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Force-Instrumented Reaction Wall for Dynamic Testing on LNEC's 3D Shaking Table

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***Abstract* – This communication presents a newly developed test set-up with force measurement capability, recently developed and installed to enable static and dynamic tests on the LNEC's 3D shaking table facility. The system consists of a reaction wall equipped with a force sensing device anchored to the laboratory's rigid floor, providing high structural stiffness and accommodating static and dynamic motions on the three orthogonal axes. Suitable sensibility to axial loads in the range 2,5 kN to 200 kN associated with low sensitivity to tangential loads, repeatability, reproducibility among other favourable metrological characteristics emphasise the sensing system attributes. A comprehensive description of the set-up development, design, construction, installation on the laboratory, force measurement chain, as well as the metrological characterization of the device was performed, highlighting the potential to test structures or devices under relative displacements. This set-up has extended the laboratory testing capabilities, making available means to perform tests on energy dissipation systems for vibration mitigation, like dampers or isolation devices, or even any structural systems under static, pseudo-dynamic or dynamic motion.**

Keywords – Reaction Wall, Static and Dynamic Testing, Shaking Table Testing, Measurement Chain Characterization, Industry, Innovation and Infrastructure

I. INTRODUCTION

Recent specification demands for testing structures under static and dynamic tests led to the development of an additional reaction wall on the North side of LNEC's testing room facilities, incorporating force measurement capability. A new test set-up was developed including the following requirements: i) possibility to be removable; ii) high rigidity structural system, ensuring a first natural frequency higher than 20 Hz; iii) accommodate static and dynamic motions on the three axis; iv) a measurement range between 2,5 kN to 200 kN on the normal axis; v) low sensitivity to tangential loads vi) aprox. 1 m^2 of installation surface area (vertical). This communication describes all the steps to develop a new Force-Instrumented Reaction Wall for Dynamic Testing on LNEC's 3D Shaking Table, from the design stage up to the installation on the laboratory and making it operational, including the measurement chain characterization. This test set-up aims to address an existing gap on testing methodologies at LNEC, enabling the possibility to test structural systems under static, and dynamic loads, like energy dissipation devices.

II. RELATED RESULTS IN THE LITERATURE

The Earthquake Engineering and Structural Dynamics Unit (NESDE) of the Portuguese National Laboratory for Civil Engineering (LNEC) has nowadays different set-up possibilities to perform static and dynamic tests using the uniaxial shaking table (ST1D) and the triaxial shaking table (ST3D) [[1]-[2]].

Since the early days LNEC has developed and installed facilities to perform experimental activities in the field of earthquake engineering. The first test bench to perform seismic tests on reduced scale models was installed at LNEC in the 60s, which comprised a Goodmans model VG-108 electrodynamic shaker attached to a movable table, that was able to reach a peak force of 3000 lbs in the frequency range up to 1000 Hz [3]. Later, in the 70s a uniaxial shaking table consisting of a 3 m × 2 m steel platform body operated by a hydraulic actuator supplied by a dedicated oil-hydraulic circuit was developed and installed at LNEC [4]. It was later provided with a vertical shake table that allows the possibility to work on the vertical direction using the same hydraulic actuator, that has to be rotated and connected to the vertical shake table [5]. With a maximum force of 250 kN, a stroke of ±100 mm, a maximum velocity of 21 cm/s in the range up to 25 Hz, this equipment allowed the possibility to test higher physical scaled models for requested studies and consultancy, support research studies and PhD programs.

