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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; and a 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 available 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, 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.

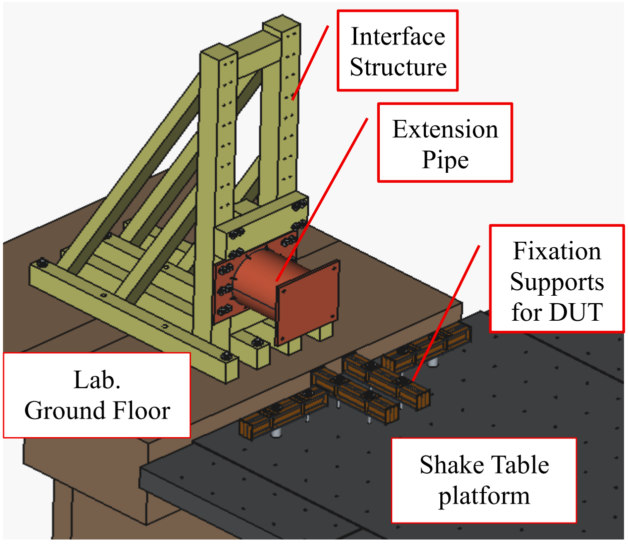

Fig. 1. Force-Instrumented Reaction Wall test set-up

The device under test (DUT) will be connected on the extension pipe end on one side and, on the 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 hollow 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 anchor side and 0,96 m × 0,86 m on the front side, 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 gauges (SGs) 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. 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 gauges, plus HBK QuantumX 840B universal amplifier and acquisition system, and a computer, as schematically depicted in Fig.2. The SGs 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.

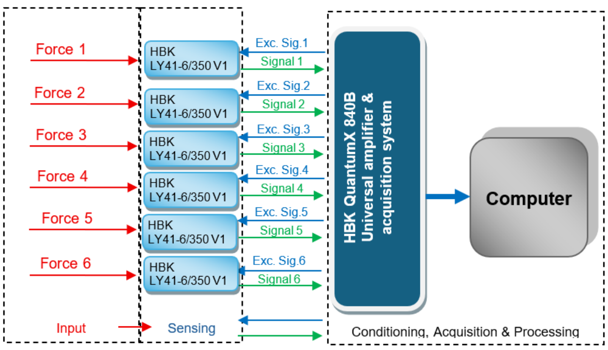

Fig. 2. Force Measurement Chain.

The adopted model ([10],[11]) 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 two SGs on the same point 90º rotated (one measuring the axial strain and the other measuring the transverse strain – Poisson effect) and, 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 gauge 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. Fig. 3 shows the final assembly of the Force-Instrumented Reaction Wall, with a DUT (not show) installed between the interface structure and the shake table platform.**Erro! A origem da referência não foi encontrada.** It is also observed the extension pipe instrumented with the six half bridge circuits, each consisting of two SGs, as well as three acceleration measurement points used to characterize the dynamic behaviour of the system prior the testing.

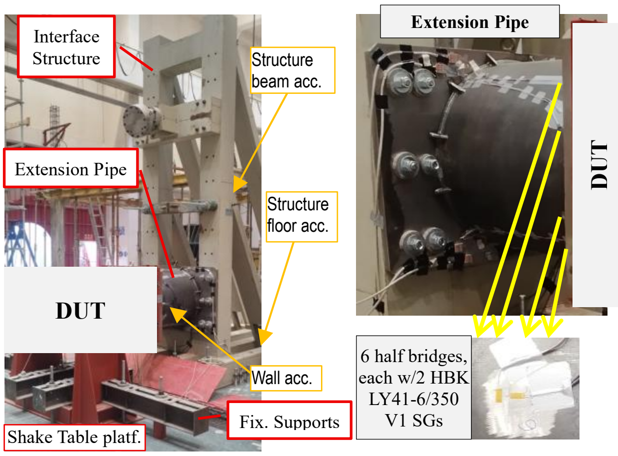

Fig. 3. Force-Instrumented Reaction Wall test set-up prepared with a device (DUT) for testing

IV. RESULTS AND DISCUSSIONS

The analysis of the interface structure throughout the numerical simulations performed on SAP2000 and experimental evaluation provided 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.4-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.4-right.
- Finally, the results of the 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.

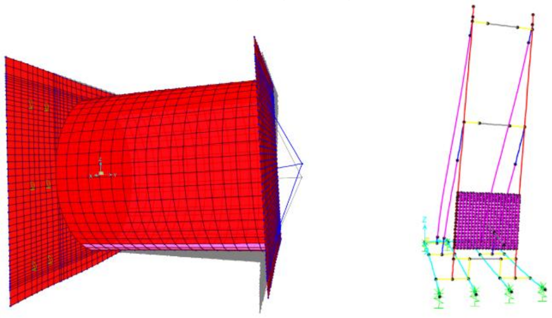

Fig. 4. Interface Structure deformed shapes of the first natural frequency: Left - extension pipe; and Right: interface structure, including reaction frame and extension pipe.

