Shaking Table Testing for Structural Analysis

I. Corbi, Z.T. Rakicevic

***Abstract*—** In the paper the dynamic behavior of structures behaving like rigid blocks and a multi-plane steel frame are considered in order to study the most appropriate control system for vibrations. In the case of the rigid blocks the motion under pure rocking is analyzed and the problem is addressed of attenuation of the dynamic response by means of dampers based on a liquid mass. In details, one refers to rigid systems with unilateral constraints exhibiting pure rocking motion under dynamic load; this application is pretty significant since it embraces a wide variety of physical objects; moreover the coupling with dissipating liquid devices of rigid blocks is rarely treated in literature. In the case of the steel frame a tuning procedure is elaborated for adjusting multiple control variables, such as gains, lead terms, and notch filters, which allows to obtain unitary gain of the transfer function between command-reference and feedback signal within the frequency bandwidth of interest. As an additional tool to fixed control techniques, the Adaptive Control Technique is used when high fidelity in signal reproduction is required.

***Keywords*—** Shaking table, digital controller, structural dynamics, rocking motion, laboratory testing.

I. INTRODUCTION

IN the last tens of years shaking table is attested as one of the most validate instrument for studying structures and sub-structures behavior under dynamic input. If properly used, they provide effective ways to subject specimens of structural components, substructures, or entire structural systems to dynamic excitations similar to those induced by real earthquakes. On the other hand, shaking table experiments represent a good substitution for information on the behavior of structures obtained under the effect of actual earthquakes.

Although in the first half of the 20th century some efforts were made to build a laboratory system for simulation of earthquakes, the first types of earthquake simulators with programmable effect were produced and made available to the earthquake engineering scientists as late as the beginning of the seventies due to the insufficient level of technological knowledge in the mechanical, electrical and electronic industry. It is considered that the era of the modern shaking tables has began with the installation of the 20 x 20ft shaking table at UC Berkeley by MTS Systems Corporation, which was formally opened in 1972. Since then, more than 110 shaking tables with programmable characteristics have been installed in laboratories worldwide.

So ideally by introducing into the system software-shaking table the seismic signal of some historical ground motions it is possible to record the seismic response of testing structures.

However its use is generally limited for many reasons the mains of which are relevant to the own complexity of shaking table and to the dimensional limit of testing specimens, which adds the difficulty to correlate the results of the scaled models to the full-dimensioned structures.

In the laboratory tests a series of problems relevant to testing specimens exist, e.g. as the scale effect of materials and specimens. So all researches about this topic must necessary draw from a wide catchment's area knowledge which spaces from the materials science to physics to structural engineering, etc.

Due to shaking table complexity, that includes a variety of mechanical, hydraulic and electronic components, there are many potential highly interdependent sources of distortion that alter the total effect of the system, so that a given command does not produce the expected response. It must be required for any case a specific setting of the systems which considers all the components of the problem.

As mentioned, the complexity of shaking table arises from the many linear and nonlinear interactions among various components [1]-[6] and the many potential highly interdependent sources of distortion that alter the total effect of the system.

Although forecasts about the seismic motion are not easy to be obtained [7]-[8], such facilities allow to understand the behavior of different typologies of structures and materials, including cases like, for example, masonry structures [9]-[21] where limits of theoretical treatment make forecasts and vulnerability assessment more complex [22]-[23], as well as to evaluate the effects of protection strategies, related to the adoption of control strategies [24]-[30], composites provisions for retrofitting of structures [31]-[33] and so on.

Therefore although the application field of shaking tables may be wider, its practical application is substantially reduced to a number of research fields: investigation of the dynamic behavior of structures by means of physical models, performance of tests for the needs of development of new technologies of construction, or new devices through which the safety of structures against the effect of different dynamic

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loads is enhanced, and tests for proving the quality of vital elements, or components in the field of mechanical and electrical industry whose exposure to earthquake effects may cause extensive direct or indirect damage.

Each of these categories related to shaking table experiments has its own specificities that have a limiting effect on planning and performing these investigations. These limitations should be known and well analyzed by professional researchers in the laboratories.

Similarly to other engineering disciplines, earthquake engineering scientists were permanently led by the idea of verification of the seismic stability of their products (the engineering structures) prior to their construction.

