TRIAL OF A MOBILE SYSTEM FOR IN-SITU DYNAMIC TESTS ON FULL SCALE STRUCTURES

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Abstract

The main results of the first trial of a mobile system, constructed to perform alternative in-situ evaluations of the dynamic response of real scale buildings, bridges and geotechnical systems subjected to potential induced seismicity, are described in this paper. The system consists of a series of mechanical and hydraulic components specifically designed or selected, including four hydraulic actuators of 1000 kN each one, a hydraulic system with flow capacity of 6000 l/min, pumps, accumulators, cooling system, hardlines and flexible hoses, a shelter power station of 600 kW, oil tanks and a digital controller. The components of the system are equipped on three trailers and a van to be transported to the destination site.

In order to perform the experimental trial, the system was assembled in a laboratory of the Eucentre Foundation simulating the same conditions of a real in-situ test, then its performances were checked imposing a series of dynamic loading histories at the base of a specifically designed specimen representing a building. In particular the setup configuration consisted of a real-scale two-storey 3D-frame, characterized by 300mm-thick reinforced concrete slabs and 3000mm-height braced steel columns, fixed to post-tensioned concrete blocks base-isolated by low friction PTFE sliding pads. The isolated base was subjected to uniaxial and biaxial excitations by acceleration time-histories imposed by different configurations of the actuators.

The experimental response of the specimen was compared to the numerical predictions in terms of spectral accelerations, displacement and shear actions. The main results concerning the functioning of the components of the mobile system were investigated with particular care devoted to assembling of the components and their combined functioning, reliability of the digital controller, actuators response (discrepancy between reference and feedback signals) and synchronization, in-plane rotation and the twisting effect.

Keywords: Mobile laboratory; In-situ tests; Experimental dynamic tests; Full-scale structures; Hydraulic actuator.

1. Introduction

Experimental test are as much reliable as they carefully represents the physical phenomenon which is investigated. In accordance with this philosophy, the study of alternative techniques to perform in-situ experimental evaluations of the dynamic response of real scale structures or geotechnical systems has always been a challenge, particularly if the objective is not so much that of imposing any simple vibration, but rather a real ground motion or even excitations at very low frequencies. Such in-situ tests were developed in the past, but with the particularity that the external excitation at the base of the structures consisted of free vibrations or vibrations at constant amplitudes; in some cases the external excitation was not even a real dynamic loading, but rather a quasi-static loading ([1], [2], [3], [4], [5]).

Although in-situ dynamic tests on real structures in real conditions are potentially more complex than more conventional laboratory ones, some significant advantages rely in the fact that they may provide indications on effects, interactions and performances of structural elements and non-structural components in the actual state of maintenance and with real material properties. Moreover, testing on site will allow re-testing after local or global strengthening measures to evaluate the effectiveness of different techniques, either at the life safety performance level or at the damage control performance level. Eucentre Foundation designed and constructed a totally independent mobile laboratory, consisting of four hydraulic actuators of 1000 kN each one, a hydraulic system with flow capacity of 6000 l/min, pumps, accumulators, cooling system, hardlines and flexible hoses, a shelter power station of 600 kW, oil tanks and a digital controller. The components of the system are equipped on three trailers and a van to be transported to the destination site.

Based on the characteristics of this dynamic testing system, various structural and geothecnical applications can be performed. Some advantages concerning in-situ tests on existing buildings have been already briefly mentioned; it has to be considered that in these cases additional specific requirements are necessary to carry out the in-situ test configuration, including the development of specific methods to build the reaction system and to prepare the base of the buildings, which has to be isolated. The system will be used also to investigate the dynamic characteristics of bridge structures and dams (evaluation of natural frequencies and vibration modes), where an excitation can be applied at the top of the structures, consisting of controlled and repeatable random signals or sine waves at constant amplitudes and variable frequency. Although vibrodynes and shakers are relatively easier to install and to fix to the structures, they need medium-high frequency values to produce an appropriate level of force, thus they are usually ineffective at low frequencies, for instance below 2 Hz ([4]). The geotechnical engineering applications may include also in-situ liquefaction tests.

The main results of the first trial of this mobile system is described in the following of this paper, devoting particular care to assembling of the components and their combined functioning.

2. Ouline of the mobile laboratory design

The preliminary design of the mobile laboratory, was based on different specific assumptions, particularly focused on the expected dynamic and loading capacities, which have to meet the requirements for the execution of the tests. Since a significant level of damage on a building may be required during a test, the force capacity has been determined taking into account the characteristics of representative structures (e.g. masonry and RC buildings up to two stories located in Northern Europe ([6]), but also limiting the geometric dimensions of the system for economical reasons and needs of transportation.

Basically, the scheme of the related hydraulic system consists of a shelter power station, pumps, accumulator system, reservoir, cooling system, hardline and flexible hoses (Fig. 1). The optimization of both geometric dimensions and energy consumption allowed to achieve a real complete autonomy: for this reason it was decided to install only one main pump, whose sole task is only to recharge the accumulators. A first estimation of total volume demand, as well as peak displacement and flow rate values, was developed performing specific flow analyses with various type of acceleration time histories, many of them used in laboratory tests carried out in the past, considering a payload of about 500 t ([8]). In such flow analyses, the peak ground acceleration (PGA) and the peak velocity cover a range of 0.1 g ÷ 1.5 g and 0.1 m/s ÷ 1.2 m/s. The maximum demands in terms of displacement, peak flow rate and total volume of oil were 233 mm, 7293.2 l/min and 570.9 l (excluding values exceeding the displacement capacity of the hydraulic system).

