are to be found in the references above. It should be noted that this control system allows conducting the shaking table tests without knowing, in an explicit way, the dynamic characteristics of the model, due to the existence of an implicit nonparametric identification of those dynamics in the decision stage.

4.2 *Power spectrum control*

When the performance index is the power spectrum, the estimator stage consists in the "determination" of the obtained power spectrum $S_a(f_k)$ by

$$S_{ai}(f_k) = \mid C_i(f_k) \mid^2 / T \qquad (1)$$

where $C_i(f_k)$ is the Fourier coefficient at the discrete frequency $f_k = k/N\Delta t$ computed by the FFT technique from the a_{mi}.

The decision stage algorithm consists in computing a new power spectrum $S_{ui+1}(f_k)$ for the output signal u_{mi+1} by the expression:

$$S_{ui+1}(f_k) = S_{ui}(f_k) S_r(f_k) / S_{ai}(f_k) \qquad (2)$$

where S_r is the desired (reference) acceleration power spectrum and S_{ui} is the spectrum for output signal u_{mi}. This algorithm assumes linearity of the model and of the hydraulic, mechanical and electrical systems involved and absence of noise.

In the test signal synthesizer stage, a pseudo-random time series u_{mi+1} is generated by the inverse discrete FFT:

$$u_{mi+1} = \frac{1}{\sqrt{T}} \sum_{k=o}^{N-1} \sqrt{S_{ui+1}(f_k)}\, e^{i(2\pi km/N + \phi_k)} \qquad (3)$$

where ϕ_k are randomized phase values which are assigned at the begining of the test and are not changed from cycle to cycle.

4.3 *Response spectrum control*

When the performance index is the response spectrum (for a given damping ς), the estimator stage consists in the determination, by the usual techniques, of the response spectrum $R(f_l^r)$ at 1/3 of octave discrete frequencies f_l^r.

The decision stage algorithm is based in the correspondence between a power spectrum and a response spectrum (Jervis Pereira et al., 1977). This correspondence identificates the response spectrum value with the 50% fractile $F_{0.5}$ of the probability distribution of the peak response of the oscilator which can be estimated by the following expression, assuming a Cramér distribution (Cramér and Leadbetter, 1967):

$$F_{0.5}(f_l^r) = \sqrt{2\sigma^2(f_l^r)(ln(f_l^r T) - ln(ln(1/0.5)))} \qquad (4)$$

where $\sigma^2(f_l^r)$ is the variance of the oscillator response:

$$\sigma^2(f_l^r) = \frac{1}{T} \sum_{k=o}^{N-1} \mid H_l(f_k) \mid^2 \mid G(f_k) \mid^2 S_{ui}(f_k) \qquad (5)$$

where H_l and G are the transfer functions of the l-th oscillator and of the controlled system. The oscillator transfer function may be simulated by:

$$\begin{array}{lll} H_l^s(f_k) = 1 & & f_k/f_l^r \leq 1 - \varsigma \\ H_l^s(f_k) = 1/2\varsigma & 1 - \varsigma \leq & f_k/f_l^r < l + \varsigma \\ H_l^s(f_k) = 0 & 1 + \varsigma \leq & f_k/f_l^r \end{array} \qquad (6)$$

Let m(l) and n(l) be indicators defined by

$$m(l) = max(k) \qquad f_k < (1 - \varsigma) f_l^r \qquad (7)$$

$$n(l) = max(k) \qquad f_k < (1 + \varsigma) f_l^r \qquad (8)$$

Then, substituting H_l by H_l^s in expression 5 the following result is obtained:

$$\sigma^2(f_l^r) = \gamma(f_l^r) + \frac{1}{2\varsigma T} \mid G_l \mid^2 S_{ui}(f_{m(l)}) \qquad (9)$$

where

$$\begin{array}{l} \gamma(f_l^r) = \frac{1}{2T}(\mid G(o) \mid^2 S_{ui}(o)) + \\ + \frac{1}{T} \sum_{k=1}^{m(l)-1} \mid G(f_k) \mid^2 S_{ui}(f_k) + (\frac{1}{2T} + \\ + (1 - \varsigma) f_l^r - f_{m(l)})) \mid G(f_{m(l)}) \mid^2 S_{ui}(f_{m(l)}) \end{array} \qquad (10)$$