Regardless the extent of similarity between different types of engineering (mechanical, electrical, civil engineering, etc), there is a characteristic in the concept of verification of the quality of products that makes them essentially different.

Namely, unlike other types of engineering, the products of civil engineering are unique from the aspect of their geometry and main mechanical properties. If one adds this fact, which is specific only for seismic excitation, then it is more than clear that the concept of seismic verification of the stability of structures should be based on another approach.

This approach is based on the idea that investigations of the stability and dynamic behavior of structures should be performed on physical models tested under simulated natural earthquake effects.

At first the paper focuses the attention on the feature of the structural control for reducing the effects of dynamic vibrations starting from the analysis of dynamics of free rigid blocks and their rocking behavior, also in case when a control system is applied at their top.

Then, another problem was investigated relevant to the dynamic response of a multi-plane steel structure, also is case it is equipped with a base isolation system.

With reference to the first considered problem, one should emphasize that the rocking response and the possibility of overturning of rigid bodies in earthquakes are central considerations in seismic safety problems, which may result in the damage of precious and ancient pieces.

These problems start from the behavior of single sculptures in the museums and go to interest Greek and Roman stone temples, ancient buildings of the monumental heritage, generally masonry fabrics, but also concrete buildings.

Generally speaking, the rocking and overturning of a variety of structures, such as electrical equipment, retaining walls, liquid storage tanks, tall rigid buildings, tombstones and so on, and the need of understanding and predicting these failures in association with the attempt of estimating the related intensity levels of ground motion have motivated a number of studies on the rocking response of rigid blocks.

Nevertheless, the starting interest in the modern theory of the dynamics of a rigid block mounted on a rigid oscillating surface is relatively recent.

The first investigations date back to Milne [34] and Perry [35], who estimated the intensity of ground shaking observing its effects on tombstones and monumental columns, whether they overturned or remained standing.

The first significant attempt to accurately describe the motion of rocking blocks was produced by Housner [36], who examined the free and forced vibration responses to rectangular and half-sine pulse excitations, and, using an energy approach, presented an approximate analysis of the dynamics of a rigid block subjected to a white-noise excitation [37].

Classification of basic motion components is due to Ishiyama [38], who individuated in slide, bounce and rock the fundamental response modes, and, finally, provided the combination of these three modes for the study of any motion of a rigid body in a plane, thus determining six different situations: rest, rotation, slide, slide and rotation, slide and bounce, rotation, slide and bounce.

Many authors (as e.g. Aslam et alii [39], Tso & Wong [40], Anooshehpoor & Brune [41]) executed experimental campaigns in order to confirm their numerical models. For example in the study by Tso & Wong [40] they consolidated many of the theoretical results on steady state rocking responses of rigid blocks, by realizing an experimental investigation on a rigid block prototype consisting of a rigid upper block pivoting on specially designed foundation pedestal.

Many problems are common to the issues as the size effect which must considerably be explored whereat, for the materials as masonry, concrete, steel, it has been proved that the strength of the materials is increased with the decrease of proportions. Namely, the strength of the materials deteriorates if their proportions increase. The investigations have proved that this change is not linear and can hardly be analytically defined.

If steel is taken into consideration for which the producers of material (bars, steel plates) usually provide the strength characteristics, for the materials of physical models which are based on concrete, these differences should be defined by the researcher and incorporated in the model computation.

Although there are a number of investigations of this effect, the referent values should be taken informatively because the dimensions of the elements (beams, columns, plates) depend on the scale of the quantities.

In the paper the shaking tests on some rigid blocks developed at the “Federico II” University of Naples and on a steel frame at the “SS Cyril and Methodius” University of Skopje are reported. Both the presented cases, even if different from each other, indicate a common path in approaching the testing by the shaking table facility which is recognized, beyond its intrinsic limits, an important instrument to study the dynamic response of a structure.

The experimental investigations treated in the paper is also aimed at evaluating the possible effectiveness of some devices for mitigating the dynamic response for the considered applications, which is also concerned to structural models exhibiting a non-linear response under dynamic excitation due to the change in sign of dynamic equations during the motion.

