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HYBRID TESTING OF SEISMIC ISOLATED STRUCTURES: FACING TIME AND GEOMETRY SCALING ISSUES

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ABSTRACT

Hybrid Testing is becoming very popular within the most advanced testing techniques; the use of sub-structuring further enhance the appeal of such testing method, allowing cost effective full scale tests. Full scale specimens, in fact, generally require large testing installations, high force and displacement capacity.
On the other hand, full or large scale specimens are often necessary in civil engineering field, to avoid distortions due to the concrete mix, rebars availability and mechanical characteristics, elements realistic damage and failure mechanisms. In some cases, scaling induces distortions that cannot be effectively compensated; this is typically the case of some isolation devices, such as Curved-Surface Slider (CSS) bearings.
Experimental data of seismic isolated structures is still very limited, mainly because of the above mentioned test requirements. In addition, since base isolation is widely recognized as one of the most effective seismic protection strategy (Dolce and Cardone 1999), new devices are continuously proposed by the manufacturers, therefore needing accurate experimental validation. The above reasons underline the importance of reliable experimental testing of isolated structures. Standard characterization tests give important information on the device response, while the structural context is almost neglected.
In this contribution, the topic of reliable and cost effective experimental testing of seismic isolated structures is addressed. The attention is mainly focused on the scaling possibilities considering both time scale and geometry. The proposed approach is supported by the experimental evidences of the dynamic hybrid testing campaigns carried out at EUCENTRE (European Centre for Training and Research in Earthquake Engineering) of Pavia, Italy, in the last 5 years. The aspects related to the reliability of the numerical sub-structure and the improvement possibilities are discussed as well. Future perspective of experimental testing of structures equipped with the most advanced nowadays available seismic devices are illustrated.

Keywords: Hybrid Simulation; Fast HS; Time Scale; Geometry Scaling; Isolated Structures

1. INTRODUCTION

The main focus of this contribution is to address the topic of the physical specimens scaling within the experimental investigation of structures through hybrid simulation with sub-structuring. Scaling aspects are discussed both in terms of geometry and time, thus analyzing advantages and drawbacks of simulations ranging from Pseudo-Dynamic to Real-Time. The proposed approach is oriented to the achievement of the highest test results accuracy and reliability, independently on the testing method.

The presented investigation is mainly focused on seismic isolated structures, topic chosen for several reasons. Base isolation is widely recognized as one of the most effective seismic protection strategy, both from technical and economic points of view. Despite its relevance and the increasing availability of novel devices, experimental data on seismic isolated structures is still quite limited, except for what concern standard characterization tests. Such tests provide useful information on the devices response, while the structural context in which they are installed is essentially neglected.

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The discussion presented in this paper was born and is supported by the experimental results obtained within the last 5-years experimental campaigns carried out at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) of Pavia, Italy, aiming at the performance assessment of isolated buildings and bridges through dynamic hybrid simulation method.

2. ISOLATION SYSTEMS ACTUAL RESPONSE

In the last decades, seismic isolation proved to be one of the most effective methods for seismic protection of several structure typologies. While some particular structures, such as long-period tall buildings, might just partially benefit from base isolation (Jain and Thakkar 2004), most of the common medium to low-rise buildings, bridges with squat piers, nuclear plants, etc. certainly do. In addition, the cost of the isolation system, compared with the cost of the whole structure, consists just in a few percents of the total. Despite the additional cost of the isolation system, a cost reduction comes from the reduced seismic requirements of the super-structure. Because of that, today, a wide variety of isolation devices are available on the market, and new devices are proposed by the manufactures every year.