accounts for the spectral contribution that is not amplified by the dynamic response of the oscillator and $\mid \overline{G_l} \mid^2$ is the controlled system "averaged" transfer function:

$$| \overline{G}_l |^2 = \frac{1}{S_{ui}(f_{m(l)})} \Big(\sum_{k=m(l)+1}^{n(l)-1} | G(f_k) |^2 S_{ui}(f_k) + \\ + (1.5 + m(l) - (1 - \varsigma) T f_l^r) | G(f_{m(l)}) |^2 S_{ui}(f_{m(l)}) + \\ + (1.5 + \varsigma(l) + (1 + \varsigma) T f_l^r) | G(f_{n(l)}) |^2 S_{ui}(f_{n(l)}) \Big) \quad (11)$$

Once those approximations are accepted the decision stage algorithm is represented by the following expression:

$$S_{ui+1}(f_k) = S_{ui}(f_k) r_k^2 \quad (12)$$

$$r_k^2 = \frac{R_r^2(f_{p(k)}^r) - s^2}{R^2(f_{p(k)}^r) - s^2} \quad (13)$$

$$s^2 = 2\gamma(f_{p(k)}^r) ln(f_{p(k)}^r T + 0.37) \quad (14)$$

where R_r is the desired (reference) response spectrum and p(k) is an indicator defined by $\{p(k) : \forall q, | f_{p(k)}^r - f_k | \leq | f_q^r - f_k |\}$.

The test signal synthesizer stage is identical to the simillar stage of the procedure with the power spectrum as performance index (expression 3).

4.4 *Control efficacy*

The experience with those control systems have shown that they work reasonably well when the test specimen does not go beyond the elastic limit (Jervis Pereira and Carvalhal, 1984; Vieira Pinto et al. 1987). Recent experiences have shown that, after an in-depth development work (Carvalhal and Oliveira Costa, 1988), the power spectrum control system could work "unexpectedly" well in masonry infilled reinforced concrete frame models.

5 DEVELOPMENTS IN SHAKING TABLE TESTING

The limitations of the existing shaking tables and the scale distorsions between reality and model of masonry and reinforced concrete structures make advisable the development of new methods to explore the *"information" given by a single or a small* number of shaking table tests. It seems safe to antecipate that those developments will be based on an explicit-numerical representation of the states of knowledge (see e.g. Klir, 1988 for a global presentation and Toussi and Yao, 1982 for an application to earthquake engineering). Another promising development are methodologies to integrate observational and numerical methods (Esteva, 1990). In this section is illustrated the use of numerical analysis in the evaluation of testing strategies in terms of the information to be obtained.

5.1 *Definition of the model*

Consider a model of a reinforced concrete four-storey structure infilled by masonry panels, constituted by three two-bay-frames in each direction. The principal characteristics of this structure where inspired in buildings used in parametric studies some years ago (Carvalho and Coelho, 1984) which have been the basis for different types of studies (e.g. Campos-Costa, 1990; Costa and Oliveira, 1990; Pipa and Carvalho, 1990). This model must be at 1:2 scale ($\gamma = 0.5$) due to the limitations of the triaxial shaking table; the weight of the model is 220 kN while the weight of the archetype is 2640 kN, thus the mass scale is $\mu = 1/12$. The scale of forces $\phi = 1{:}4$ is defined by the requirement that stresses are equal in model and archetype. From μ and ϕ follows that the scale of accelerations is $\alpha = 3 : 1$; from α and γ the value of the time scale $\tau = 1 : \sqrt{6}$ is determined. In order that the same normalized axial force exists in model and archetype, each floor of the model must have a vertical pre-stressing of 605 kN. The general characteristics of the model are presented in figure 5.

