Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999 H04/3

Shaking Table Tests of Reinforced Concrete Columns under Horizontal and Vertical Loading

Rogerio Bairrao[1], Carlos Vaz[1], Rimantas Kacianauskas[2] and Romualdas Kliukas[2]

1) National Laboratory for Civil Engineering, Portugal
2) Vilnius Gediminas Technical University, Lithuania

ABSTRACT

Many columns, piers and towers used in civil engineering, on road construction, power engineering, off-shore engineering and other fields are made of high-strength concrete structural members of hollow circular cross-section with longitudinal and spiral reinforcement. In spite of the existence of numerical methods and design codes to evaluate the actual behaviour of those structures, it was decided to carry out an experimental programme to check their behaviour under severe dynamic conditions.

Two identical columns (concrete strength 80Mpa, steel strength 500Mpa) were designed and built. This paper presents their tests at the LNEC shaking tables facility.

INTRODUCTION

In spite of the existence of several numerical methods and design codes, experimental testing remains a powerful and reliable research tool. Advanced and innovative experimental techniques, using computer controlled displacements, provide a base for realistic simulation. The test of structural members submitted to combined longitudinal and transverse loading belong to the category of the most complicated experiments.

For that purpose two main experimental techniques are used, namely, reaction wall/floor systems and shaking tables (1, 2). It should be underlined that computer controlled imposed displacements may be considered as a common feature of both techniques. In the first one, in spite of a complicated dynamic loading history, the external loading may be considered as quasi-static, since velocities are very small and so only mechanical properties insensible in respect to velocities can be correctly analysed.

Shaking tables are essential tools in earthquake engineering research since they allow the study of true inertia forces effects on the specimens. However, the models are normally constructed at reduced scale, and this can limit the scope of the tests. In contrast, reaction wall test rigs allow full-scale specimens to be tested, but not under true inertia forces and real time.

Several shaking tables throughout the European Union are being used to develop research activities about the dynamic effects on civil engineering structures. A different type of triaxial shaking table was designed and built in the Portuguese National Laboratory for Civil Engineering (LNEC) in Lisbon (3).

The present paper is mainly focussed on the description of the shaking table technique used to test reinforced concrete columns working as plane cantilever beams under the action of horizontal and vertical concentrated loads. Two tests, up to failure, on two high-strength reinforced concrete specimens with annular cross-section and spiral containment were carried out at the LNEC facilities. Descriptions of the shaking table testing capability, construction of the specimens, set-up, testing procedure and acquisition of data are given in the following text. Finally, an experimental force-displacement diagram is presented in order to illustrate the observed behaviour of the specimens in the elastic and plastic phases.

LNEC TRIAXIAL SHAKING TABLE

Shaking table testing plays a very prominent role in the validation of design procedures because it is the only possibility to directly generate earthquake and other dynamic effects in conditions allowing their systematic and scientific observation. In order to advance its experimental activity in engineering, which started in the late fifties, LNEC decided to study and build a new type of earthquake simulator mainly conceived for the testing of civil engineering structures, such as buildings and bridges, being, however, also useful for the validation of the dynamic behaviour of some mechanical and electrical equipment.

This very particular simulator has three independent translational degrees of freedom which are driven by hydraulic actuators, whereas its rotational degrees of freedom are minimised by torque tube systems, one for each axis (roll, pitch and yaw). Under the horizontal cranks, either passive gas actuators, to cope with the dead weights of the shaking table and of the testing specimen, or rigid blocks, eliminating the vertical motion of the table, can be inserted.

At each end, the torque tubes are linked, by means of a crank, with a stiff connecting rod between them and the moving platform. The vertical connecting rods are pinned at both ends, and horizontal motion of the platform is allowed. When the platform moves vertically, it either pulls or pushes the connecting rods, rotating both cranks by the same angular displacement, and the respective torque tube likewise. In fact, if there is an overturning moment inducing a rotation on the platform, then vertical movement in opposed directions appears at the upper end of the connecting rods, which, in turn, causes small opposite rotating forces in the cranks. However, this is resisted through a large reaction force generated by torsional stiffness of the concerned very stiff torque tube, resulting only in an insignificant platform rotation.

