JET-PACS PROJECT: JOINT EXPERIMENTAL TESTING ON PASSIVE AND SEMIACTIVE CONTROL SYSTEMS

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ABSTRACT :

An extensive experimental dynamic testing programme named JetPacs is being carried out at the Structural Laboratory of the University of Basilicata. The JetPacs Project has been developed within the RELUIS 2005-08 project (Research Line 7: Technologies for the seismic isolation and control of structures and infrastructures), involving partners from different Italian universities. With regards to dissipating bracing systems, the main objectives of the programme are: (i) to increase user awareness of specific aspects of the currently available techniques, (ii) to carry out a performance assessment of the different techniques, and (iii) to simplify and to suggest a design standardisation procedure.

Shaking table tests are carried out on a 2:3 scaled structural model derived from a prototype building, namely a 2-storey, 1-bay, three-dimensional steel frame. Both passive and semi-active bracing systems are used featuring the following energy dissipating materials and principles: (i) viscous fluids; (ii) viscoelastic materials; (iii) magnetorheological fluids; (iv) visco-re-centring elements and (v) hysteretic components. The structural model is subjected to three different sets of natural and artificial earthquake records, compatible with the Italian seismic code response spectra for A, B and D soil types. The seismic intensity is progressively increased until the design performance criterion is achieved.

In this paper, model dynamic identification test results are presented and key features of the experimental shaking table testing programme are outlined.

KEYWORDS: Energy dissipating devices, shaking table tests, experimental model, passive control, semi-active control.

INTRODUCTION

Traditional retrofitting techniques for framed structures are based on widespread strengthening of the structure and alternatively on the introduction of additional, very stiff, structural members. In recent times, innovative strategies for the passive and semi-active control of structures have been studied and experimented, such as those based on the insertion of energy dissipating braces in the frame. However, widespread application of these techniques has not yet been achieved, mainly due to the lack of extensive experimental information allowing for the adoption of less conservative design rules. These techniques have shown their effectiveness in reducing seismic effects on existing frames, but extensive experimental investigations are required to provide reliable analysis and design data.

Unfortunately, the increasing number of numerical and experimental studies on a large number of dissipating devices [Dolce et al. 2005] and the analysis of real life applications [9ISIED 2005] have not yielded an improvement in related codes and guidelines, in much the same way as for other innovative techniques (e.g. seismic base isolation techniques). In Europe, new seismic codes only implicitly allow for the use of such devices [CEN 2004, D.M. 14.01.2008], while very few codes worldwide provide for simplified design criteria [FEMA 356, 2000].

Various experimental methods are available for the seismic response assessment of structures equipped with dissipating devices. Shaking table tests are, in principle, the most reliable experimental method for this purpose [Dolce et al., 2001]. An extensive dynamic experimental testing programme, named JetPacs (Joint Experimental Testing on Passive and semiActive Control Systems), is scheduled to be carried out at the Structural Laboratory of the University of Basilicata. The JetPacs Project has been developed within the DPC-RELUIS 2005-08 project (Research Line 7), involving several partners from different Italian Universities.

This paper provides an overview of the experimental model set up and focuses specifically on presenting the detailed aspects of the experimental model, seismic inputs, test apparatus and sensor set up, energy dissipating devices and dynamic characteristics of the experimental model.

2. EXPERIMENTAL MODEL, TEST APPARATUS AND SENSOR SET UP

The 2/3-scale model used for dynamic testing has been obtained from a steel building prototype. Figure 1 shows the general layout of the experimental model. The test structure is a 2-storey, single bay steel frame featuring a 4m span in the test direction. The inter-storey height is 2m and a 100mm thick steel-concrete slab (4.2m by 3.2m in plan) is connected to the primary beams. Primary and secondary beams have equal structural sections (IPE 180) for all storeys and the columns have constant cross section (HEB 140) along the height.