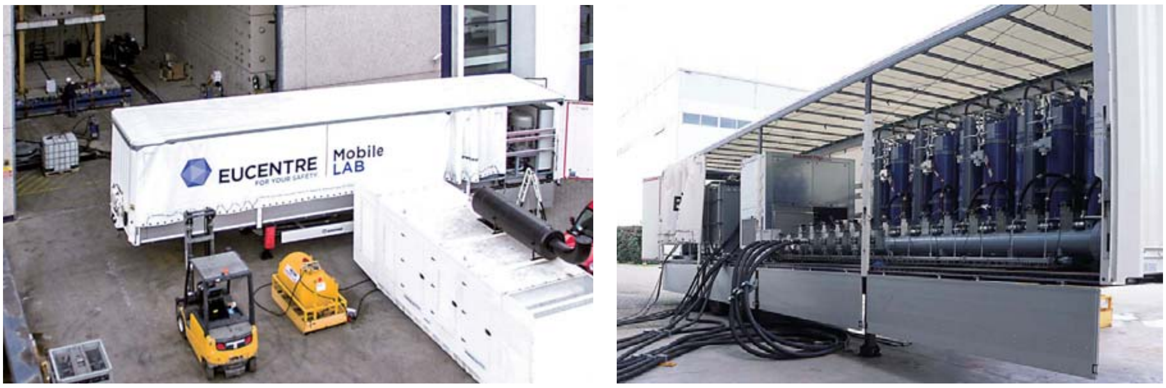

Fig. 1 – Overview of main trailer, pump, power station (left) and detail of the accumulators installed on the main trailer (right)

The final adopted configuration consists of four actuators with a global force capability of 4000 kN, so that a mass of about 10000 t may be excited even if the friction at the base is equal to 4% (ostensibly, in the case of real buildings, the limiting friction value is due to the initial static friction rather than to the dynamic friction at high frequencies, which usually assumes significantly lower values). Compared to further previous experiences ([7]), a maximum stroke of 500 mm was considered reasonable, since higher displacement capacities would require greater amount of oil volume, not easy to transport and manage on site.

A peak velocity of 500 mm/s and an acceleration capacity up to 0.3 g or 1.2 g for specimens with mass respectively less than 100 t or 150 t (Fig. 2) have been defined after investigations based on the results of specific flow analyses. In particular, the expected peak velocity represents a compromise to guarantee a high level of dynamic performance and an appropriate limitation of the dimensions of the hydraulic components. The three stages servo valves installed on each actuator provide the flow rate (about 6000 l/min) necessary to guarantee the required performances in terms of velocity.

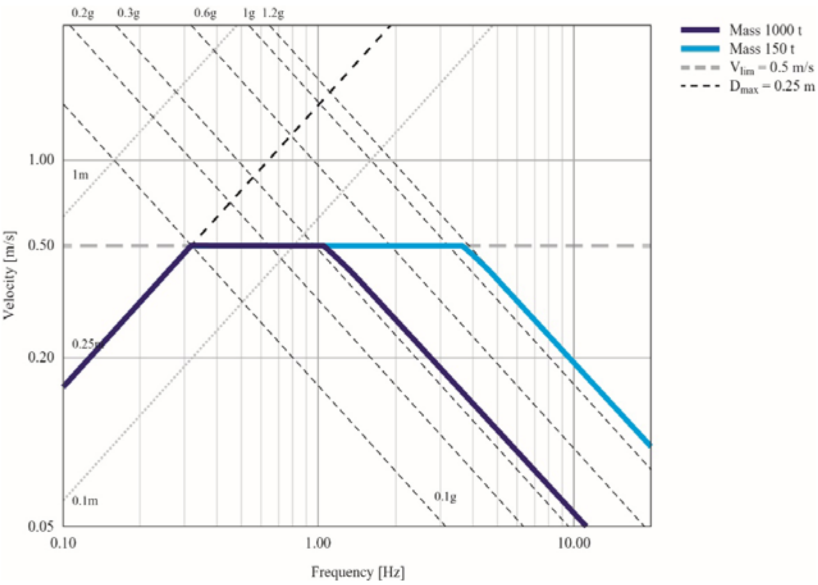

Fig. 2 – Expected performances of the mobile laboratory as a function of the frequency

3. Test of the system

3.1 Test set-up

The mobile system was assembled simulating conditions compatible with those of a real experimental in-situ test. A two-storey structure was then designed and constructed to test each component imposing a series of loading histories in accordance with the seismic input described in Section 3.2 ([8]).

The specimen consisted of a basement made by four post-tensioned concrete blocks with total mass of 65 t, supporting a two-storey steel frame with concrete floors (Fig. 3). At each storey, four 3m-high steel columns braced with L-shaped steel elements along only one direction supported a 300 mm thick RC mass of 10 t, 3.5 x 3.85 m in plan. Additional masses of about 4 t were added at the first floor. The entire structure was resting on eight low friction (PTFE) sliding pads, connected to 750 x 750 mm steel plates 50 mm thick. The columns are European wide flange HE200B (in accordance with [9]) and the diagonal braces a L-shaped 50 x 50 mm, 6 mm thick. According to [10], the material used for columns, plates and braces was S275 steel. The base of each column was welded to a steel plate connected to the base slab by steel tightened coach screws injected with chemical resin.

The four actuators of the mobile lab were acting on the steel beams of the post-tensioning system and re-acting on the strong walls of the laboratory. Two configurations were studied, imposing acceleration histories at the base in the direction of the braces or in two orthogonal directions contemporaneously (Fig. 3).