The main characteristics of this shaking table are an area of 5.6 m x 4.6 m, a table mass of about 40 t, a maximum allowable specimen weight of 400 kN, a frequency range from 0 to 15 Hz, maximum accelerations of 1.1, 0.5 and 1.8 g for the transverse, vertical and longitudinal axis respectively, and maximum displacements of ± 175 mm for all the three axes. Detailed information on the characteristics of the shaking table can be found in (4).

SPECIMENS GEOMETRY AND MATERIALS DATA

The specimens have been erected using high-strength concrete with about f_{ck}=80 MPa. Those piers have a circular hollow section with wall thickness of 6 cm. Longitudinal reinforcement consisted of 8 bars of 10 mm diameter and transverse reinforcement was a spiral made up with 6 mm diameter bars spaced 5 cm at the critical section. The entire specimens were produced as monolithic units consisting of a massive footing and a specified column. Specimens did contain special holes, voids and stiffening details necessary for the application of external loads and for insuring the testing conditions (Figure 1).

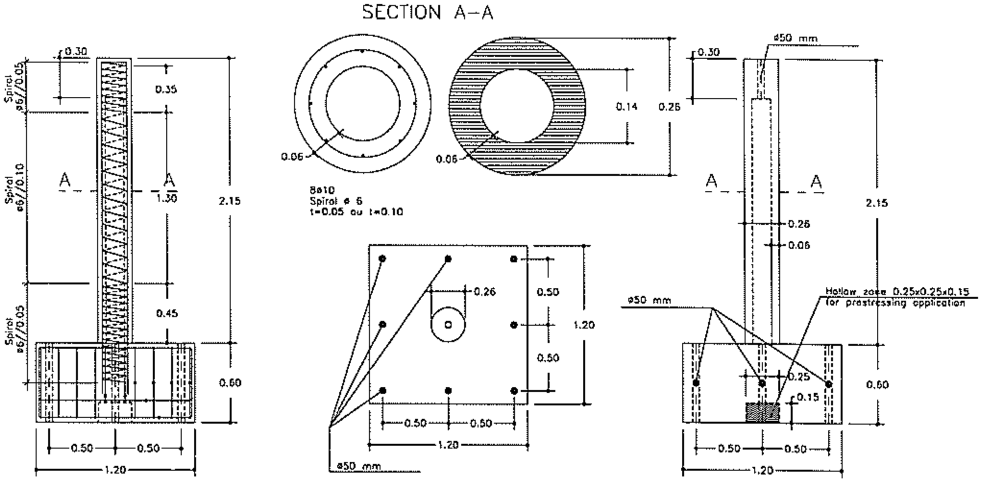

Figure 1 – General dimensions and reinforcement arrangement of the specimens

TESTING TECHNIQUE

The tested columns were considered as vertical cantilever beams loaded by combined vertical and horizontal actions. A vertical load of 187.5 kN, producing the axial force, was applied before the tests and remained constant during the entire testing period. It was implemented by prestressing a cable positioned inside the column, at its centre line, and connected from the top of the column to a hollow zone under the footing.

The horizontal time dependent loading was produced by the motion of the shaking table and by an inertia mass involving a set of external additional masses and a connecting rod. The total value of this mass was 12 t. Motion of the shaking table was prescribed as a function of transverse horizontal time-dependent displacement. For these experiments, sine type signals, controlled in amplitude and frequency, were used. The loading history consisted of one initial sine sweep, four successive sine wave stages of increasing amplitude and a final longer sine sweep, as shown in the next table. Details can be found in (5).

Table 1 – Test stages

Stage	Amplitude (mm)	Frequency (Hz)	Duration (s)	Attack Time (s)	Type of the loading
S1	6.3	3.0 ÷ 1.0	20	*none*	Sine-sweep
S2	8.0	2.0	20	10	Sine wave
S3	12.7	2.0	20	10	Sine wave
S4	23.0	1.4	20	10	Sine wave
S5	36.0	0.9	20	5	Sine wave
S6	32.0	1.0 ÷ 0.1	150	*none*	Sine-sweep

SETUP AND INSTRUMENTATION

A set of masses has been assembled and rigidly connected to constitute an inertial mass device. This set was connected to an L-shaped steel structure laying on teflon pads which were attached on the top of a fixed supporting structure located outside the shaking table. The L-shaped structure together with the attached mass was presumed to be able to slide over the supporting structure with very low friction forces and was linked to a ring at the top of the pier by means of a connecting rod. The connection of this rod to the ring and to the L-shaped structure was made with spherical swivels, thus allowing free rotations along all directions. A general aspect of the setup is shown in Figure 2.