Additional masses have been placed on each slab in order to account for non structural dead loads and an adequate amount of live loading (30%), as well as the mass-similitude scaling contribution. Additional steel beams (HE220B) at the base of the experimental model are added to obtain the connection with the shaking table system, as described later in the paper. Dead and live loading values considered in the prototype design are typical for a residential housing type of structure. The experimental model is constructed utilizing Fe360 grade steel having the following characteristics: Young's modulus, E = 206000N/mm^2 and yield strength, f_y = 235N/mm^2.

The theoretical weight of the experimental model (W_m = 98.08kN) is obtained from the prototype model weight (W_p = 180.88kN) by taking the length scaling (S_L) and material scaling (S_E) factors equal to 2/3 and 1, respectively. The actual total weight of the JetPacs experimental model (W_m) has also been estimated utilizing dynamic identification tests carried out at the Structural Laboratory of University of Basilicata, as described below. An additional weight of about 26kN is required to obtain the total model scaling weight contribution. The additional weight due to dead loads and to part of the equivalent mass-similitude scaling contribution is obtained by producing floor slabs with increased thickness. The remaining part of the equivalent weight and live loading (30% DL) is applied at each storey by means of 8 additional concrete masses having the characteristics (coordinates and weight) reported in Table 2.1 and shown in Figure 2, for both symmetrical and eccentric (5% of the bay span in the Y direction) mass configurations.