Most common seismic isolation technologies (Figure 1) include elastomeric bearings, with or without a dissipation lead plug, and curved surface sliders (CSS) (Christopoulos and Filiatrault 2006). Several innovative devices have been added to the common ones, such as CSS with variable surface radius (Shaikhzadeh and Karamoddin 2015), triple pendulum systems (Constantinou 2004), bearings equipped with dissipative steel elements, etc.

a b c

Figure 1. Seismic isolation devices recently tested at EUCENTRE through Dynamic Hybrid Testing method: a) double-curvature Curved Surface Slider; b) Triple Pendulum System; c) Lead-Rubber bearing

The devices are subjected to initial type and factory production control testing before being installed; such tests, conducted with pre-determined displacement and/or force sine/triangular loading, provide important information on the device characteristics (e.g. estimation of the friction coefficient for CSS, post-elastic behavior for elastomeric bearings, etc.), while the structural context in which they will be installed is just considered in a very simplified way, and their interaction is not accounted for in any way.

In recent experimental campaigns carried out at EUCENTRE of Pavia, it has been observed that the actual response of the isolation devices, inserted in their structural context and subjected to seismic-induced loading, may be different from what observed in standard sine/triangular characterization tests. The last experimental campaign was implemented to study the response of a seismic isolated 6-storey RC building equipped with 24 Double-Curvature CSS devices. A preliminary devices characterization (Figure 3) has been carried out by means of sinusoidal displacement-controlled tests on a full scale specimen, tested on the EUCENTRE Bearing Tester System (Peloso et al. 2012, Figure 2).

Figure 2. EUCENTRE high-capacity Bearing Tester System

The results have been used to tune the numerical model of the isolators, which have been then integrated in the numerical model of the whole 6-storey structure. Finally, the experimental investigation of the isolated building through the dynamic hybrid testing technique has been performed.

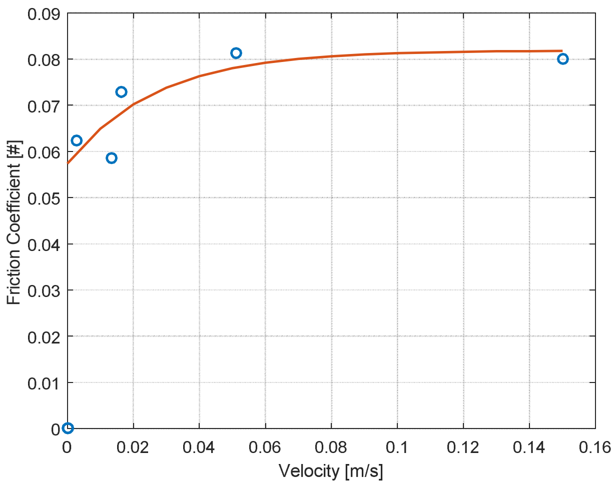

Figure 3. Experimental friction characterization of a Double-Curvature CSS with carbon-filled PTFE sliding material

In Figure 4, the hysteretic response of a Double-Curvature CSS device under seismic load is shown. The blue curve refers to the numerical simulation based on the initial characterization of the isolators. It can be observed that the actual friction coefficient, observed in the hybrid testing campaign of the full scale physical isolator, is higher than the one considered in the simulation. This can be due to the displacement path experienced by the isolator during a seismic test, different from sinusoidal; moreover, the wear of the sliding material can modify its tribological properties. In Figure 5, the numerical simulation has been corrected with the friction coefficient observed during the hybrid testing campaign, leading to a very good matching between simulation and experimental tests, both in terms of force and displacement response.