Afterwards, the measurement chain was characterized onsite by applying several steps of compression force using a SI traceable reference force standard inserted between the extension pipe and the force input device, generated by the shaking table. The results in Fig. 5 show a suitable repeatability and the third-order polynomial adjusts to the data with low values of residuals (1,2 % of tested measurement range). This model is specified in ISO 376 for force transducers and force testing machines and considered suitable because the resulting residuals are generally of low magnitude and exhibit a random distribution over the 10% to 100% measurement range. The adoption of a third-order polynomial model reflects a compromise between accuracy, stability, simplicity and consistency. The observed nonlinear relationship is primarily attributed to mounting effects, although other factors, including material nonlinearities, SG characteristics, mechanical hysteresis, and nonlinearities in the signal conditioning system, may also contribute to the transducer response.

The analytical model in equation (1) assumes a linear relationship between the applied force and the Wheatstone bridge output and was used for the initial instrument design. The linear term of the model can be calculated from the: cross-section area of the pipe A=23656 m2; the Poisson ratio ν=0,3 and the Young's modulus E=210 GPa of the material, and the SG gauge factor k=2,1. Table 1 summarizes the results obtained from the linear fit, including the correlation coefficient and the residuals. The large discrepancy between the maximum and minimum residuals is noteworthy. As illustrated in Fig. 6, the residuals follow an approximately half-sine pattern, indicating that the relationship between the variables is not strictly linear. This non-linearity is also evident in the comparison between the calculated values and the reference standard values shown in the same figure.

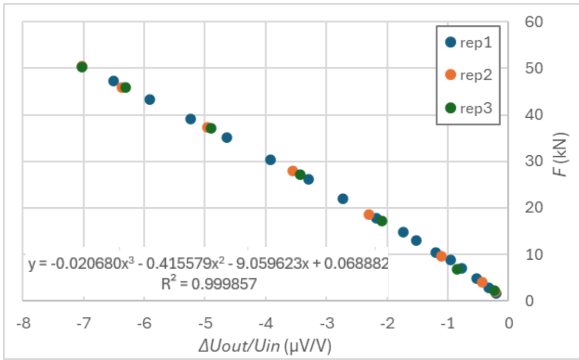

Fig. 5. Calibration test results: reference standard force measurement vs. measurement chain bridge output.

Table 1. Model parameters, correlation coefficient and residuals for the three polynomial models.

Model F=a·x^3+ +b·x^2+c·x+d	**1st order**	**2nd order**	**3rd order**
a [kN/(μV/V)^3]	0	0	-0,02068
b [kN/(μV/V)^2]	0	-0,19772	-0,41558
c [kN/(μV/V)]	-7,24433	-8,47082	-9,05962
d [kN]	0	0,362877	0,06888
Correl. coef. - r	0,997877	0,999776	0,999857
Residuals (kN) [min & Max]	-2,42 0,63	-0,56 0,54	-0,62 0,45

Note: x on the model is the bridge output $\Delta U_{out}/U_{in}$

The application of a second-order polynomial model resulted in calculated values that are in better agreement with the reference standard values. In contrast to the linear model, the residuals are distributed approximately randomly around zero and present significantly smaller amplitudes. Additionally, the relationship between the calculated and reference standard values is essentially linear, demonstrating the improved accuracy of the polynomial model and supporting the presence of non-linearity in the original data.

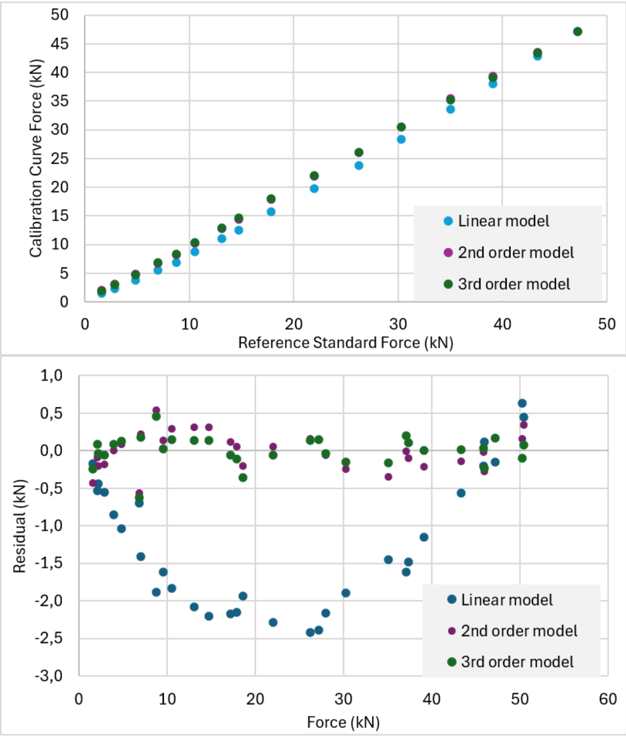

Fig. 6. Calibration curves results' for three polynomial models and residuals.