II. SHAKING TABLE TESTING AT THE LABORATORY IN NAPLES

II.1 Shaking Table and Control System

At the Laboratory of Materials and Structural Testing of the University of Naples "Federico II" some testing are developed on a unidirectional shaking table moving in the horizontal direction. The shaking table is an MTS system and it is automatically connected to a system which both gives the input signal to the table and records the output signal from the block (Fig.1). The interest basically lays in the intrinsic non-linearity and uncertainty affecting the beavhiour of rigid blocks [42],[43].

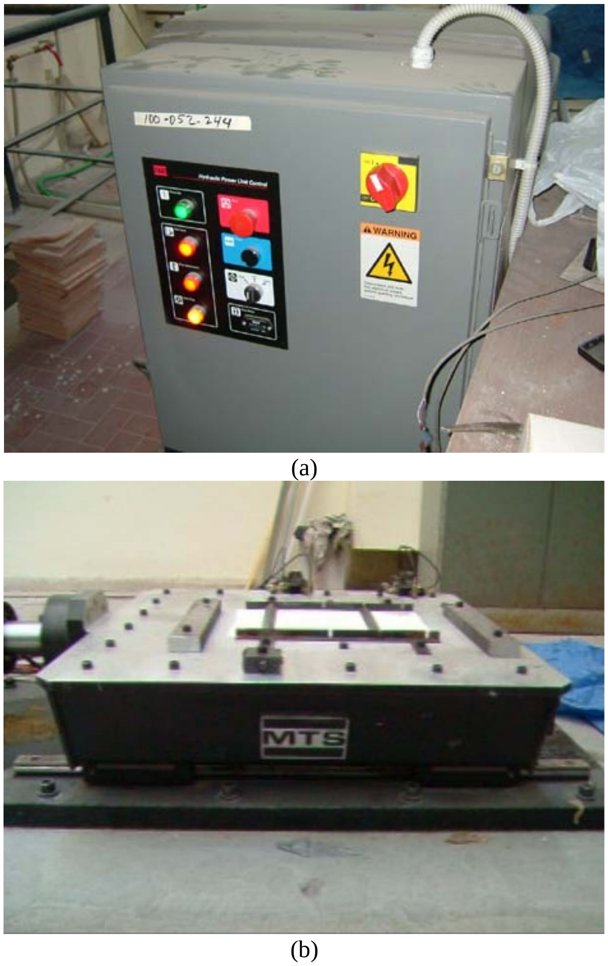


Fig.1– a) Hydraulic pump and b) moving plate of the shaking table system at the Laboratory of Materials and Structural Testing in Naples (Italy).

The experiments were executed keeping a fixed span for any testing cycle and varying the frequency value of the sine base-excitation inferred by the shaking table in the range from 1 Hz and 50 Hz with frequency steps of 1 Hz, and using different span values in the different testing cycles (for details see [26]).

In order to monitor the response of the adopted rigid blocks one used a PCB capacitive accelerometer, placed on the top of each block.

As well known, since integrating accelerometer time histories without proper filtering usually produce drifts in the calculated accelerations, some signal processing is generally necessary, especially for integrating accelerometer records.

Although the ruggedness and high bandwidth of modern accelerometers makes them a preferred choice for measuring vibration, these attributes can also result in measuring unwanted high-frequency noise. While mechanical filters and proper mounting techniques can reduce the effects of this noise, electronic filters can accomplish the task as well.

In the specific case, one adopted a high-pass filtering created in a LabVIEW environment with a 10th order Butterworth filter mainly in consideration of the characteristics of the adopted accelerometer.

II.2 Rigid block' testing

The experiments were executed on some rigid blocks made by Ytong and on some aluminum parallelepipeds both having various sizes and aspect ratios (thickness/height). The aluminum blocks are empty and made of thin aluminum plates, each one 0.5cm thick (Fig. 2).

Fig.2– Sample of tests executed in Naples on aluminum blocks equipped with TLD.

The whole prototype was thought in such a way to have the impact or pivotal points between the block and the base plane at well defined positions, which resulted in the two requirements that no sliding of the model should occur on the base and the blocks should be sufficiently stiff such to be considered rigid.

Under these assumptions, only rotations around the two base edges of the blocks were allowed according to the motion of the shaking table.

This case is complicated by the motion's characteristics of the block, which exhibits some peaks due to the impacts of the block with the plane of the shaking table and that need to be corrected by an additional appropriate filter.