The increasingly demanding requirements for reproducing seismic excitation along all three directions led to the development of a triaxial shake table, which has been installed and operational since the mid-1990s [3]. The LNEC-ST3D shake table is a large-scale experimental facility designed to reproduce seismic actions for the dynamic characterization and structural assessment of civil engineering systems. The testing platform has the geometry of a triangular prism and provides a useful testing dimensions of 6,4 × 5,6 m², enabling the installation of full-scale or reduced-scale physical models. An oil-hydraulic system supplies oil to the actuators of each axis, managed by a servo-control system commanded by a supervision system where the reference signals are defined. The system main characteristics are: maximum payload of 40 tons; three independent orthogonal axes, allowing the imposition of longitudinal (±200 mm, ±50 cm/s, ±500 kN), transversal (±200 mm, ±60 cm/s, ±750 kN), and vertical (±200 mm, ±40 cm/s, ±1250 kN) motions; passively restrained rotational degrees of freedom through torsion bars; frequency range between 0 Hz and 40 Hz. The building where this facility is installed is provided with three reaction walls (on South, East and West sides) built around the LNEC-3D with a maximum height of 7 m, that adds additional test set-up possibilities. Due to its characteristics, the LNEC-3D shake table has been a working mainly for research applications in structural and earthquake engineering founded by national and international research programs, and also, at a lower number, on static and dynamic tests for seismic qualification of equipment and components for the manufacturing industry and electric power distribution [1]. Recently, these facilities have been upgraded to allow the possibility of performing substructuring tests to overcome the limitations of shake table tests on reduced scale models [2], [6], [7]. One of those substructuring test type is the experimental evaluation of reinforced concrete (RC) frames' seismic response taking into account both the in-plane and out-of-plane behaviour of their enclosures. An innovative Testing device for Innovative Masonry infills (TIM) was developed, that together with the shaking table ST3D and one reaction wall, creates the boundary conditions for testing wall panels with simultaneous actions in both horizontal directions [8]. This technique has been used in several research projects since then [7]. Another type of substructuring tests developed at LNEC is based on the so-called hybrid simulation which is a technique that blends the numerical and experimental approaches to evaluate the response of structures under seismic actions. The dynamic behaviour of a structure under analysis is conducted by experimentally testing a critical component (or a substructure) while numerically modelling the rest of the structure, by keeping the compatibility on the degrees of freedom (DOFs) on both models, such the restoring forces measured on the physical model in a laboratory are returned to the numerical model at each time-step of the analysis to define the next input on the experiment. A robust framework software for hybrid simulation tests was developed and validated for a two-dimensional steel moment-resisting frame (MRF) [9].

III. DESCRIPTION OF THE METHOD

The idealized test set-up to fulfil the requirements consists of a steel interface structure (steel frame / reaction wall) that is positioned and attached to the laboratory floor using 7× M30 screws with a tightening torque of 1720 N·m. An extension pipe structure with one rigid plate on each side is linked to the reaction wall through 12× M24 screws tightened at 700 N·m. This one has the possibility to be positioned at a minimum height of 1m (from the floor) and at higher levels in steps of 0,3 m. On Fig.1 it is depicted the idealized test set-up.