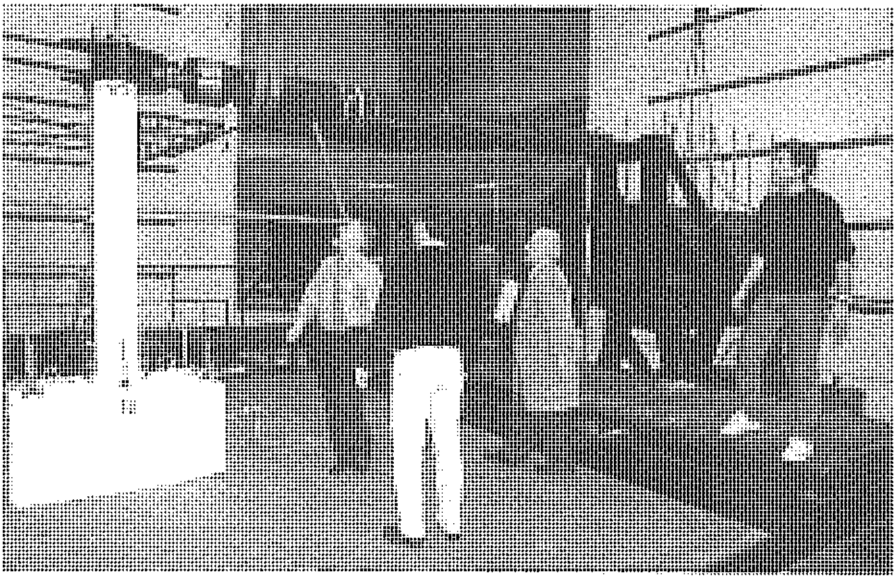

Figure 2 – Test setup

During these tests, 21 channels were acquired. Optical transducers and LVDTs (linear variable differential transformers) were used to measure the displacements at 13 pre-selected points of the specimens. The positions of these displacement transducers, noted d1 to d13, are showed in Figure 3. For identifying the orientation of the specimen all sides are marked with capital letters W, S, E and N corresponding to their geographical directions. Shaking table movements are defined as longitudinal (NS), transverse (WE) and vertical, the positive senses being oriented towards S, E and down, respectively. The movement of the shaking table was imposed along its transverse direction.

Any eventual sliding of the footings on the shaking table was measured by the inductive transducer d1. All the other horizontal movements were measured using optical transducers, mainly fixed at the South side. Transducers d8 to d11 acquired transverse (in plane) displacements at prescribed points of the column while transducer d12 has controlled the out of the plane displacement. Additionally, transducer d13 measured the transverse displacements of the shaking table itself. The measurement of vertical displacements (transducers d2 to d7 at prescribed points on the E and W sides of the columns) was mainly devoted to evaluate longitudinal deformations.