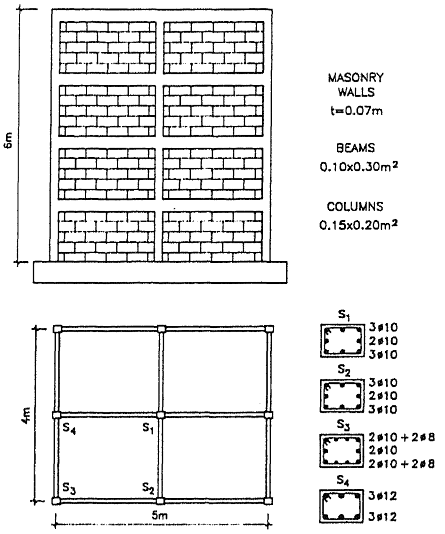

Fig. 5 - General characteristics of a 1:2 scale model

5.2 *Numerical analysis*

The physical model to be tested on the shaking table was idealized by a computer model with 6 degrees of freedom per node and spatial beam elements. Post-elastic behaviour is assumed to take place in plastic hinges at the top and bottom of the columns of the first storey; this assumption idealizes the typical behaviour of masonry infilled structures which consists in the breakage of the masonry panels in the first storey; after this breakage the columns are not resistant enough to transmit the earthquake forces needed to break the masonry in the upper storeys; this behaviour has been identified in real earthquakes (Duarte, 1981), in shaking table tests (Ravara, Mayorga and Carvalho, 1977) and in computer analysis (Campos-Costa and Duarte, 1990).

The moment-rotation loops in the plastic hinges

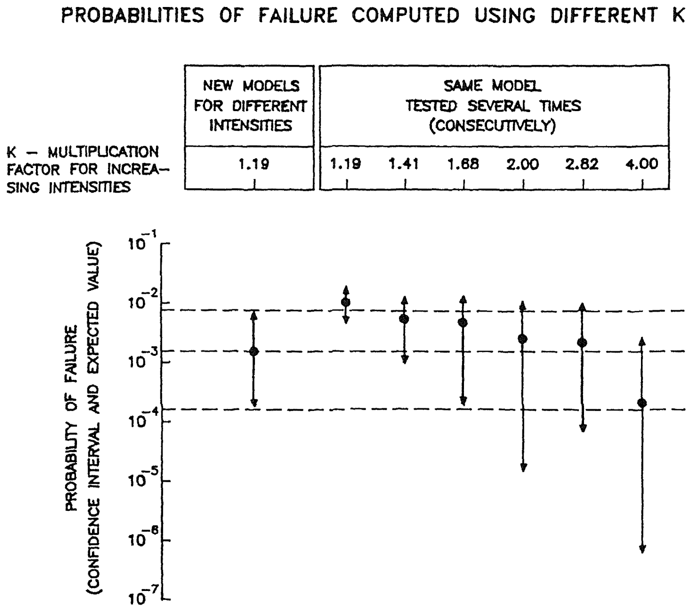

Fig. 6 - Probabilities of failure obtained by testing with a geometric progression of intensities with common ratio K

are represented by a fibre model (Vaz, 1992) which discretizes the beam section in a large number of concrete "filaments" and considers each one of the steel bars. The response is computed step-by-step with the Newmark method.

An important advantage of performing numerical simulations before the model is constructed is that the largest model size that do not exceed (with reasonable reliability) the capacities of the shaking table may be determined.

5.3 *Testing strategy*

The principal characteristic of collapse testing is that each model can be tested only once. Given this unavoidable fact it is worthwhile to develop testing strategies that optimize the "information" that is obtained from the test. Such information may be represented under the form of the 90% confidence interval and the expected value of the probability of failure evaluated by bayesian methods (Duarte et al., 1990; Ritto-Corrêa and Duarte, 1992). Those methods were developed for a situation in which probability of unrepaired damage from a small earthquake is small compared with the probability of a large earthquake. Thus the "errors" given by this method are a measure of the difference in action effects between a single earthquake and a succession of increasing amplitude earthquakes. The development of bayesian methods to optimize the information obtainable from a given testing strategy is in progress. A possible testing strategy is to start with a low intensity vibration on the shaking table and then increase, by a factor K, the intensity until collapse takes place. The problem with this strategy is that if K is small, damage from the previous tests "apparently" reduces the resistance of the model; if K is large the "true" collapse intensity may be affected by a large uncertainty, if one test causes only small damages in the model and the next test causes a very fast collapse. Numerical simulations of this testing strategy are presented in figure 6. For comparison purposes the results that would be obtained by using a small K [1] and a new model in each test are shown on the left. The uncertainties in this case are mainly the result of the randomness of the "resistances" of the model and of the fact that only one earthquake time history is used. The results show that when K is small there is a substantial reduction in the estimate of the probability of failure, due to damage from lower intensity tests, and a significant reduction in the estimate of the confidence interval, due to the "information" given by a large number of tests. When K is large there is a good estimate of the probability of failure but there is an increase in the confidence interval due to a decrease in the number of tests; when K is too large, accuracy is lost in the evaluation of the probability of failure and of the confidence interval.