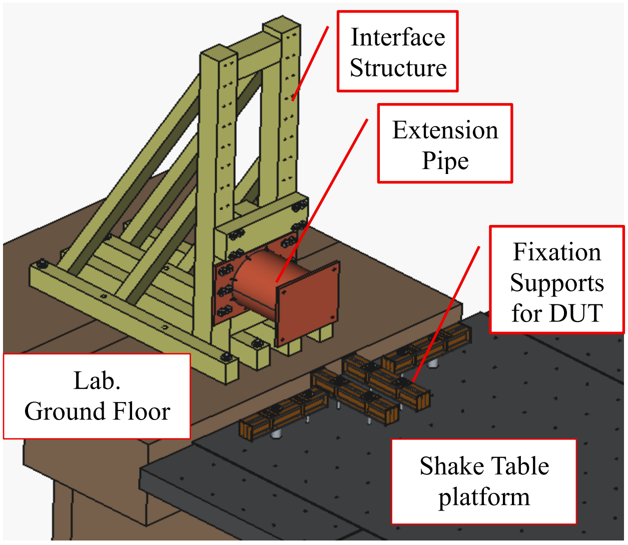

Fig. 1. Force-Instrumented Reaction Wall test set-up

The device under test (DUT) will be connected on the extension pipe end on one side and, on shake table platform on the other side, enable relative displacement experimented by the DUT. Fig.1 shows also one example of fixation on the shake table platform using rigid fixation supports and M30 screws. The interface structure will act as a reaction to the forces expected to be developed by the DUT during the tests. This set-up was designed sufficiently rigid, strength and compatible with the geometrical constraints expected for fixation of the DUTs. Regarding to the adopted solution, a steel frame already available at the NESDE facilities was used as the interface structure, whose mechanical behaviour had to be verified against defined requirements. This structure is a welded construction frame comprising closed section profiles I, U and rectangular pipe sections, with the following main dimensions: 4,46 m height, 3,2 m length and 1,7 m width. On the other hand, the extension pipe is also a welded construction frame designed with 40 mm thick plates with 1,3 m × 0,86 m on the fixation plate and 0,96 m × 0,86 m on the front plate, and a 0,76 m of external diameter × 0,82 m length × 10 mm thickness circular pipe, within the plates. The material used on these frames is the structural steel grade S235. A numerical model of the structure and extension pipe was developed in SAP2000 software to verify the structural strength and stiffness through static and dynamic analysis. First, a 3D model of the extension pipe alone was developed to guarantee enough strength, stiffness and estimate the strain field on the pipe to support the strain gages placement for force measurement. The model was built using shell elements and, spring elements connecting the 12 holes to the ground (model analysed alone - all DOF restrained) were set to reproduce the local connection stiffness due to the screwed joint (comprising the interface structure steel frame local stiffness, extension pipe plate local stiffness and screw). The local stiffness between the extension pipe and the reaction steel frame was calculated as 1×10^9 kN/m and was considered as boundary condition. A numerical model of the complete interface structure (interface structure steel frame and extension pipe) was also carried out using SAP2000 software using beam elements and, as boundary condition, vertical springs were applied at the front and back connections between the interface structure steel frame and the floor, having stiffnesses of $6{,}35\times10^5$ kN/m and $6{,}77\times10^5$ kN/m on bottom and front connections respectively. These springs reproduce the local stiffness of the connection, i.e. concrete slab (different slab thickness conducting to different stiffnesses), steel frame local stiffness and screw. Moreover, a static verification was carried out on the elastic state, considering the worst expected loading scenario: 100 kN of axial compression force and vibration in the 3-axis with 60 % of the axial load, i.e. 40 kN to 160 kN on the longitudinal axis and ±60 kN on both transverse axes (horizontal and vertical).

Regarding to force measurements, those are carried out through a measurement chain consisting of six half bridges with HBK LY41-6/350 V1 strain gages, plus HBK QuantumX 840B universal amplifier and acquisition system, and a computer, as depicted in Fig.2. The strain gages were installed on six points equally spaced along the pipe perimeter for strain measurement and connected to the HBK QuantumX 840B acquisition systems, to complete the bridge, supply the input voltage and measure the bridge output. The bridge output was converted into the correspondent force after the calibration tests and the force of each point (Force 1 to 6) will be measured and recorded, as well as the average value of the six measurements during the tests.

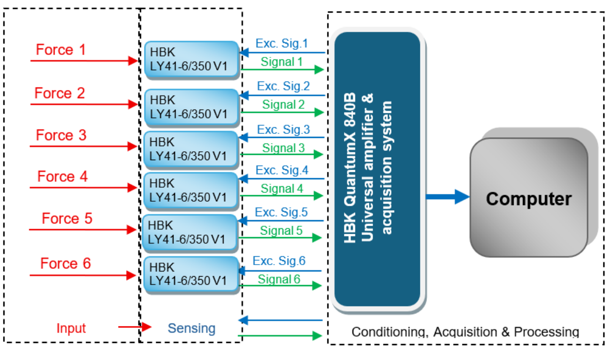

Fig. 2. Force Measurement Chain.

The adopted model ([10],**Error! Reference source not found.**) for each measurement channel is an output-input relationship $\Delta U_{out}/U_{in}$ of the bridge taking into account an half bridge circuit with identical resistances on electrical strain gages, two strain gages on the same point 90º rotated (one measuring the axial strain and the other measuring the transverse strain – Poisson effect), taking the Hook's law, $\Delta U_{out}/U_{in}$ is

$$\frac{\Delta U_{out}}{U_{in}} = \left(\frac{(1+\upsilon)\cdot k}{4}\right)\cdot\varepsilon = \left(\frac{(1+\upsilon)\cdot k}{4\cdot A\cdot E}\right)\cdot F, \qquad (1)$$

where: k is the gage factor, ν is the Poisson ratio, A the pipe's cross-section area, E is the Young's modulus, ε is the axial strain on the pipe and, F the correspondent force.