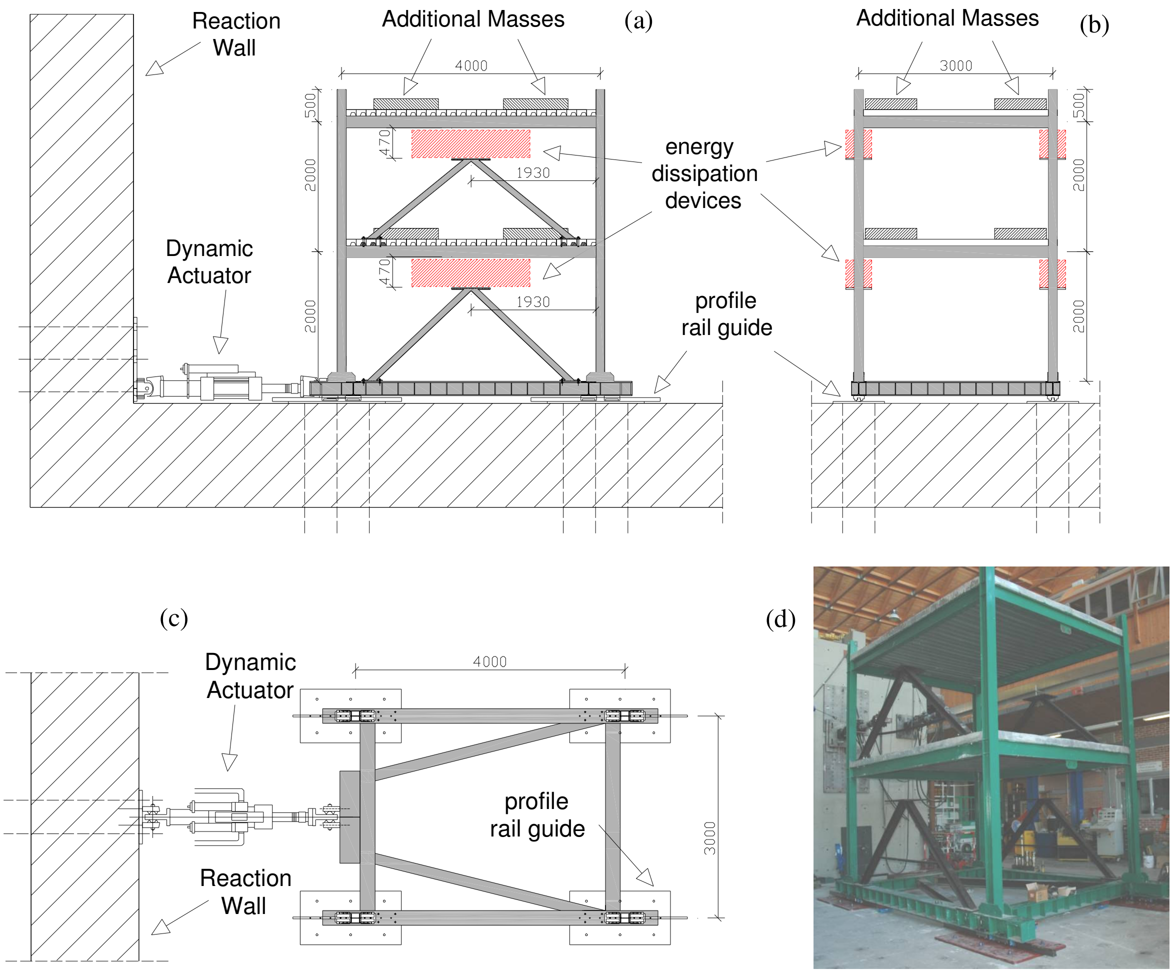


Figure 1. Structural model selected for the tests (a) Frame (Test) X Direction; (b) Frame Y Direction; (c) Shaking table plan; (d) 3-D view of the test rig

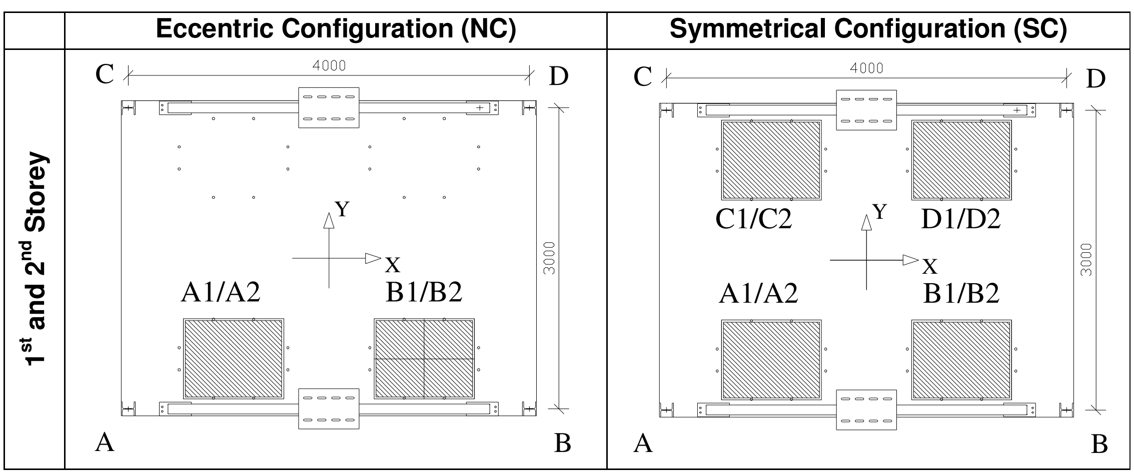
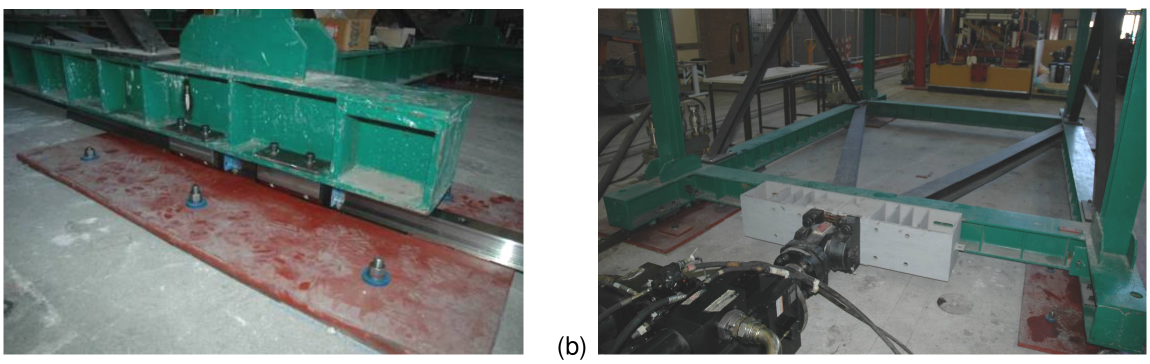