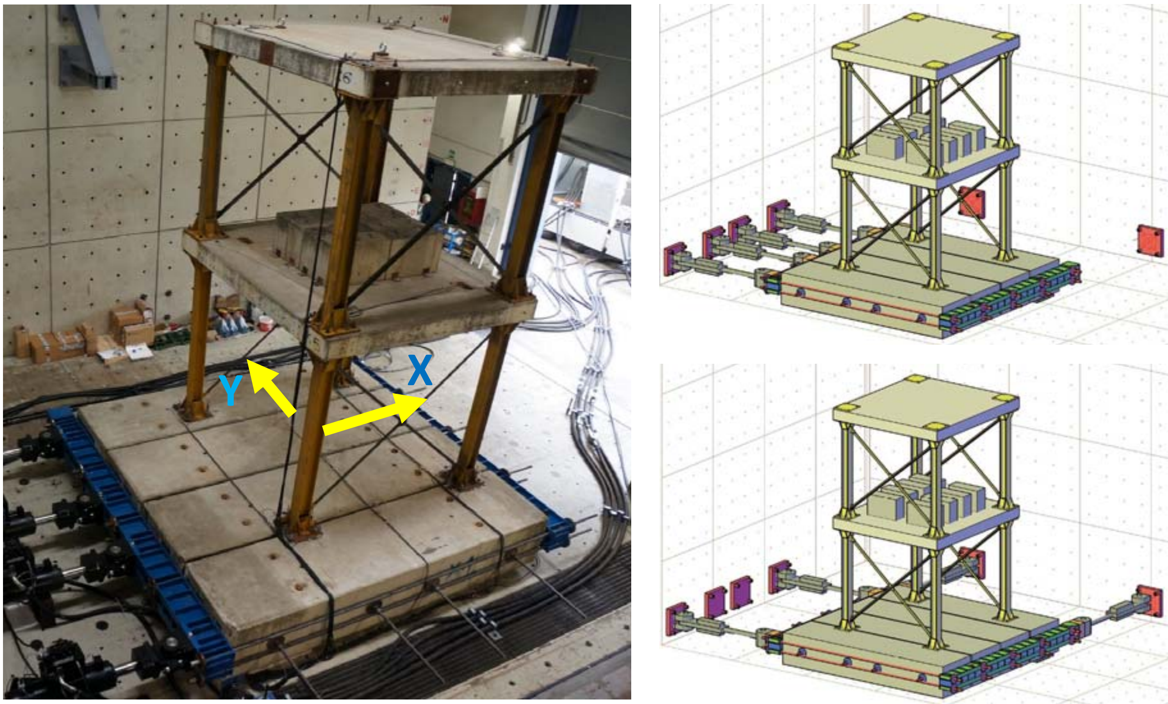

Fig. 3 – Overview of the specimen designed for the first trial of the mobile system (left) and layout of the two set-up configurations: four parallel actuators in the strong direction (top right) and couples of actuators to impose two orthogonal components of the excitation contemporaneously (bottom right)

3.2 Prediction of the seismic response

Two different couples of orthogonal accelerograms (SC1 and SC2), consistent with the ground motions expected at the real testing site ([12], [13]), were selected to be used in the experimental trial (the longitudinal components of the ground motions and their acceleretion and displacement spectra are depicted in Fig. 4 and Fig. 5). In order to cover values of PGA ranging from about 1 m/s^2 to 8 m/s^2, the signals were scaled by amplification factors up to 4.

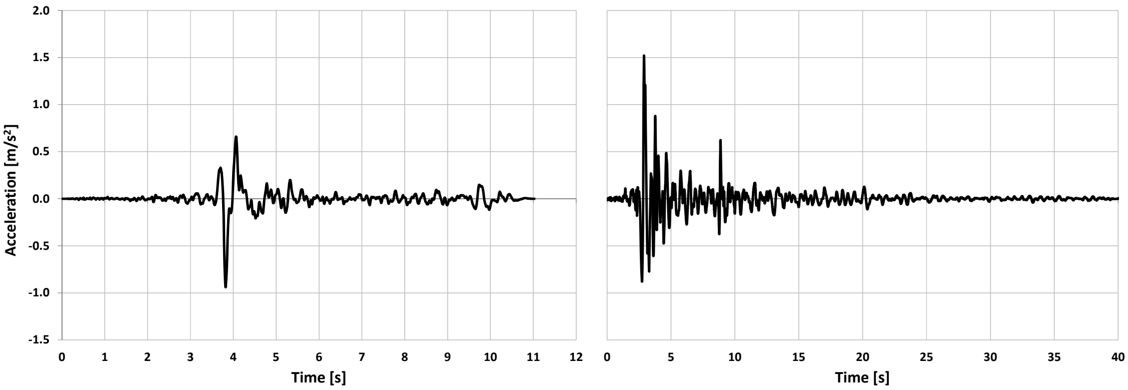

Fig. 4 – Longitudinal component of the accelerograms SC1 (left) and SC2 (right), scale factor = 100%

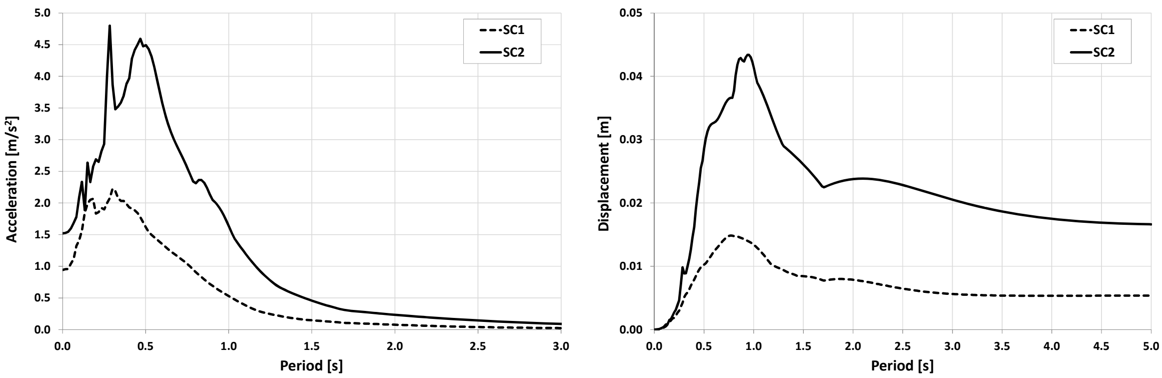

Fig. 5 – Acceleration (left) and displacement (right) spectra of the longitudinal component of the accelerograms SC1 and SC2 calculated assuming amplification factor 100% and damping ratio 2%

The natural frequencies and mode shapes of the specimen could be modified varying the configuration of the braces and/or the amount and location of the masses. Several configurations were studied developing numerical models and performing modal analyses to evaluate their dynamic characteristics and compatibility with the seismic demand. The dynamic properties of the considered configurations, characterized by different brace systems and added mass distributions, are summarized in Table 1. The effect of the braces, which are provided only along the X axis, is to reduce the period of vibration of about one half, whilst the additional masses give only small increments of the period (about 15%).