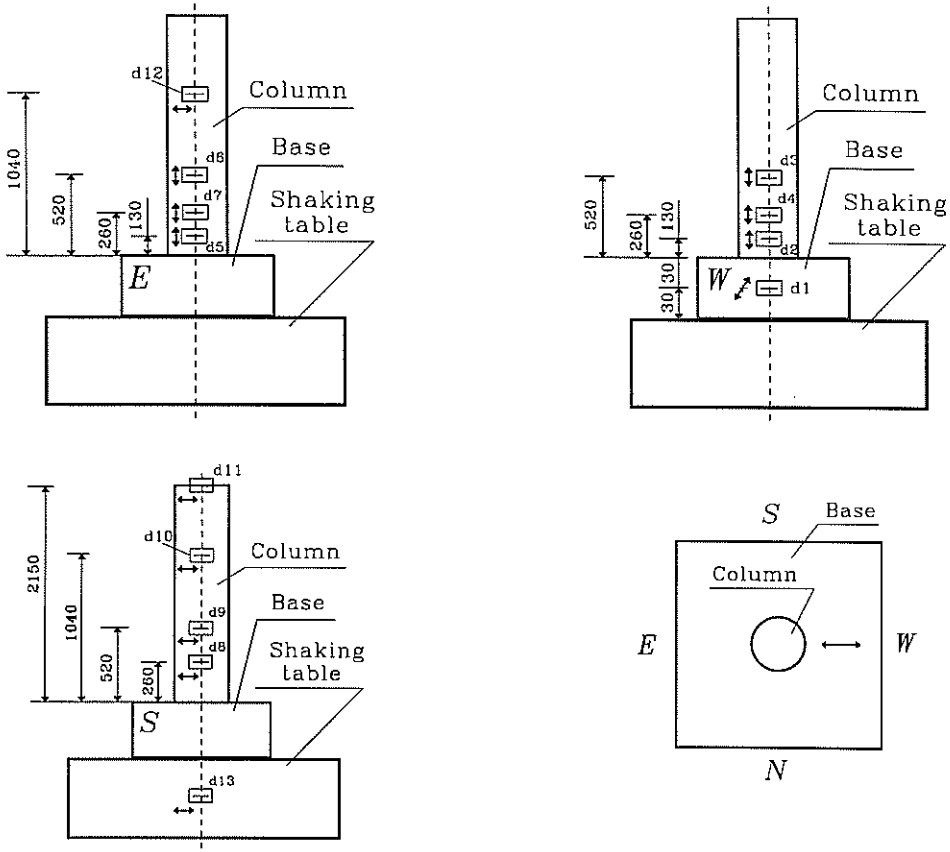

Figure 3 – Location of the displacement transducers

Accelerations were measured at 7 points using variable capacitance accelerometers; four on the shaking table platform, two on the specimen and one on the inertial mass device. The four accelerometers on the shaking table were located in three different points and used to detect eventual rotations. Two have measured transverse accelerations at two different points, while another two took account of the longitudinal ones at one of the previous points and at an extra one. The two accelerometers on the specimen were placed at the top of the column in longitudinal and transverse directions. Finally, the accelerometer on the inertial mass, was, naturally, oriented in the transverse direction.

The horizontal forces, generated at the top of the columns, were measured by a loading cell, inserted as part of the connecting rod between the specimens and the inertial mass.

RESULTS AND CONCLUSIONS

Both the specimens have exhibited a behaviour clearly dominated by the flexure, as it should be expected from their slenderness ratio.

At the final stages, flexural cracks (Figure 4) were very well marked, and simultaneously cover spalling and some crushing of the concrete occurred (Figure 5).

The force-displacement at stage 5 is shown in Figure 6. In this figure the pinching effect is very clear, possibly due to some bond degradation and bar slippage. However, significant strength degradation was not observed and both models maintained their resistance.

As far as the longitudinal reinforcement was concerned, no failure, or even buckling, was observed.

The experimental results obtained will be used, in Lithuania, for modelling reinforced high strength concrete columns as well as to understand better the properties of this type of concrete.