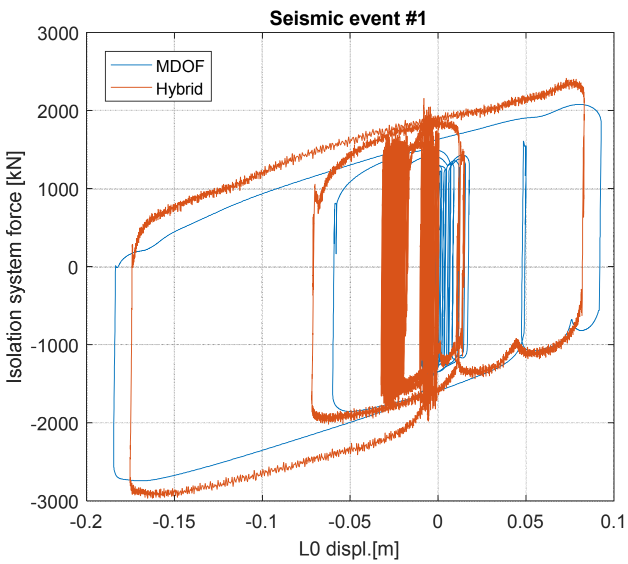

Figure 4. Hysteretic response of a Double-Curvature CSS device under seismic load: numerical simulation (blue) vs. experimental results

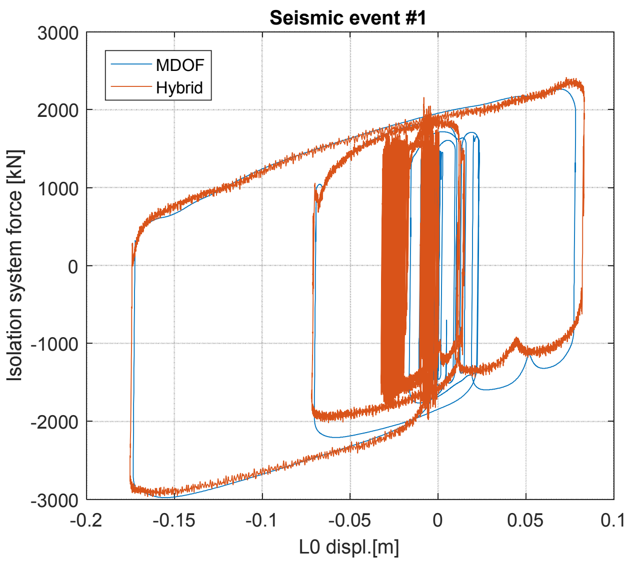

Figure 5. Hysteretic response of a Double-Curvature CSS device under seismic load: corrected numerical simulation (blue) vs. experimental results

Further phenomena that can lead to discrepancies between the nominal and the actual experimental response of the isolators are the sliding material ageing, the trespassing of the physically available stroke of the slider during an earthquake, the different contact pressure of the sliding material because of the different displacement path, etc.

3. EXPERIMENTAL TESTING OF SEISMIC ISOLATED STRUCTURES

Seismic isolation has been widely investigated in the last decades, both numerically and experimentally. However, the experimental test of isolated systems is very challenging from several points of view. Shake table testing is likely one of the most reliable method to be employed to this end, while the mass and dimensions of the specimen require very large and powerful installations.

Furthermore, in case of an isolated bridge, the need for a shake table array and a very accurate tuning and control of the testing system against a physical coupling of the tables may prevent a successful test implementation. In any case, such onerous and complex testing campaigns are very rare case-studies, and cannot constitute a statistically meaningful database.

Isolated structures have been investigated in some cases through Pseudo-Dynamic testing procedure (PsD Abbiati et al. 2015B), well known method firstly implemented in the late 60s (Hakuno et al., 1969) and then considered for the assessment of several structural systems (Negro et al. 2004, Buonopane and White 1999). PsD technique, however, is not the best option when the physical specimen shows a rate-dependent response. Phenomena like viscosity, friction and stick-slip (Czichos 1978, Berger 2002), etc. strongly depend on the load application speed, therefore resulting in significant results distortion for an extended time-scale testing.

A common feature of the majority of the isolated structures is to concentrate the non-linearities of the dynamic response in the isolation layer, while the remainder portions of the system are expected to behave linearly. This suggests a fruitful application of the sub-structuring technique, in which a reliable numerical model, typically linear or with well characterized non-linearities, is coupled and considered together with one or more physical sub-structures (PSs). This allow for a proper representation of the entire structure under investigation, with relevant cost reduction, which is predominantly associated to the construction, instrumentation and test of the PS. In addition, considering as PS just the isolation devices allows for test repetition, parametric and optimization analyses, since they are unlikely to get damaged within a reasonable number of tests. In the case of CSS devices, a simple substitution of the sliding material will allow for a further extension of the testing campaign.