The highest accuracy was achieved using the third-order polynomial model. As shown in Table 1, this model yields the highest correlation coefficient and the smallest residuals, whereas the linear model produces the lowest correlation coefficient and the largest residuals. However, the improvement in accuracy from the second-order to the third-order model is only marginal. Consequently, the values calculated using these two models are almost indistinguishable, as illustrated in Fig. 6. This suggests that, although the third-order model provides the best statistical performance, the second-order model may already offer an adequate representation of the data while maintaining a lower level of complexity. However, as already stated before, the third-order polynomial was used to model the data.

In order to assure measurement quality within the modern metrology probabilistic approach, the evaluation of measurement uncertainty and traceability was performed according to the Guide to the Uncertainty in Measurement [12]. The procedure used is intended to evaluate the measurement uncertainty taking into account the most relevant sources of uncertainty resulting from the mathematical model parameters, model deviations, reproducibility, repeatability and, the uncertainties associated with the reference standard measurements.

First, the maximum absolute errors resulting from the mathematical model (interpolation errors) were calculated from the residuals at each force step. The repeatability error was evaluated using the maximum absolute error obtained for each repetition. Likewise, the reproducibility error was determined from the maximum absolute error between two tests performed under different reproducibility conditions. Fig. 7 presents a graphical representation of the maximum absolute errors at each step, expressed as a percentage of the corresponding force step. It can be observed that the total error decreases with increasing force, following a power-law trend, from approximately 55% at the first step (≈2 kN) to about 1% at the final step (≈50 kN). The first steps also exhibit in general higher errors for each category that decrease as the force magnitude increase. Although the errors associated with the initial force steps are significant when expressed relative to the step value, they remain below 2% of the full measurement range of the test.

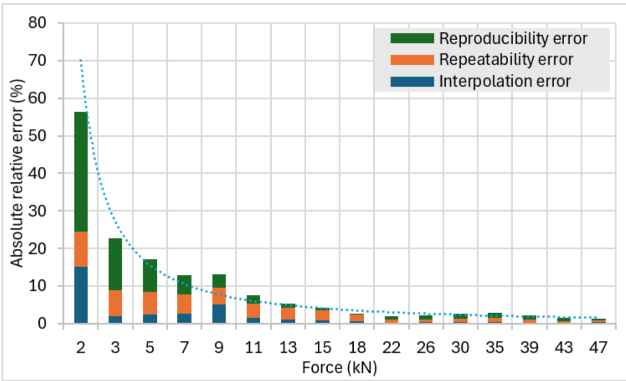

Fig. 7. Absolute relative errors (reproducibility, repeatability and interpolation) for each test step.

The measurement uncertainties were subsequently evaluated for each component according to the law of propagation of uncertainty [12], applied to the adopted third-order polynomial model. The corresponding sensitivity coefficients, correlation coefficients, and uncertainties associated with each model parameter were used to calculate the uncertainty contribution of the fitted polynomial model. The repeatability contribution was estimated from the standard error of the sample mean, assuming a normal distribution, whereas the reproducibility contribution was evaluated assuming a uniform distribution. The contribution of the reference standard was also considered, although its effect was relatively small compared with the other uncertainty sources. The combined standard uncertainty was then calculated for each force step and expanded using the Student's t-distribution. The results are presented in Fig. 8, where the estimated values and their corresponding uncertainty bounds are shown. As previously observed for the absolute errors, the first force steps exhibit relatively large uncertainties when expressed as a percentage of the step value. This effect is more pronounced in the uncertainty preliminary associated with the reproducibility component, which was penalized by the limited number of tests performed under reproducibility conditions (only two). Nevertheless, the maximum expanded uncertainty remained below 3.5% of the full measurement range of the test (50 kN), which is adequate under the adopted test conditions. Since the equipment is intended to operate over a higher force range, up to 200 kN, it is expected that the uncertainties at higher force levels will be lower, as indicated by the trend observed in Fig. 7 and confirmed by previous laboratory tests conducted under controlled conditions. Consequently, the maximum expanded uncertainty relative to the full scale (FS) drecreases to approximately 0.9% FS.

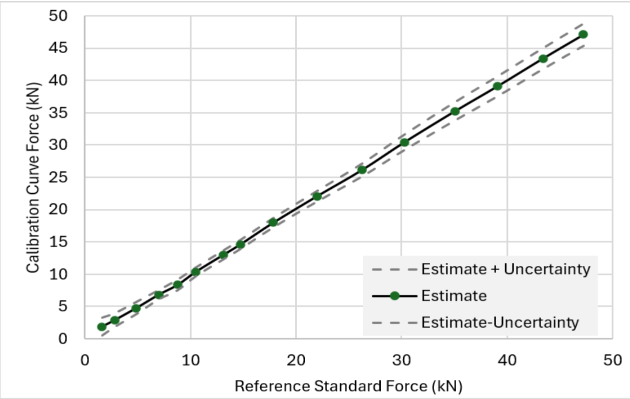

Fig. 8. Calibration curve results within the measurement range: estimate with the correspondent uncertainty bounds.

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.

VI. ACKNOWLEDGMENTS

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