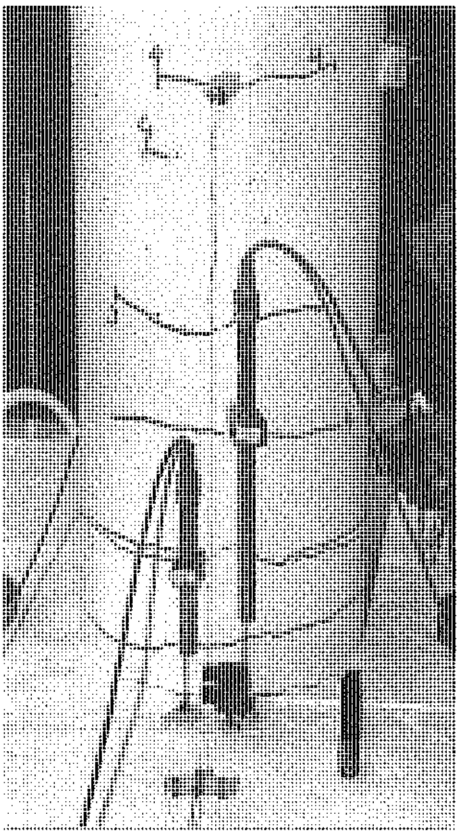

Figure 4 – Flexural cracking

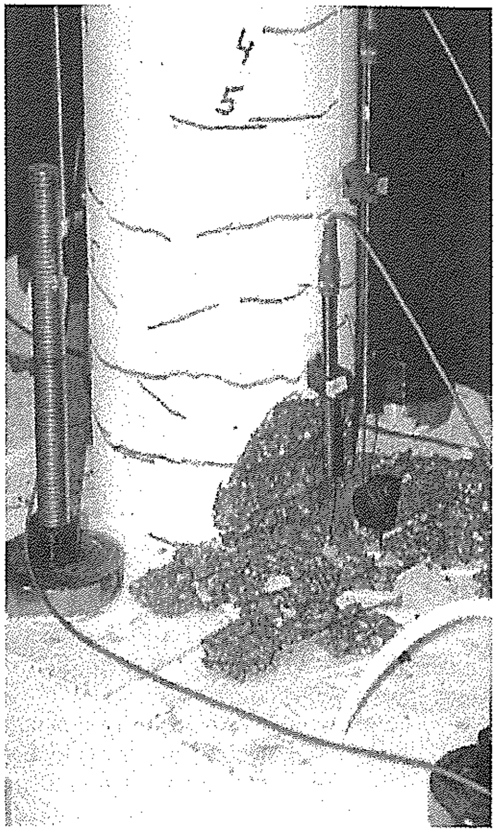

Figure 5 – Detail of concrete crushing

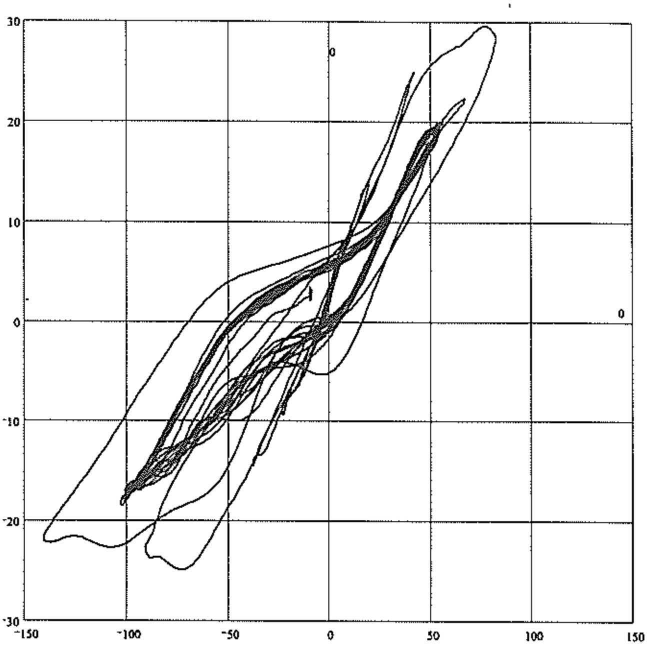

Figure 6 – Force-displacement at stage 5 (kN, mm)

REFERENCES

1. Pinto, A. V.
Earthquake Performance of Structures. Behavioural, Safety and Economical Aspects.
PhD Thesis, Instituto Superior Técnico, Lisbon, Portugal, 1998.

2. Carvalho, E. C.
Seismic Testing of Structures.
11th European Conference on Earthquake Engineering, Paris, France, September 1998.

3. Emílio, F. T., Duarte, R. T., Carvalhal, F. J., Costa, C. O., Vaz, C. T. and Corrêa, M. R.
The New LNEC Shaking Table for Earthquake Resistance Testing.
Document LNEC-757, 1989

4. Duarte, R. T.
Report of Working Group 11: Development of Shaking Table Testing Techniques.
10th European Conference on Earthquake Engineering, vol. 4, pp. 3135/3144, Vienna, Austria, August/September 1994

5. Bairrão, R., Vaz, C. T. and Duque, J.
Dynamic Tests on High-Strength Reinforced Concrete Columns under Combined Vertical and Horizontal Loading.
Report LNEC/C3ES/SES-236/98, 1998

ACKNOWLEDGEMENTS

The studies described in this paper were partially funded by the European Community Programme "Access to Large Scale Facilities – The Large Installations Plan", in the framework of ECOEST, "European Consortium of Earthquake Shaking Tables", contract ERBCHGECT 920010, supplementary agreement ERBCIPDCT 940089, PECO, for the support to scientists from Central and Eastern European Countries.

Armol-Freyssinet S.A. has supplied and applied the prestressing free of charge.