As previously mentioned, the velocity of the test execution plays a fundamental role to achieve accurate results, because of the sensibility to the loading rate of the PS. The geometry scale of the PS is important too, in the same way it is important for a shake table testing campaign. Those aspects are detailed analyzed in § 4.

4. OPTIMAL GEOMETRY AND TIME SCALING IN HYBRID SIMULATION

The partition of the structure into physical and numerical sub-systems offers relevant advantages from the geometry scaling point of view. The NS and each PS do not necessarily need to be considered with the same scale, unless PSs are physically coupled and tested in contact with each other.
For simplicity, the NS is generally considered with no scaling; moreover, some macro-models such those representing infill walls are typically calibrated on real dimensions elements. Differently, the most appropriate scaling factor of the PS is not unique and strongly depends on the structural typology. Some elements (e.g. steel beams), are more suitable to be scaled, being still representative, as long as relevant scale-dependent phenomena (e.g. warping) do not play an important role.
The proper scaling of other PS typologies, such as masonry walls, infills, reinforced concrete members, etc. is much more challenging. As shown in Frumento et al. (2009), the interpretation of the in-plane cyclic response of small or scaled clay brick masonry walls specimens might be critical. Often the ratio of the bricks dimensions, the brick-to-panel dimensions ratio and the higher confinement effect of the panel surrounding elements (e.g. RC edge beam) produce distortions that might affect both the resistance and the failure mechanism of the specimen.
Reinforced concrete members are very sensitive to the concrete mixture. Furthermore, the rebars are not available for any diameter, thus imposing limited scaling possibilities (ø8 classic stirrups 1:2 scaled, i.e. ø4, are not commercially available). Less common structural components, such as Liquid Tuned-Mass-Dampers (L-TMD, Fujino et al. 1992), cannot be scaled without any distortions because of their physical nature.

Seismic isolation devices would significantly benefit from a proper scaling to be experimentally investigated, because of their typically very high vertical load in operating conditions. However, while for elastomeric bearings similarity laws (Buckingham 1914, Buckingham 1915, Lanese et al. 2008) might be fulfilled under certain circumstances, Curved-Surface Slider (CSS) devices cannot. The geometry scaling, the isolation period, the recentering force, the pressure on the sliding material and its distribution (boundary effects) and its rate-dependent response have incompatible interconnections with each other, thus implying some distortions. For such reasons, the experimental investigations shown in this paper are all based on full-scale isolation devices.

In hybrid simulation, the scaling concept applies to the time axis, i.e. the speed of the test execution, too. According to the adopted time scale, hybrid simulation can be subdivided in Pseudo-Dynamic, Dynamic or Fast, and Real-Time.
Tests with a significantly extended time scale (PsD, scale factor typically ranging from 80 to 200 or more) show relevant advantages from the implementation and execution points of view. Since the displacement of the structure is applied very slowly, there are only minor requirements for the servo-hydraulic system. The pumping plant is not required to provide much oil flow, and the actuators servovalves can be small and with limited dynamic. This imply costs significantly lower compared to typical shake table systems. Furthermore, a slow load application allows for a very accurate actuator tracking and makes the dynamic interaction specimen-actuators (Le Maoult et al. 2009) negligible. Finally, since hybrid simulation is strongly affected by the delay between observed and actual quantities (Lanese 2012), big time scale factors make negligible this discrepancy, allowing for more accurate results with no need for compensation procedures.
Distortions in the PsD test results start arising when the structure shows a rate-dependent behavior. Some phenomena are prone to relevant changes according to the velocity: this is typically the case of friction (Figure 6, stick slip effect).