Since the real aim of the test was to study the behaviour of the testing system, rather than the response of the speciumen, this one was assumed to respond linearly. A series of about 400 time-history linear analyses were performed considered twelve configurations and assuming parameters like the two orthogonal directions, the two accelerograms (SC1, SC2) and five levels of amplification factors (1 to 4).

The demand to capacity ratio of each configuration, particularly in terms of strength and interstorey drift were thus investigated to prevent both critical damages to the connections and excessive displacement levels. The main results concern the fact that yielding conditions of the columns in the strong direction is never attained. Slightly less conservative conditions, however without limitations, arise along the weak direction (Y) of the frame, due to two specific reasons: i) the absence of the bracing system may result in higher acceleration amplifications, ii) that direction corresponds also to the local weak direction of the columns, so the yielding condition is reached at shear actions lower than orthogonal strong direction.

The displacement of the isolated basement is substantially independent of the configuration, since the global mass is quite constant. A higher demand is imposed by accelerogram SC2 amplified at 400% (about 3.5 times the demand of accelerogram SC1 at the same amplification). The capacity of the system is anyway never attained. The top floor displacement demand is more critical along the weak direction, where the braces are absent. A maximum total drift of about 1.5% results for the configuration #11 excited by SC2 at 400%; this configuration corresponds to a double additional mass at the second floor. In all other cases the displacement demand is less than a half (drift 0.67%).

Table 1 – Natural frequencies and mode shapes of twelve different configurations of the specimen evaluated by modal analyses of numerical models

ID(1)	Braces in X direction(2)	Additional masses	X direction				Y direction				In-plan rotation Z-Z			
			1° mode		2° mode		1° mode		2° mode		1° mode		2° mode	
			T [s]	Mx [%]	T [s]	Mx [%]	T [s]	Mx [%]	T [s]	Mx [%]	T [s]	Mx [%]	T [s]	Mx [%]
1	No	No	0.26	90	0.09	8	0.37	92	0.13	6	0.29	91	0.10	7
2	No	Yes	0.30	90	0.10	8	0.43	92	0.16	6	0.34	91	0.12	7
3	Yes	No	0.13	89	0.05	9	0.37	91	0.14	6	0.17	90	0.06	7
4	Yes	Yes	0.15	89	0.05	9	0.43	92	0.16	6	0.19	90	0.07	8
5	2nd floor	No	0.23	96	-	-	0.37	92	0.13	6	0.26	96	-	-
6	2nd floor	Yes	0.26	97	-	-	0.43	92	0.16	6	0.30	97	-	-
7	No	2 x 2nd floor	0.33	90	0.09	7	0.46	92	0.14	6	0.36	91	0.11	7
8	Yes	1st floor	0.14	89	0.05	8	0.39	92	0.15	5	0.17	90	0.07	7

1 – Additional configurations 9, 10, 11 and 12 are identical to 5, 6, 7, 8. In the following, the first eight configurations are considered subjected to an excitation in the X direction, whilst the configurations 9, 10, 11 and 12 are excited in the Y direction.
2 – The braces are provided only in the X direction. The Y direction is always unbraced.

These results were confirmed considering pushover capacity curves (Fig. 6) obtained imposing a triangular distribution of the lateral forces and calculating the acceleration vs. displacement curves of the equivalent SDOF systems corresponding to each configuration. In Fig. 6 all configurations involving the strong direction of the frame are considered; the capacity appears to be always greater than the demand. Configurations #7 and #8 are reconsidered in Fig. 6 together with their counterparts loaded in the weak direction (configurations #11 and #12); the same accelerogram is considered in both longitudinal and transversal direction; SC2 amplified at 200% seems enough to induce yielding.

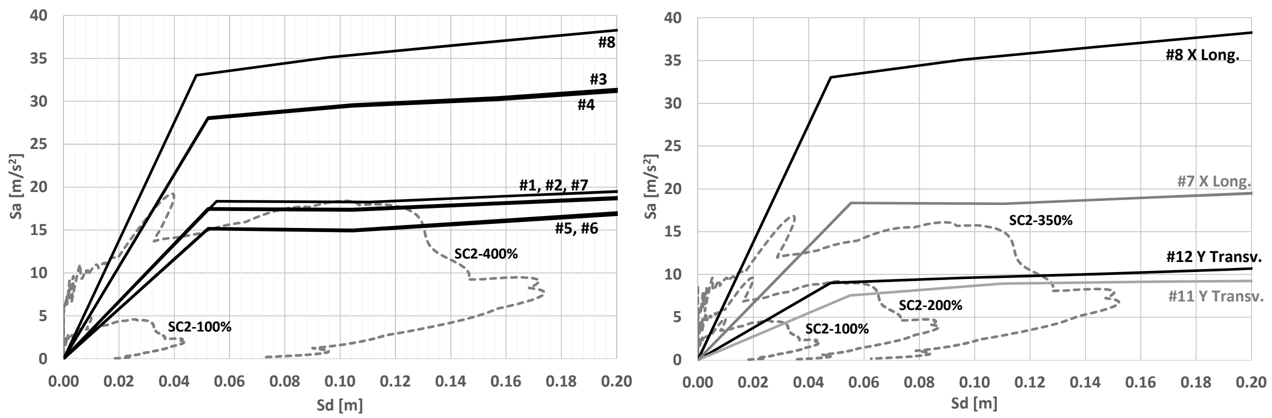

Fig. 6 – Pushover capacity curves of equivalent SDOF systems compared to ADRS spectra SC2 with various amplification factors: comparisons of the eight configurations along the strong direction of the frame (left); comparisons of the cases #7 and #8 with the corresponding cases #11 and #12 in the weak direction (right)

Finally, also the capacity of the connections was checked. In the case of the configurations #8 (the one selected to be tested) an unsafe condition was found in the transversal direction, thus the transversal component of the accelerogram was reduced respect to the longitudinal one in the experimental biaxial tests.