Figure 2. Concrete block positions for symmetrical (SC) and eccentric (NC) mass configurations

The test apparatus at the University of Basilicata Structural Laboratory comprises a single degree of freedom shaking table driven by an MTS dynamic actuator, with ±500kN maximum load capacity and ±250mm stroke, fixed to a (6m high by 10m wide) reaction wall and to the base of the test model by means of cylindrical joints, as shown in Figure 3. The actuator is operated by three MTS SilentfloTM 505-180 hydraulic pumps, each capable of a 600litres/min flow rate.

Table 2.1: Concrete block positions and weights for symmetrical and eccentric mass configurations

Storey	Position ID	Coordinates (m)		Weight	Eccentric
		X Dir.	Y Dir.	(kN)	Configuration
1	A1	-0.95	-1.00	3.32	Yes
	B1	0.95	-1.00	3.34	Yes
	C1	-0.95	1.00	3.30	No
	D1	0.95	1.00	3.30	No
2	A2	-0.95	-1.00	3.30	Yes
	B2	0.95	-1.00	3.34	Yes
	C2	-0.95	1.00	3.32	No
	D2	0.95	1.00	3.24	No



(a) (b)

Figure 3. Shaking table: (a) SKF profile rail guide; (b) Model base

The shaking table consists of a four profile rail guide system (SKF-Model: LLR HC 65 LA T1), with two carriages for each guide, located under each column of the experimental model, as shown in Figure 3a.
A friction factor of less than 1% ensures accurate linear movement in the test direction.
The rigid diaphragm condition at the base level is achieved by an adequately braced steel girder (HEM 300), as shown in Figure 3b. The model is a 2 degrees of freedom system in the test direction, corresponding to the 2 horizontal floors displacements, where most of the structural mass is concentrated.
The actuator applied force is measured by a piezoresistive load cell mounted at the actuator end. A total of 26 acquisition channels are employed to record the structural response. The horizontal displacements of each floor are measured by 4 Temposonic ±250mm digital transducers (2μm resolution) fixed to an external steel reference frame. Floor accelerations are recorded utilising a total of 8 horizontal servo-accelerometers (4 in the X-direction and 4 in the Y-direction, FGP, ±2g, model FA101-A2) and 1 vertical servo-accelerometer (±0.1g Columbia, model SA-107LN). The table-model base accelerations are recorded by 4 horizontal servo-accelerometers (2 in the X-direction and 2 in the Y-direction, ± 1g Columbia model SA-107LN) and corresponding displacements by 1 Temposonic digital transducer also fixed to the external steel reference frame. The remaining 8 input channels are used to measure forces of the energy dissipating devices by a total of 4 piezoresistive load cells (AEP, Mod. TC4: 10kN cells, 25kN cells and 50kN cells) mounted at the end of each device and their relative displacement by means of 4 Penny & Giles LP displacement transducers (±50mm, type HLP190/SA).
Additional displacement transducers are added during dynamic testing of the model equipped with semi-active energy dissipation devices, in-house designed by the Research Units.

3. SEISMIC INPUTS

During testing, response of the structural model subjected to both natural and artificial earthquakes is assessed. In particular, the model is subjected to three different sets of earthquake records, each compatible with the response spectra of the Italian and European seismic code for A, B and D soil types. Specifically, the following seismic inputs are used:

i. a set of natural records obtained from the RELUIS web site (www.reluis.it) for plane analyses, compatible with the response spectrum provided by Eurocode 8 for soil type A, Seismic Zone 1 (Figure 4a);
ii. a set of natural records obtained from RELUIS web site for plane analyses, compatible with the response spectrum provided by Eurocode 8 for soil type B, Seismic Zone 1 (Figure 4b);
iii. a set of artificial acceleration profile type Spectrum-compatible waveforms with the response spectrum provided by OPCM 3431 for soil type D, Seismic Zone 1 (Figure 4c).