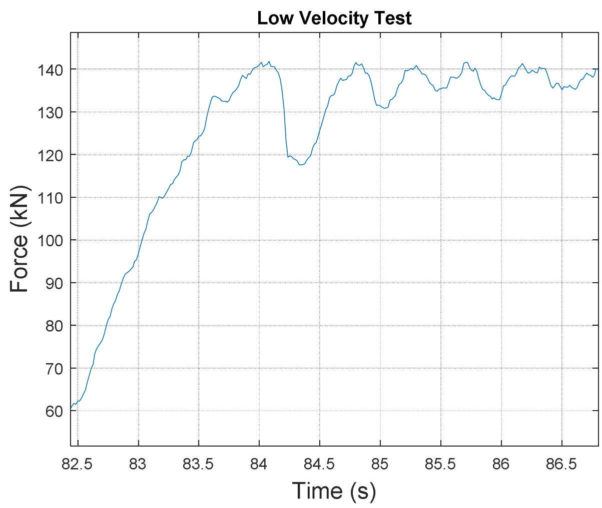

Figure 6. Stick slip effect of a steel mass sliding over a flat polymeric layer under a constant 0.15 mm/s movement

Relaxation effects have been studied within PsD testing campaigns, leading to the implementation of continuous loading procedures (Pegon and Magonette 2002), improving the previous concept of “stop-and-go” testing scheme.
Most seismic devices show a certain rate-dependent response, while a unique indication for the time scaling cannot be defined. Velocity dependent devices (EN15129:2009, 2009), such as Fluid Viscous Dampers (FVD), necessarily need a real-time loading to be properly considered (Carrion et al. 2009); friction-based elements show a different response according to the material and pressure at the sliding interface, for which a non-real-time, but still dynamic, loading might be the best choice. This aspect is detailed discussed in § 5.

5. RECENT EXPERIMENTAL EVIDENCES

The focus of this paper is not related to a single testing campaign, but aims to collect some of the experimental evidences observed in the last few years of hybrid simulation campaigns implemented at EUCENTRE of Pavia.
In Abbiati et al. (2015a), the experimental investigation of an existing bridge through the hybrid simulation technique, both in as-built and seismic isolated configuration, is described. The considered bridge features two 12 m hollow cross-section concrete columns carrying a 135 m long continuous concrete deck. A pair of CSS were interposed between the deck and each pier and each abutment as a suitable seismic retrofitting scheme. Nominally identical RC piers were also object of a previous experimental campaign (Peloso and Pavese 2009), numerically modeled and tested at EUCENTRE in 2008 with Pseudo-Static testing procedure. Such elements showed a peculiar damage mechanism, mainly governed by a rocking response, thus very different from a classical flexure or mix-shear-flexure response of RC beam elements. The isolators, as previously mentioned, show a highly non-linear response, which might differ from what can be expected based on standard sinusoidal/triangular characterization tests.
For the above reasons, 1 RC pier and 1 isolation device have been considered as Physical Sub-structures (PSs) for the bridge assessment through hybrid simulation (Figure 7). The considered geometry scaling was different between the PSs, selected in order to represent the most realistic conditions, having PSs compliant with the testing facilities capacity. The scale factor chosen for the RC pier was equal to 2, which was compatible with the reaction wall height and the horizontal and vertical force required, but still admissible in terms of rebars availability and realistic concrete mix. The isolator was a full scale Double-curvature CSS, with design load of 3100 kN, stroke of ± 260 mm and radius of 3.1 m. A different geometry scale factor between the two PSs has been possible because of their physical decoupling, being them separately tested on two different facilities. A full scale CSS was strictly needed to avoid distortions, as mentioned in § 4.