3.2 Loading history and instrumentation

On the base of the results of the numerical predictions, configuration #8 (Table 1) was selected to be tested applying a uniaxial and a biaxial input in accordance with the information of Table 2. The loading protocol has been defined also checking the required oil flow compared to the capacity of the system. The most severe test in terms of velocity and displacement of the actuators, as well as flow rate and volume demand, is the test BF2T8. Despite a peak flow rate demand of 4000 l/min, the laboratory capacity was fully compatible.

Table 2 – Loading history for uniaxial tests along the strong (X) direction of the frame

Uniaxial tests – longitudinal direction					**Biaxial tests – longitudinal and transversal directions**				
Test N.	**Test ID**	**Accelerogram**	**Ampl. factor X dir.**	**PGA X dir. [g]**	**Test N.**	**Test ID**	**Accelerogram**	**Ampl. factor X dir.**	**PGA X dir. [g]**
1	F1T1	SC1_150cc	SC1	1.50	12	BF1T1	SC2_XY_050b	SC2	0.50
2	F1T2	SC1_200c	SC1	2.00	13	BF1T2	SC2_XY_075a	SC2	0.75
3	F2T3	SC2_80b	SC2	0.80	14	BF2T3	SC2_XY_100a	SC2	1.00
4	F2T4	SC2_100d	SC2	1.00	15	BF2T4	SC2_XY_150b	SC2	1.50
5	F2T5	SC2_150b	SC2	1.50	16	BF2T5	SC2_XY_200a	SC2	2.00
6	F2T6	SC2_200c	SC2	2.00	17	BF2T6	SC2_XY_250c	SC2	2.50
7	F2T7	SC2_150ll	SC2	1.50	18	BF2T7	SC2_XY_300a	SC2	3.00
8	F2T8	SC2_200b	SC2	2.00	19	BF2T8	SC2_XY_350a	SC2	3.50
9	F2T9	SC2_250a	SC2	2.50	20	BF3T9	SC2_XY_Y250	SC2	-
10	F2T10	SC2_300a	SC2	3.00	21	BF3T10	SC2_XY_Y300	SC2	-
11	F2T11	SC2_350a	SC2	3.50					

The digital controller of the actuators allowed a complete assessment of the movements of the specimen base, in terms of displacement, rotation, velocity, acceleration and force. Additional instrumentation was provided on the specimen, comprising linear potentiometers and bi-axial accelerometers; an external optical acquisition completed the acquisition system. An accelerometer was provided at each column at three levels (basement, first and second floor). A system of three vertical displacement transducers with stroke of 25 mm was provided at the base of each column to capture the potential detachment of the base plate from the concrete slab. An additional optical acquisition employed a system of co-axial infrared cameras and retro-reflective markers applied to the specimen to estimate a complete set of displacements of each floor, including the basement

4. Results

4.1 Efficiency of the control system

The efficiency of the control system was checked comparing the reference and the feedback signals of the time-histories and of the acceleration spectra at the base. This comparisons are very important, because it is expected that the capacity of the hydraulic system and of the servovalves are sufficient to impose more demanding accelerograms, but it is not so predictable that the controller and the system are able to produce a feedback very close to the reference signal also at low oil flow rate demand. The acceleration spectra of the imposed and recorded signal of two of the most demanding cases (F2T8 ÷ F2T11 for uniaxial loading and BF2T5 ÷ BF2T8 for biaxial loading, see Table 2) are compared in Fig. 7 and Fig. 8. In the case of the uniaxial tests, the maximum discrepancies, evaluated instantaneously for periods greater than 0.15 s, are generally less than 10%, whilst in the biaxial tests slightly they increase to values in the range of 20%. In all other not mentioned cases the differences between imposed and recorded spectra are less than 2%.

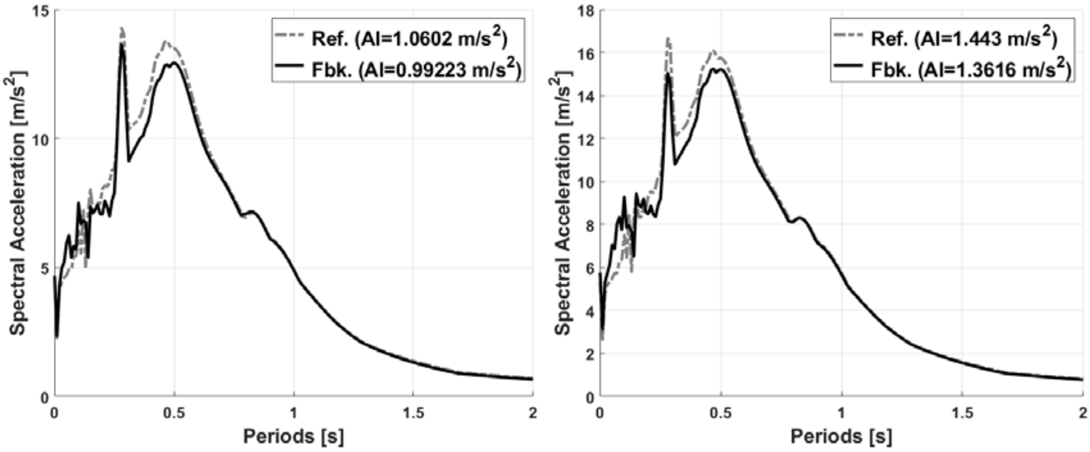

Fig. 7 – Reference vs. feedback acceleration spectra at the base of two severe uniaxial tests: F2T10 (left), F2T11 (right). AI represents the Arias Intensity:

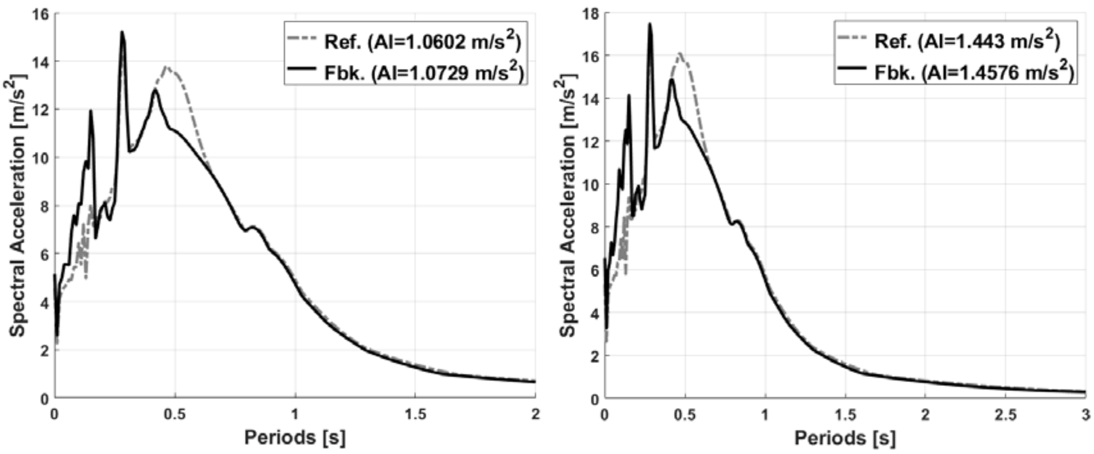

Fig. 8 – Reference vs. feedback acceleration spectra at the base of two severe biaxial tests: BF2T7 (left), BF2T8 (right). AI represents the Arias Intensity:

A comparison in terms of time histories is shown in Fig. 9 for the biaxial test BF2T8 excited by accelerogram SC2 with amplifications 350% (X direction) and 43.8% (Y direction). In the figure on the left, the mean acceleration recorded in the longitudinal direction at the four column bases is compared with the imposed signal, whilst in the one on the right the imposed and the recorded longitudinal displacements are compared between them; an almost perfect matching is to be highlighted in both cases.

In Fig. 10 the force contribution (calculated as a function of the pressure) of the four actuators is compared; since the tests were performed in displacement control, some differences were expected mainly because of the friction effects, imperfections of the basement, non symmetrical distribution of the masses. In any case they are substantially lower than 10% of the maximum capacity of the actuators for the uniaxial and biaxial test. In addition, the resonance effect in the transversal direction of the biaxial test is particularly evident. No evident rotational effects due to asymmetrical force distributions have to be highlighted.

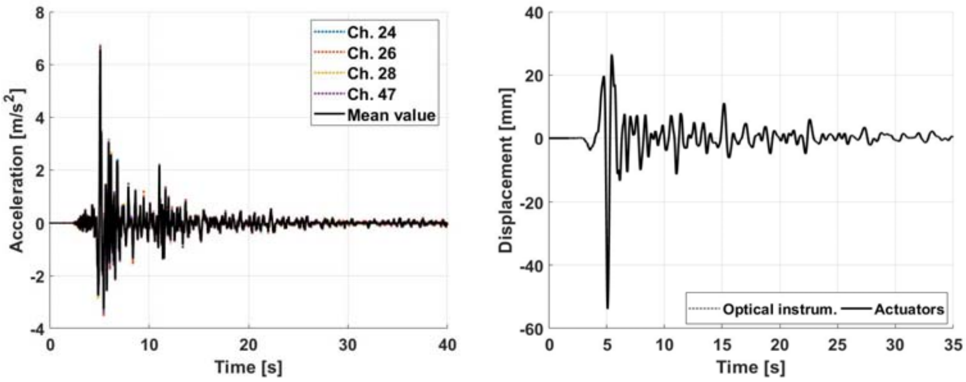

Fig. 9 – Test BF2T8, X direction: accelerations at the base of each column (left); comparison between the displacements of the actuators and of the basement, the latter through optical acquisition system (right)

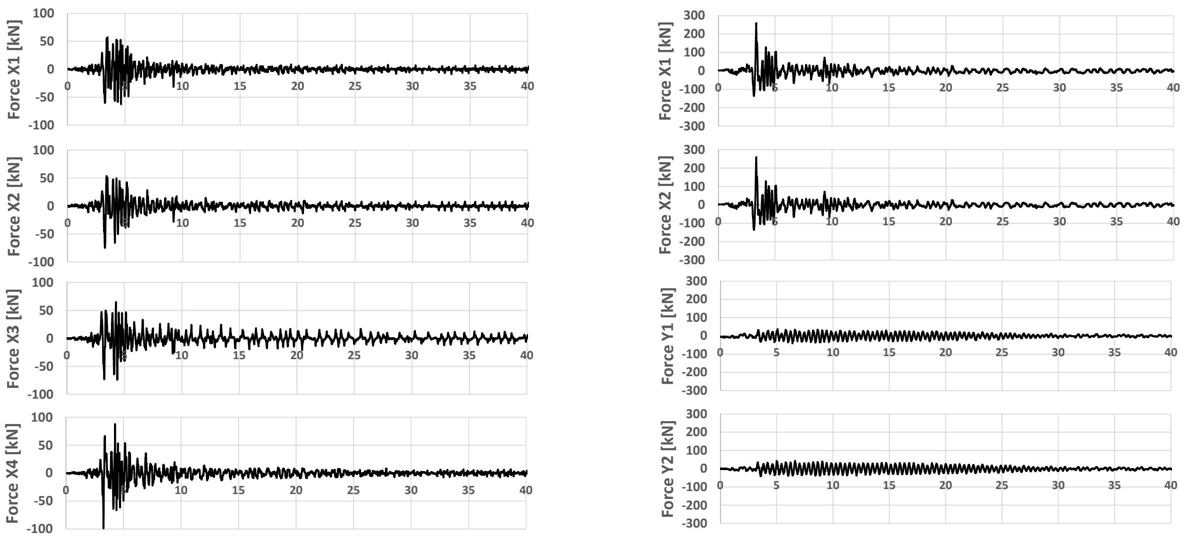

Fig. 10 – Force contribution of each actuator: uniaxial tests F2T11 (left) and biaxial test BF2T8 (right)