6 ACKNOWLEDGMENTS

Due to its interdisciplinary character and to the time-scale its involves, shaking table testing needs necessarily the contribution of a large number of persons. The authors gratefully acknowledge the contribution of:

---

[1] The value 1.19 $\simeq \sqrt[4]{2}$ results from convenience in organization of the computations.

J. Ferry Borges, J. Jervis Pereira, A. Ravara, C.S. Oliveira, E. Cansado Carvalho, A. Vieira Pinto, J.A. Gil Saraiva, F.H. Alves, F.J. Carvalhal, F.T. Emilio, C. Oliveira Costa, E. Tavares Cardoso e J. Almeida Garret

to the development of shaking table studies in LNEC. The first author also appreciatively remembers several very interesting conversations with Professors R.T. Severn and P. Gr. Carydis on the topics of this paper.

REFERENCES

1. Buland, P. 1992. Shaking table testing, in *Recent Advances in Earthquake Engineering and Structural Dynamics.* Ed. V.E. Davidovici, 795-806 Ouest Editions, Nantes, France.
2. Campos-Costa, A. 1990. Nonlinear torsional design of R/C buildings under bi-directional seismic actions, *Proc. 9th European Conf. on Earthquake Engrg.,* 8:246-255 Moscow.
3. Campos-Costa, A. & R.T. Duarte, 1990. Earthquake behaviour of 4 storeys reinforced concrete frame structures infillede with brick masonry panels, *Proc. 9th European Conf. on Earthquake Engrg,* 2:144-153 Moscow.
4. Carvalhal, F.J. 1979. *Adaptive control in the simulation of seismic actions.* Thesis, LNEC, Lisbon (in portuguese).
5. Carvalhal, F.J. 1987. *Control systems engineering - A contribution for the development of their applications to research in the field of civil engineering,* Research Programme, LNEC, Lisbon (in portuguese).
6. Carvalhal, F.J. & C. Oliveira-Costa, 1988. *Real time servoadaptive control on the unidirectional simulation of seismic actions - Analysis of a parametric identification problem with servohydraulic actuators.* LNEC report 192/88, Lisbon (in portuguese).
7. Carvalho, E.C. & Ema Coelho, 1984. *Seismic analysis of building structures following the new regulations.* LNEC Report S322, Lisbon (in portuguese).
8. Clark, A.J. 1992. Dynamics of large multiple degree of freedom shaking tables. *Proc. 10th World Conf. on Earthquake Engrg.,*5: 2823-2828, Rotterdam: Balkema.
9. Costa, A.G. & C.S. Oliveira, 1990. Influence of vertical and horizontal irregularities on seismic response of buildings. *Proc. 9th European Conf. on Earthquake Engineering.,* 2:164-173, Moscow.
10. Cramér, H. & M.R. Leadbetter, 1967. *Stationary and related sochastic processes.* New York: John Wileys & Sons.
11. Dake, A. & A. Wildavsky, 1990. Theories of risk perception: who fears what and why. *Daedalus,* 119:41-60.
12. Duarte, R.T. 1981. The El-Asman earthquake of October 10, 1980. *Revista Portuguesa de Engenharia de Estruturas,* N° 11 (in portuguese).
13. Duarte, R.T. M. Ritto-Corrêa, C.T. Vaz & A. Campos-Costa, 1990. Bayesian methodology for the quantification of the probability of failure and the optimization of the analysis. *2nd Portuguese Meeting on Structural Engineering,* Lisbon (in portuguese).
14. Emilio, F.T. R.T. Duarte, F.J. Carvalhal & J. Jervis Pereira, 1986. A new type of three-degrees-of-freedom shaking table, *8th European Conf. Earthquake Engineering,* 4:7.1/9-7.1/16 Lisbon.
15. Emilio, F.T., R.T. Duarte, F.J. Carvalhal, C. Oliveira-Costa, C.T. Vaz & M. Ritto-Corrêa, 1989. The new LNEC shaking table for earthquake resistance Testing. Technical paper N° 757, LNEC, Lisbon.
16. Esteva, L., 1990. Probabilistic framework for the calibration of theoretical seismic reliability models. *Proc. 9th European Conf. Earthquake Engrg.,* 9:393-401, Moscow.
17. Ferry Borges, J. 1980. Harmonization of rules for seismic design, *Proc. CSNI Specialist Meeting on Probabilistic Methods in Seismic Risk Assessment for Nuclear Power Plants,* Lisbon.
18. Jervis Pereira, J., C.S. Oliveira & R.T. Duarte, 1977. Direct and inverse conversion from power spectra to response spectra. *Proc. 6th World Conf. on Earthquake Engrg.* 2:279-285. New Delhi: Sarita Prakashan Meerut.
19. Ferry Borges, J., J. Jervis Pereira, A. Ravara & J. Oliveira Pedro, 1963. Seismic studies on concrete dam models, *Proc. Symposium on Concrete Dam Models,* LNEC, Lisbon.
20. Jervis Pereira J. & F.J. Carvalhal, 1984. Adaptive control techniques for the simulation of seismic actions, *Proc. Seminar on Design of Concrete Structures - The Use of Model Analysis.* London: Elsevier.
21. Jervis Pereira, J., R.T. Duarte & F.T. Emilio, 1985. Shaking tables and seismic testing of structures and equipments. *Transactions 8th Int. Conf. on Structural Mechanics in Reactor Technology,* Brussels.
22. Kusner, D.A., I.D. Rood & G.W. Burton, 1992. Signal reproduction fidelity of servohydraulic testing equipment. *Proc. 10th World Conf. Earthquake Engrg.* 5:2683-2688. Rotterdam: Balkema.
23. Oliveira-Costa, C. 1987. *Contribution for the estimation of continuous parameters of a sampled system, by spectral and non-spectral techniques* M.Sc. thesis. IST, Technical University of Lisbon (in portuguese).