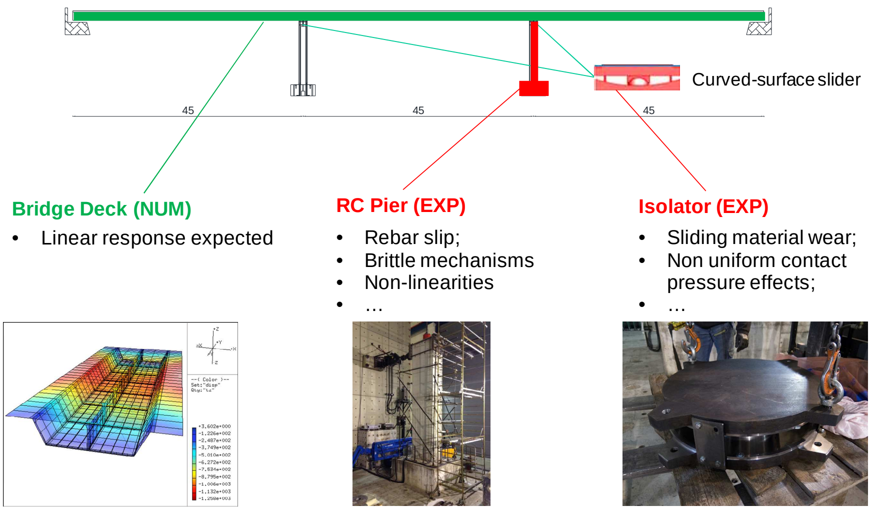

Figure 7. Existing bridge tested at EUCENTRE in as-built and seismic isolated configuration through Hybrid Testing method

Tests have been carried out both in isolated and as-built configuration (Abbiati et al. 2015a). While for the as-built configuration, scale factors of 128 and 256 were suitable (also to test online model updating as shown in Abbiati et al. 2015a) and ensured a perfect actuators tracking, in the retrofit configuration, a real-time numerical compensation for the isolators response (as in Molina et al. 2002) was required. This was facilitated by the smooth and regular dependency of the friction of the CSS from the velocity (Figure 3), while it does not ensure the maximum results reliability.
In more recent testing campaigns, the focus was moved to the isolation system, which was the only PS. Three typologies of isolators have been considered – a Lead-Rubber bearing, a Double-Curvature CSS and a Triple Pendulum – (Figure 1), aiming at investigating the response of building and bridge

structures equipped with different isolation systems. The tests have been performed at different time scale, ranging from 128 up to 4, in order to investigate the best balance between realistic PS response and effective actuator tracking.

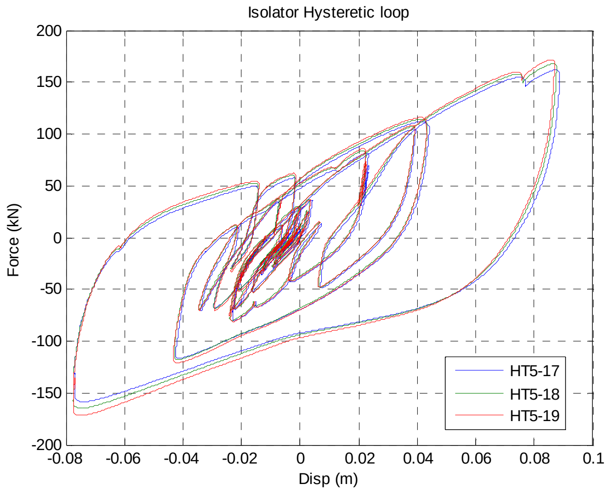

Figure 8. Hysteretic response of a LRB device under seismic load (scaling factors of 16, 8 and 4)

In Figure 8, the hysteretic response of a LRB device, being part of the isolation system of the RC bridge previously described, for the same PGA level equal to 6 m/s^2 for different time scale factors of 16, 8 and 4 is compared. The dissipated energy remains essentially constant in all dynamic tests; minor discrepancies can be observed, while part of them is due to the slightly less accurate control moving towards faster test rates. Elastomeric bearings are less sensitive to the loading rate compared to friction-based devices; in the case shown in Figure 8, a time scale of 16 is sufficient to provide the correct solution.