The need of predicting and preventing failures associated to rocking and overturning of rigid structures undergoing strong ground shaking have motivated a consistent number of studies on rocking response and the possibility of coupling some sloshing devices with rigid blocks for attenuating their response to dynamic excitations is of clear interest.

To this aim, a large number of results relevant to experimental investigations on the aluminum blocks and on their coupling with Tuned Liquid Dampers (TLDs) was collected and some samples of those are shown in Figs.2-3.

Fig.3– Sample of testing in Naples on aluminum blocks equipped with TLD.

Comparison between the various liquid depth levels reveal the potential efficiency of the liquid damper system in damping the vibrations of the structural model.

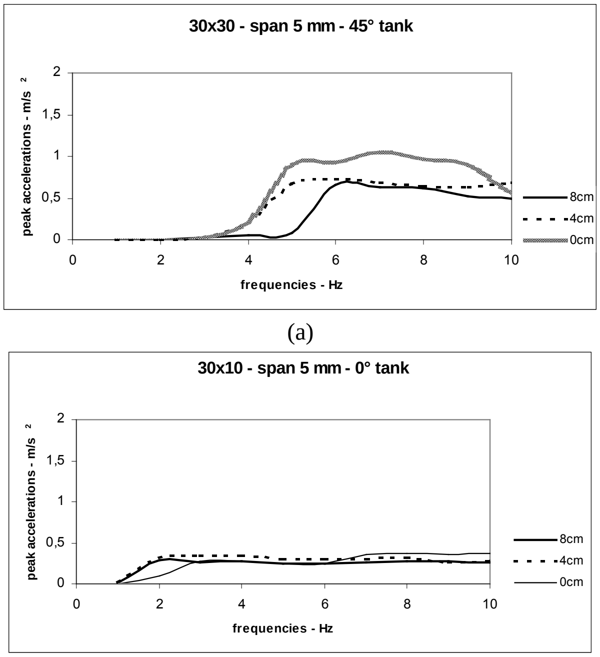
Looking at the results of the experimentation, some basic features can be outlined (Fig. 4).

The benefit by the liquid damper is not homogeneous on the frequency range, but it is dependent on the frequencies at which the power of the excitation is lumped. In particular the benefit is much higher in some frequency range which also depends of the geometrical/inertial properties of the structure under observation.

Moreover the design of the liquid damper (the liquid mass and the shape of the tank) is determinant for the performance of the device.

In all the tests the benefit potentially appears very significant but some cases have been encountered where the device increases the risk.

In conclusion a theoretical settlement cannot be ignored and the device has to be carefully designed with regard to the shape and the entity of the sloshing liquid mass, keeping into account both the excitation's character and the object's inertial properties.



(a)

(b)

Fig.4 – Recorded responses for: a) the block 30x30 equipped with a trapezoidal TLD for different levels of liquid, and b) the block 10x30 equipped with a rectangular TLD for different levels of liquid.

III. IZIIS SHAKING TABLE TESTING IN SKOPJE

III.1 Shaking Table and Control System

The Dynamic testing laboratory at IZIIS is equipped with a MTS Systems Corporation servo-hydraulic 5.0 x 5.0m in plan 5-DOF (degrees-of-freedom) shaking table with nominal 40 t payload capability, which has been in continuous operation since 1982 (Fig.5).

Its original analog Three Variable Control (TVC) system, although it was functional, was out dated and the ageing effect contributed for reducing the overall characteristics of the shaking table. Therefore, in order to keep sustainability and top peak performance of the seismic system, high bandwidth response and system fidelity, at the end of Q1 2011, the original analog control system has been replaced with the digital MTS state-of-the-art real-time TVC system of the latest generation.

The table is made of pre-stressed reinforced concrete having mass of approximately 33t. The table is supported by four MTS 206.42s vertical hydraulic actuators located at four corners at a distance of 3.5m in both orthogonal directions, while in horizontal-lateral direction the shaking table is controlled by two MTS 204.81s hydraulic actuators at a distance of 3.5m. In the longitudinal direction, two pressurized bearings have been installed, one for controlling the displacement and the other for controlling the force. The horizontal and vertical actuators of the table are supported by reinforced concrete rigid structure. The total mass of the supporting structure is 1200 t and this structure is separated from the rest of the laboratory structure by an expansion joint.