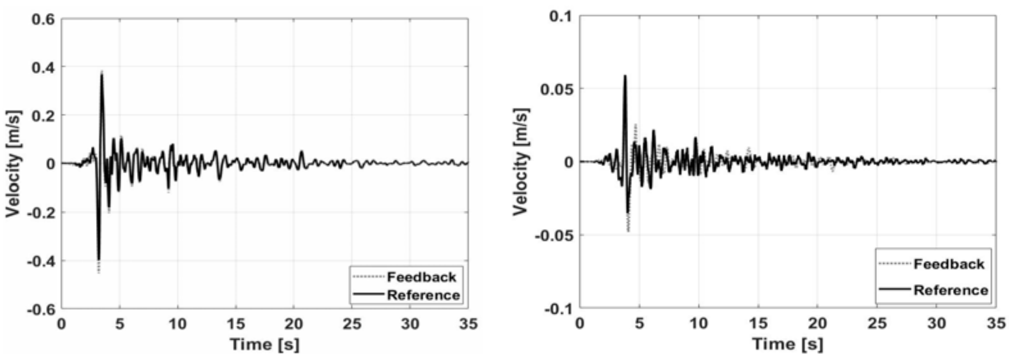

Fig. 11 – Test BF2T8, comparison in terms of velocity between the reference signal and the feedback of the actuators: longitudinal (left) and transversal (right) directions

Further checks were done on the velocity of the actuators, in-plan rotation of the system and twisting effects. For what concerns the velocity, comparisons between the reference signal (integration of the acceleration time-history) and the velocity calculated from the sensors of the actuators (derivation of the displacements for frequencies below 35 Hz, integration of the accelerations otherwise) were evaluated. The results of the comparisons were almost positive, in Fig. 11 a severe case (test BF2T8) is shown.

Differently from biaxial tests, the in plane rotation of the uniaxial tests was not controlled. In the most demanding test (F2T11), peaks of transversal forces of about 70 kN (equivalent to rotational moments of 180 kNm) were observed, without evident rotations at the end of the test.

4.2 Experimental results and comparisons with numerical predictions

The loading protocols were defined to remain within the limit of an elastic response. The recorded response generally confirms this assumption, with limited energy dissipation in all tests, as shown in Fig. 12 for two cases. The top displacements are relatively small (around 20 mm in the cases shown) and the small energy dissipation is due to the connections, which had to be tightened a few times.

The experimental value of the base shear was calculated summing up the contributions of the storey shear evaluated from the accelerations recorded at each column base. It was also derived from the forces recorded at the actuators, subtracting the contribution of the basement mass. The base shear time history obtained from both approaches is compared in Fig. 13. In principle, excluding uncertainties in the calculation of the inertia force, the difference between the signals should correspond to the friction force at the sliders. This estimate is fully compatible with the results of the biaxial test, while in the case of the uniaxial test the value appears greater, particularly because of unsimmetrical effects.

The time histories in terms of acceleration recorded at the basement and at each floor of the two sample tests are depicted in Fig. 14. A significant amplification in the weak direction of the biaxial test is evident. This effect is due to the coincidence between the first period of vibration in that direction and the maximum amplification of the acceleration spectrum.

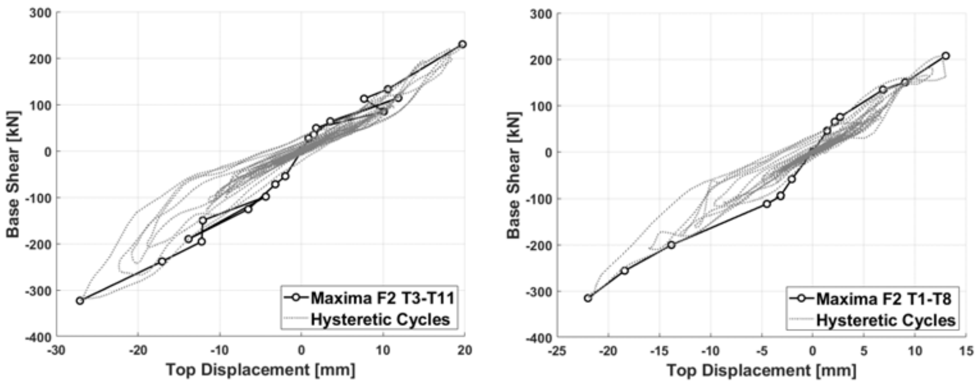

Fig. 12 – Tests F2T11 (left) and BF2T8 (right): longitudinal base shear vs. top displacement hysteretic cycles and envelope of the maximum values

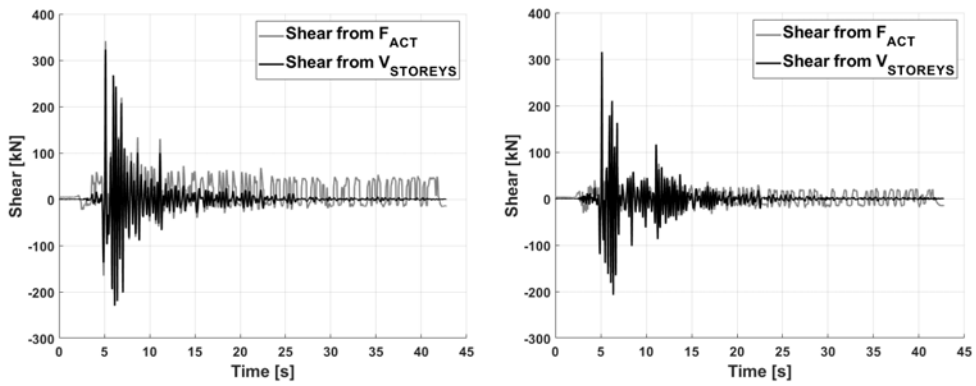

Fig. 13 – Tests F2T11 (left) and BF2T8 (right): comparison between the shear actions evaluated from the actuators and the storey forces