24. Pedro, J.O., R.T. Duarte & C.A. Brito Pina, 1988. The activity of the National Laboratory for Civil Engineering in the field of structural mechanics - Present situation and possible developments. Technical paper N° 723, LNEC, Lisbon.

25. Pipa, M. & E.C. Carvalho, 1990. Experimental evaluation of the behaviour of structures designed for two ductility levels. *Proc. 9th European Conf. on Earthquake Engineering.*, 6:133-142, Moscow.

26. Press, F., 1984. The role of science and engineering in mitigating natural hazards. *Proc. 8th World Conf. on Earthquake Engrg.* Post-conference volume, 13-22. Englewood Cliffs, New Jersey: Prentice-Hall.

27. Ravara, A., A. Mayorga & E.C. Carvalho, 1977. Seismic tests of infilled reinforced concrete frames. *Proc. 6th World Conf. on Earthquake Engrg.* New Delhi: Sarita Prakashan Meerut.

28. Ritto-Corrêa, M. R.T. Duarte, 1992. Optimal nonlinear analysis by bayesian methods, *Proc. 10th World Conf. Earthquake Engrg.* 7:3757-3762. Rotterdam: Balkema.

29. Toussi S. & J.T.P. Yao, 1982. Assessment of structural damage using the theory of evidence. *Structural Safety*, Vol. 1, No. 2, Amsterdam: Elsevier.

30. Vaz, C.T. 1992. *Seismic behaviour of bridges with reinforced concrete piers - checking of structural safety.* Ph.D. Thesis, LNEC-Oporto University (in portuguese).

31. Vaz, C.T. 1992. Quantification of behaviour coefficients for RC bridges. *Proc. 10th World Conf. on Earthquake Engrg.* 8:4897-4902. Rotterdam: Balkema.

32. Vieira Pinto, A., J.A. Gil Saraiva & R.T. Duarte, 1987. Seismic tests on physical models. *Transactions of the 9th Int. Conf. on Structural Mechanics in Reactor Technology.* Rotterdam: Balkema,

33. Wellstead, P.E. & M.B. Zarrop, 1991. *Self-tuning systems, control and signal processing.* Chichester: John Wiley & Sons.

34. Klir, G.I., 1988. Methodological principles of uncertainty in inductive modelling: a new perspective, in *Maximum-Entropy and Bayesian Methods in Science and Engineering,* 1: 295-304. Dordrecht: Kluwer.