(a)

(b)

Fig.5 – (a) The shaking table and (b) the relevant hydraulic system at the Laboratory of IZIIS in Skopje (Republic of Macedonia).

A three bay steel frame model of a hypothetical building has been tested at IZIIS on biaxial shaking table under two different supporting conditions (Fig.6).

At first, the model having the total mass of approximately 24.0 t was tested with Base Control System (BCS), produced by GERB GmbH, Germany, and after that, more or less, the same excitations were repeated for fixed base model (without BCS). For both supporting conditions large number of experimental data has been recorded in terms of time histories of accelerations, displacements, axial and bending strains at various locations of the frame structure.

The gravity load due to table and the model mass is sustained by a special system with static supports which utilizes nitrogen. The total bearing capacity for static loads is 720kN. This system is located in the lower part of each of the four vertical actuators.

In order to provide the required power of the actuators, three inter-connected hydraulic pumps, MTS model 506.71 hydraulic power supplies (HPS), with a maximum flow of 1,250l/min and a maximum pressure of 350 x 105Pa are used.

The required electric power to feed the three pumps is 1,020A. In order to increase the working flow of the system, four additional pressured accumulators with capacity of 60 liters of hydraulic fluid are used.

The maximum over turning moment is 460kNm and the bandwidth of operating frequency is 0.1-80Hz.

As control system the MTS 469D Digital Control system was designed to provide simpler shaking table tuning, system operation, and test execution.

The controller consists of MTS console assembly, associated cabling and control software.

The MTS console assembly has imbedded processors, real-time MTS 494 series hardware.

The control software consists of the real-time control software and the control panel software.

The real-time control software drives the processors to generate command and error signals using state-of-the-art Three-Variable-Control (TVC).

Fig.6 – Geometry of the steel frame tested to IZIIS.

The control panel software runs on a PC and has a graphical user interface consisting of interactive, modeless dialogs that are used to enter system parameters and execute a test [see e.g. 3-5].

III.2 Multi-planes steel frame’ testing

The multi-planes steel frame shown in Fig. 6 and having the total mass of approximately 24.0 t was tested with Base Control System (BCS), produced by GERB GmbH (Germany), and after that, more or less, the same excitations were repeated for fixed base model (without BCS).

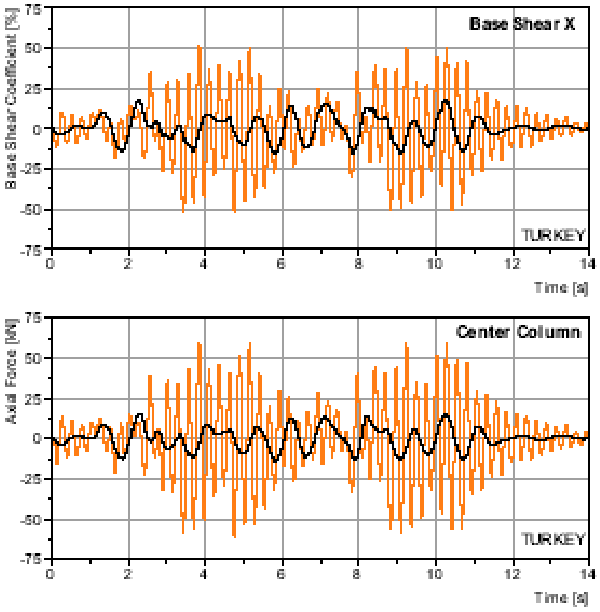


Fig.7 – Sample of data relevant to the tested steel frame: comparison of response time histories for BCS and fixed model.

The tested steel frame model with BCS is shown in Fig. 6. The columns, as well as the beams are made of steel hollow profiles appropriately welded at the joints. The structure in the central span has special bracing substructure, which is used for modeling of the stiffness for other test. In the orthogonal direction the frame model has only one span on a distance of 1.5m, but by adding of bracing along the height of structure, the stiffness in this direction has been significantly increased. The height of each floor is 0.75m, while all three spans are equal 1.5m each.