IV. RESULTS AND DISCUSSIONS

The analysis of the interface structure throughout the numerical simulations performed on SAP2000 and experimental evaluation showed the following results:

- The stresses analysis evaluated numerically on the whole structure allowed us to conclude that the structure meet the strength specification, since the resulting von Mises stresses in the interface structure compared with the yield strength of the structural material considered (235 MPa), leads to safety factors larger than 3,0.
- Regarding to the structural rigidity, the adopted set-up showed to be enough rigid, since a maximum displacement of 1,6 mm was obtained at the end part of the DUT (0,4 m out of the front plate, centred) for the worst force scenario combination (160 kN on the longitudinal axis and 60 kN on both transverse axes), which corresponds to 1,6/900=0,17% of maximum deflection.
- The dynamic analysis on the extension pipe showed that this component verifies the stiffness requirement since the results of the numerical simulation presented a first vibration mode of translation in the vertical direction with a natural frequency of 35,1 Hz, as shown in Fig.3-left. The dynamic analysis of the complete interface structure (reaction steel frame and extension pipe) showed to meet the requirements, since the first natural frequency of the ensemble is 23,9 Hz, corresponding to a vibration mode in the transverse direction of the structure, as shown in Fig.3-right.
- Finally, the results of experimental model analysis through impact hammer testing showed a first mode of vibration at 19,4 Hz with the same configuration as in the numerical simulations. This result, although bellow the specified one (20 Hz) is still reasonable. This difference is mainly attributed to the screwed joint, where a dependence between the natural frequency and the screw tightening force was found. The numerical model was updated by adjusting the spring stiffness.

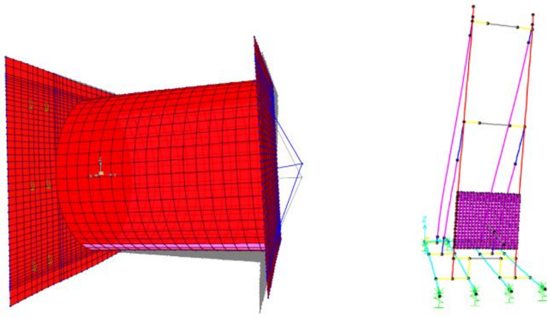

Fig. 3. Interface Structure deformed shapes of the first natural frequency: Left - extension pipe; and Right: interface structure, including reaction frame and extension pipe.

Afterwards, the measurement chain was characterized by applying several steps of compression force using a SI traceable reference force standard inserted between the pipe and the force input, generated by the shaking table. The results (Fig. 4) show a suitable repeatability rand the 3rd order polynomial adjusts to the data with low values of residues (1,2 % max). Moreover, the model in equation (1) reasonably reproduces the measurements although with a linear relationship.

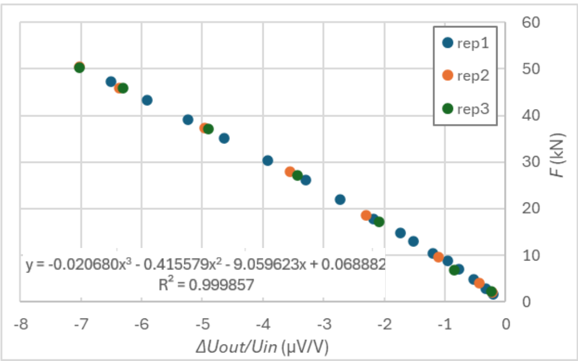

Fig. 4. Calibration test results: reference standard force measurement vs. measurement chain bridge output.

V. CONCLUSIONS AND OUTLOOK

The work presented on this communication demonstrates the successful development, installation, and validation of a new Force-Instrumented Reaction Wall for Dynamic Testing on LNEC's 3D Shaking Table. Consists of a reaction wall incorporating a force sensing device ranging from range 2,5 kN to 200 kN, anchored to the laboratory rigid floor that accommodates static and dynamic motions on the three orthogonal axes.

An idealized solution was proposed resulting on a custom-designed, adaptable, and cost-effective alternative, allowing the configuration of the test set-up to be tailored to specific experimental needs. The numerical and analytical models developed, were essential for designing a solution that meets the requirements, namely structural strength, stiffness and strain. The developed and installed solution was characterized by experimental techniques, where the structural stiffness was evaluated through a dynamic analysis by impact hammer testing, and the metrological characterization was performed using a traceable force reference standard. The experimental results obtained showed good agreement with the results of the numerical and analytical models, validating and highlighting the adopted design methodology.

The proposed solution is a contribution to sensors, diagnostics, optimization & control research area with potential application to perform tests on structures or devices experiencing relative displacements, extending the testing capabilities of the laboratory on static, pseudo-dynamic and dynamic tests.

The solution has already been applied with success on the characterization of energy dissipation devices to reduce the vibration level of structures, validating the proposed solution in the application field.

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