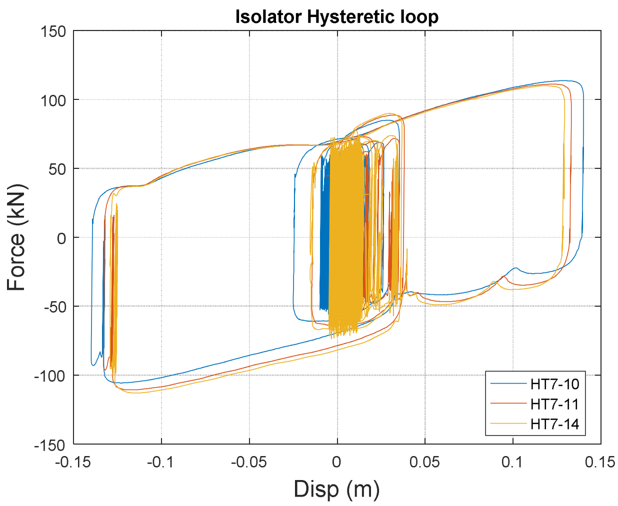

Figure 9. Hysteretic response of a Double-Curvature CSS device under sesmic load (scaling factors of 32, 16 and 8)

The same comparison at different time scale factors has been carried out considering a Double-Curvature CSS isolation device being part of the isolation system of the same structure. In Figure 9, the hysteretic response of the physical isolation device under seismic loading (same acceleration record and same PGA = 4.373 m/s^2) is shown. The effect of the rate-dependency can be well observed: at slower test rate (test HT7_10, T_{scale} = 32), the friction coefficient is lower than the one expected at high speed (Figure 3). The force response is actually lower than tests HT7_11 and HT7_14 and,

consequently, the experimental peak displacement is higher. Increasing the speed of the test (HT7_11, T_{scale} = 16), the average force response is higher and the displacement becomes smaller (-6%). By further doubling the test speed test (HT7_14, T_{scale} = 8), the same effect can still be observed, while the difference is now less than 2% both in terms of peak displacement and dissipated energy.
From the illustrated experimental results, it can be clearly observed that a further reduction of the time scale factor, towards a real-time test execution, will not produce more accurate results, while the loss of the accuracy in the actuators tracking will surely have a negative impact. The "convergence" of the time scale factor to the most accurate solution obviously depends on the PS response. The authors want to underline the importance of investigating the best compromise between proper consideration of rate-dependent PS response and accurate actuators tracking and control, since the final goal is to achieve the highest results accuracy. The appealing real-time execution, still needed for PS such as Fluid-Viscous Dampers, will not give, in the presented case study, results as accurate as the considered Fast (T_{scale} = 8) test execution.

6. CONCLUSIONS

In this paper, the need for further and extensive experimental testing of seismic isolated structures has been discussed. Dynamic hybrid simulation proved to be perfectly suitable to this end, properly accounting for the structural context in which isolators are installed, allowing for parametric tests and isolation system design optimization.

The scaling aspects, both in terms of geometry of the physical sub-structure(s) – PS(s) – and time (i.e. from Pseudo-Dynamic to Real-Time) have been detailed discussed. The authors want to underline that the whole set of scaling factors need to be calibrated in order to achieve the highest results accuracy. For several structure typologies, full or large scale specimens are often needed to avoid relevant results distortions. On the time scale side, seismic devices such as velocity-dependent Fluid-Viscous Dampers need a Real-Time testing, while several isolation devices, such as LRB and CSS, can be probably better considered with a moderately extended time scale (T_{scale} of 8 or 4). The experimental results of the last 5-years dynamic hybrid testing campaigns carried out at EUCENTRE of Pavia are in support of the presented discussion; a more detailed analysis of the results will be presented in a future publication.

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