Natural record acceleration values are scaled by using the Scaling Factor (SF) suggested by RELUIS. To ensure consistency with the scale of the model, all acceleration profiles are then scaled down in time by the factor $(1.5)^{1/2}$. During testing of the model equipped with energy dissipation systems, the seismic intensity is progressively increased from the initial value of 0.05g up to the attainment of the design performance criteria corresponding to a moderate and a high intensity earthquake [Ponzo et al. 2008a and 2008b].

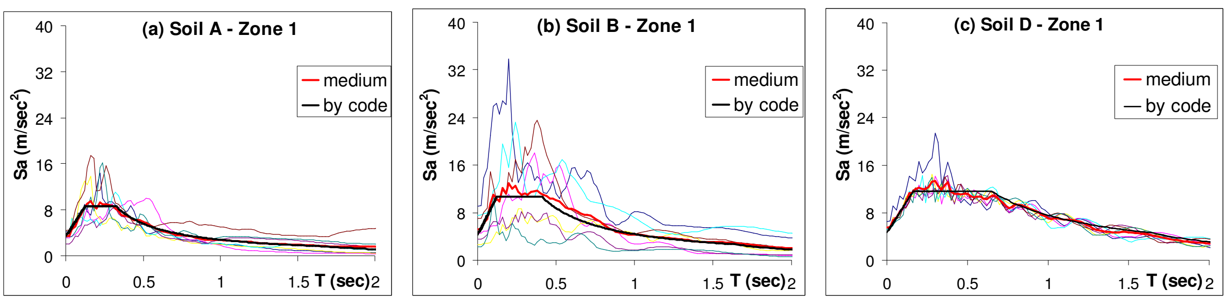


Figure 4. Elastic response spectra of sets of natural accelerograms for Seismic Zone 1 and (a) soil type A; (b) soil type B and (c) soil type D; time scaled by t/√1.5.

4. ENERGY DISSIPATING DEVICES

The JetPacs Project has been supported by several partners from different Italian Universities which in turn have developed or studied a number of energy dissipation devices based on different materials and/or principles. During testing, a total of six different passive or semi-active energy dissipating devices based on currently available technologies (i.e. viscous and hysteretic damping) or innovative systems (i.e. shape memory alloy wires, magnetorheological fluids) are used, as summarised in Table 4.1. Below, a brief description of each device is given:

- The dampers provided by the research unit of the University of Naples are four nonlinear viscous fluid dampers manufactured by the Italian company FIP Industriale and characterized by a maximum nominal force of 50 kN and a constitutive law $F=cv^\alpha$, where c=60 kN (sec/m) and $\alpha=0.15$. The very low value of the velocity exponent allows a much higher energy dissipation capacity, compared to traditional linear viscous dampers.
- A highly non-linear fluid-viscous damper, manufactured by Jarret SL, France, is used by the University of Udine. Its distinguishing mechanical characteristics are: total self-centering capacity, ensured by the pressurization of the inner casing; and flow of the silicone fluid through a very narrow annular space between piston head and inner casing, which provides a very high normalized damping capacity of this type of dissipater within the class of viscous devices.
- Two full-scale prototype semi-active magnetorheological (MR) dampers have been designed and manufactured by the German company Maurer Söhne for Parthenope University of Naples. The overall dimensions of the devices are 675mm (length) x 100mm (external diameter) and their mass is about 16 kg each.

A maximum force of 30 kN can be developed along its longitudinal axis, whereas the presence of special spherical pin joints at both ends prevents the rise of bending, shear and torsional moment in the piston rod. The dampers have a stroke of ± 25 mm, and the external diameters of the piston head and of the piston rod are 100 mm and 64 mm, respectively. A magnetic circuit composed by three coils, each of them with a resistance R = 1.11 Ω and an inductivity L = 92 mH, can generate the magnetic field in the device. The electrical power in this circuit, in the range of i = 0÷3 A, is provided by a power supply commanded by a voltage input signal.