In the case of the steel frame a tuning procedure is elaborated to adjusting multiple control variables, such as gains, lead terms, and notch filters, which allows obtaining unitary gain of the transfer function between command-reference and feedback signal within the frequency bandwidth of interest. As an additional tool to fixed control techniques, the Adaptive Control Technique is used when high fidelity in signal reproduction is required.

Out of large number of analytical data of the response time histories for acceleration at Level 5, axial forces in corner and center columns, shear base coefficient obtained by the analysis of the BCS model and fixed base model for USNRC and Turkey earthquakes scaled to input PGA=0.20g were collected and a sample of them is presented in Fig. 7.

From all these data it appears the BCS model has much more favorable behavior compared to fixed base model, thus reducing accelerations (inertial forces), base shear, and axial forces in corner columns in order of 2 to 3 times, depending of the storey level. Reduction of axial forces in center columns is even higher.

IV. CONCLUSION

With reference to the data relevant to some laboratory testing on some rigid blocks and on a multi-plane steel frame placed on a shaking table and to the adopted control devices for reducing their dynamic responses, some considerations can be figured out.

Recent growing insert in liquid dampers for application to structures is attributable to several advantages, including: low coast, easy to install in existing structures and effective even for small-vibrations.

In all the tests on the rigid blocks coupled to the TLD the benefit potentially appears very significant but some cases have been encountered where the device increases the risk.

Therefore a theoretical settlement cannot be ignored and the TLD device has to be carefully designed with regard to the shape and the entity of the sloshing liquid mass, keeping into account both the excitation's character and the structure's inertial properties.

In the case of the steel frame, the testing data demonstrate that the BCS model has much more favorable behavior compared to fixed base model, thus reducing accelerations (inertial forces), base shear, and axial forces in corner columns in order of 2 to 3 times, depending of the storey level.

Then a methodology was developed for a seismic design and strengthening of mixed reinforced concrete masonry buildings built in the mid 1950s as a part of the large seaside hotel complex in Rimini-Italy (Fig.8). Some experimental investigations were developed as a part of the research work carried out within an international project accomplished by the University of Bologna and IZIIS and financially supported by the Emilia Romagna Italian Region [5].

The strain rate effect, for example, in different models is of concern to be analyzed for small scale models. In the case of smaller scales (1/100), this effect should certainly be seriously considered and incorporated in the final results from the investigations.

The remaining effects as the long term effects, the ductility, the fabrication, the creeping, the shrinkage, etc, that do not depend on the remaining similitude factors but have effect upon the real model reproduction should be analyzed with particular attention in order to evaluate their individual effect upon the final results.

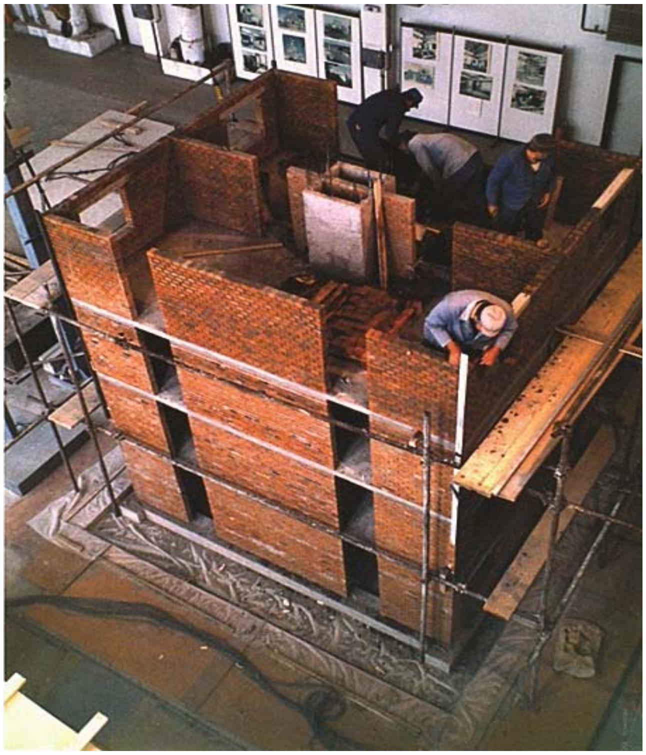


Fig.8 – Some testing on a masonry multi-plane structure in IZIIS.

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