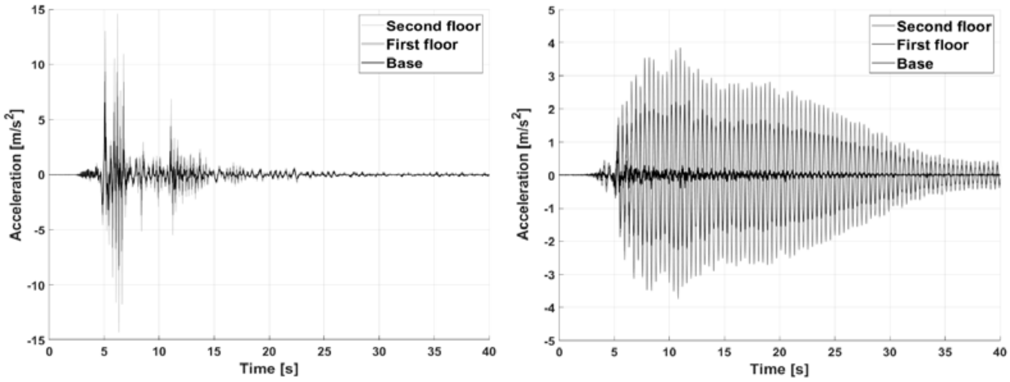

Fig. 14 – Test BF2T8: acceleration at the basement and at each floor of the frame evaluated as the mean value of the signals of the four accelerometers provided at each floor. Longitudinal (strong) direction (a), transversal (weak) direction (b)

The large amplification obtained in the weak direction is more evident in Fig. 15, where the recorded signals are processed in terms of response spectra. In the strong direction, the spectral amplification increases with height, with values compatible with the numerical predictions. Actually, at a period of vibration of 0.14 s, corresponding to the main mode of vibration, the amplifications measured during the tests were: i) 1.5 and 3.0 for test F2T11; 1.3 and 2.4 for test BF2T8. In the weak direction, the main period of vibration is about 0.39 s and the amplification values recorded at the two floors were about 16 and 23 with respect to the basement spectrum. These values are clearly affected by resonant effects, inducing floor accelerations of 44 m/s^2 and 70 m/s^2 at the first and second floor.

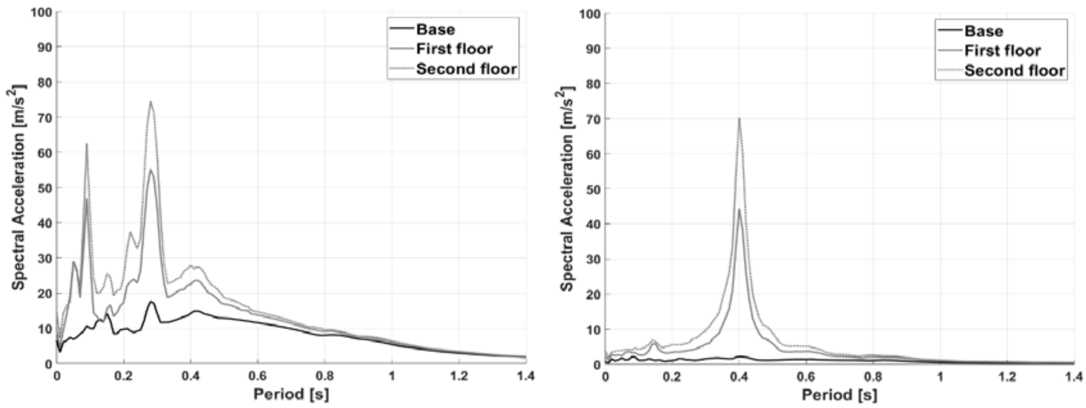

Fig. 15 – Test BF2T8: acceleration spectra at the basement and at each floor of the frame in the longitudinal direction (left) and in the transversal direction (right)

5. Conclusions

A first experimental trial on a completely independent mobile system, constructed to perform in-situ evaluations of the dynamic response of real buildings, has been described in this paper. The global performances that represented the target of the design were: i) maximum displacement, velocity and accelerations equal to ±250 mm, 500 mm/s, 1.2 g for specimens with mass less than 150 t (or 0.3 g for masses of 500 t); ii) maximum static force of 4000 kN; iii) peak flow capacity of 6000 l/min. The characteristics of this dynamic testing system allow to perform various in-situ structural and geothecnical applications, among them: dynamic tests on buildings, evaluations of the dynamic characteristics of bridge structures and dams even at very low frequencies, in-situ liquefaction tests.

The mobile system was assembled simulating conditions similar to a real in-situ test with the aim of checking the effectiveness of its components when they are stressed by imposing a series of loading histories on a specific specimen which consisted of a full scale two-storey one-bay 3D frame with steel columns and RC slabs. The frame was fixed to a basement of post-tensioned RC blocks supported by PTFE devices.

The main issues regarding the response and the functioning of the components of the mobile system were investigated during and after the tests devoting particular care to the assembling phase, the reliability of digital controller and the response of the actuators. Although the relatively low acceleration level due to the seismic input, the trial was very demanding for the controller, because it is not so predictable that the controller and the system are able to produce a feedback very close to the reference signal also at low oil flow rate demand. The main results of the trial were: i) peak flow rate demand of almost 4000 l/min (60% of the capacity of the system); ii) maximum discrepancies between reference and feedback signals, evaluated for periods greater than 0.15 s, less than 10% (most demanding uniaxial tests), less than 20% (most demanding biaxial tests) and less than 2% in all other cases; iii) no relevant rotations correspooding to thr maximum in plane rotational moment; iv) resonant effects on the specimen consistent with the prediction, particularly relevant in the weak direction; v) very high floor spectral amplifications especially in the weak direction.

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