- The University of L'Aquila uses, as semi-active energy-dissipating devices, two magnetorheological dampers (Lord RD1005-3) positioned at the first floor. The hysteretic properties of the magnetorheological fluids are modified by external magnetic fields induced by a pair of potential differences, namely the control inputs. The two independent command signals are determined on the basis of a clipped-optimal control, in which a LQG control is designed to use the four acceleration measures at each floor. Different levels of control activities are considered [Gattulli et al., 2008].
- The University of Basilicata tests a visco-re-centring device obtained by coupling two viscous fluid velocity-dependent energy-dissipating devices with a shape memory alloy (SMA) re-centring element [Ponzo et al. 2008b].
- The University of Basilicata jointly with University of Calabria examines the behaviour of elasto-plastic devices based on the hysteretic properties of steel plates capable to provide the necessary additional horizontal strength, stiffness and energy dissipation capacity whilst limiting interstorey drifts [Ponzo et al. 2008a].
- The Polytechnic of Bari considers an hysteretic device obtained by considering an aluminum shear panel made up of a central aluminum plate and two lateral steel plates with 12 rectangular openings. The aluminum plate emerges in the steel openings to avoid slip phenomena. The steel plates provide the necessary stiffness and strength to the panel, while aluminum is the preferential energy dissipation area. The device has been optimized in order to have a wide plastic behaviour together with a low yielding interstory drift.

The energy dissipating devices described above are mounted on the top of two stiff V-inverted steel braces (HEA100), as shown in Figure 1. Bolts ensure the rigid connection between the stiff braces and the experimental model. In order to ensure an adequate safety system, two additional V-inverted steel braces (UPN 80) have been constructed orthogonally to the test direction. The design criterion for all devices is to ensure the experimental model to be maintained in its elastic condition during dynamic testing.

Table 4.1 Tested energy dissipation devices

No.	**Device Type**	**Manufacturer**	**Research Unit**
1	Viscous fluids	FIP Industriale, Italy	University of Naples Federico II
2	Visco-elastic	Jarret	University of Udine
3	Magnetorheological fluids	Maurer&Söhne, Germany	University of Naples Parthenope
4	Magnetorheological fluids	LORD Corporation, USA	University of L'Aquila
5	Visco-re-centring	TIS Spa, Italy	University of Basilicata
6	Hysteretic	TIS Spa, Italy	Univ. of Basilicata and Univ. of Calabria
8	Hysteretic camper (TEC)	TEC S.r.l., Italy	Polytechnic of Bari

5. DYNAMIC IDENTIFICATION TESTS

Structural dynamic identification tests of the JetPacs frame are carried out by considering a number of different excitation sources: ambient noise, instrumental hammer impact excitations and sine-sweep ground motion induced by operating a nearby devices test machine.

During the tests, three different mass configurations of the model are considered, obtained by using additional concrete blocks placed at each slab level, as shown in Figure 2: i) Basic Configuration (BC), with no additional masses; ii) Eccentric mass Configuration (NC), with two blocks at each storey level; iii) Symmetric mass Configuration (SC), with four blocks at each storey level (see Table 2.1 also). The model response is recorded by a total of 16 uni-directional servo-accelerometers (±0.1g, Columbia, model SA-107LN), of which 13 on the experimental model, 2 at the ground level and 1 on the dynamic actuator.

The experimental data acquired under various excitations for each mass configuration considered is used to

obtain structural natural frequencies, masses (due to some uncertainty in their direct evaluation), modal shapes and damping values. In order to obtain robust outcomes, the averaged values come out from different only-output modal analyses techniques were considered.
In Table 5.1, dynamic test results are reported in terms of natural frequencies for each mass configuration. It is worth noting that almost identical results have been obtained by the research teams involved in the identification procedure.
Careful analysis of the results reported in Table 5.1 sheds light on the occurrence of two distinct experimental modes (denoted as IV°a and IV°b) instead of a single fourth mode, displaying relatively close frequencies and very similar mode shapes. These are clearly incompatible with the physical model and it appears that the global behaviour of the experimental model, in this configuration (without any dissipating device), is influenced by the transverse stiffness of the V-inverted rigid braces at the second floor, which acts as a Tuned Mass Damper (see Figure 1). In the dynamic test configuration of the controlled model this phenomenon vanishes because the V-inverted rigid braces are connected to the floor through the energy dissipation devices (see Figure 3).
In Figure 5, the normalised shapes of the different modes, obtained by each Research Unit by means of an averaging procedure over the whole experimental test data, are shown and the model modal regularity is highlighted.
In order to improve damping estimation accuracy, a rough calculation obtained from impact tests measurements yields a modal damping factor lower than 0.3-0.4% for the first three modes.
In Table 5.2, model mass identification parameters for each storey in the basic configuration are reported, as obtained by each Research Unit involved. The relatively small discrepancies observed can be accounted for by the different evaluation methods used [Ponzo et al., 2007; Gattulli et al., 2007; De Stefano et al., 2008].

Table 5.1: Natural frequencies of the experimental model

Configuration		**BC**	**NC**	**SC**
Mode	**Dir.**	Freq. (Hz)	Freq. (Hz)	Freq. (Hz)
I°	Uy	3.42	3.12	2.83
II°	Ux	4.20	3.81	3.61
III°	Rz	5.86	5.47	5.10
IV°a	Uy	9.40	8.90	8.42
IV°b	Ux	11.28	10.75	10.54
V°	Ux	14.65	12.99	12.41
VI°	Rz	18.75	17.39	16.40

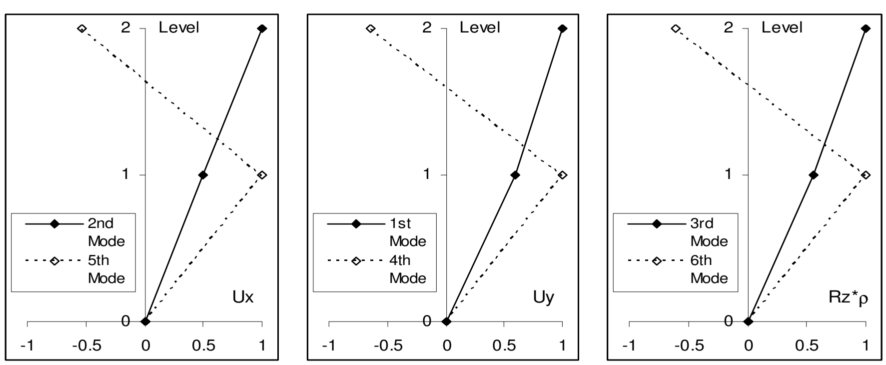


Figure 5. Model mode shapes of the SB configuration for the test direction

Table 5.2: Masses of the experimental model evaluated by different Research Units

Configuration (BC)	**UNIBAS**	**UNIAQ**	**POLITO**	**UNINA**
Level	Mass (kg)	Mass (kg)	Mass (kg)	Mass (kg)
I°	3755	3391	3422	3607
II°	3412	3351	3214	3385

6. CONCLUSION

An extensive dynamic experimental testing programme named JetPacs (Joint Experimental Testing on Passive and semi-Active Control Systems), involving partners from several Italian Universities, has been scheduled to be carried out at the Structural Laboratory of the University of Basilicata.
In this paper, the design of the JetPacs experimental scale model and the details regarding the model set up, seismic inputs used, test apparatus and sensor set up are given. The results obtained from dynamic identification tests are reported, in terms of actual mass, fundamental periods of vibration, modal damping and mode shapes of the experimental model. It is shown that almost identical values of fundamental periods of vibration, modal damping and mode shapes have been obtained by each Research Unit. A lower than 10% difference in mass values has been observed, due to different evaluation methods adopted.

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