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SHAKING TABLE TESTS ON RC RETROFITTED FRAME WITH FRP

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SUMMARY

This paper describes the experimental work undertaken on FRP seismic strengthening of a RC structure as part of the "Ecoleader" European program. Shaking table tests were performed on a one-bay, 2 storey, full-scale spatial RC-frame (4 m x 4 m, 6.6 m high, 30 t mass) at CEA Saclay on the AZALEE shaking table. Two further papers in this conference will describe the analytical work relating to the tests. The main objective of the program was to assess different strengthening strategies and techniques on a seismically under-designed R/C frame structure, in order to develop simple and rational techniques for use in FRP-strengthening of R/C structural elements (i.e., beams, columns and joints) and quantify their effectiveness through design equations. The original frame was shaken until severe damage was achieved and a sway mechanism was developed. It was subsequently strengthened with Carbon FRP aiming to change the collapse mechanism. The strengthening procedure proved to be amazingly successful and the frame resisted shaking up to the limits possible by the capacity of the shaking table.

1. INTRODUCTION

Much of the existing RC building stock in Europe has been designed using old standards and obsolete design details. Particular problems include strong beam – weak column frames, inadequate anchorage of joint flexural reinforcement and inadequate anchorage for shear links. Such problems are often revealed in buildings subjected to earthquakes such as the Athens 1999 earthquake [Lekkas, 2001] and are dealt with concrete jacketing [Vandoros and Dritsos, 2006]. However, during the past decade, FRP strengthening has emerged as the most popular method for seismic retrofitting in Europe. FRP strengthening is simple and requires little preparation. In addition, it does not change the overall dimensions of the structural elements. Much of the initial applications were done on the basis of guidelines provided by the industry supplying the materials. More recently, there are design guidelines that engineers can use for FRP seismic strengthening, such as Fib Bulletin 14 [Fib, 2000] and EC8 [CEN, 2004]. However, little experimental work has been undertaken in the past on full scale structures to assess the ability of FRP to strengthen RC structures [Balsamo et al., 2005].
This project was initiated under the EU funded project Ecoleader and aimed to assess two different strengthening strategies on a seismically under-reinforced RC frame structure. The frame was designed using typical old European standards and had beams with a higher strength than columns. The anchorage of reinforcement in the joint was just adequate according to the old standards but not adequate enough according to modern standards. It was anticipated that the frame would initially fail due to soft storey mechanism and subsequent repair and strengthening would aim to enhance the column capacity and develop hinges in the beams.
This paper, which is one of the three in this conference dealing with this project, will concentrate in presenting the experimental details and procedure [Papastergiou et al. 2006, Kyriakides et al. 2006a and 2006b]. It will present the details of the frame, the repair procedure, the seismic excitation series and the main test results.

2. DESIGN OF THE FRAME

The specimen tested was a typical one-bay, 2 storey, full scale spatial RC bare frame structure.. The total height of the specimen was 6.87 m. The specimen consisted of:

- 4 square columns : 0.26 m section,

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- 2 square slabs : 0.12 m thickness and 4.26 m wide,
- 4 beams per slab: 0.40 m x 0.26 m section.

The total weight of the structure was about 20 tons. For the tests, an additional mass of 9 tons (4.5 tons per slab) was added. Figures 1 and 2 present the geometry of the specimen.

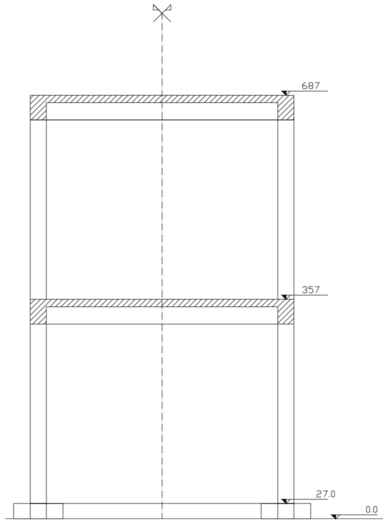

Figure 1: Side view of the specimen

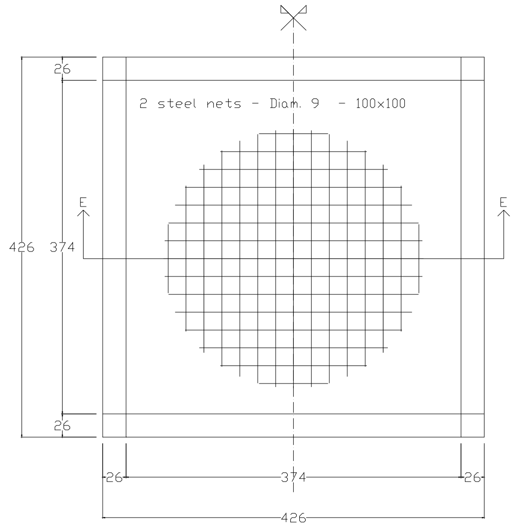

Figure 2: Plan view of slab

The steel longitudinal reinforcement (tensile strength of 550 MPa) was as follows:

- columns:
  3ϕ14 + 2ϕ14 + 3ϕ14 for the 1st floor,
  2ϕ14 + 2ϕ14 for the 2nd floor,
- beams:
  4ϕ14 top and bottom

The transverse reinforcement (stirrups) of beams and columns consisted of 6 mm and 8 mm diameter steel bars, respectively. The slab reinforcement consisted of steel mesh top and bottom (ϕ9 mm – 100 x 100 mm). The concrete cover was 30 mm. Figure 3 shows a sketch of the steel reinforcement of the frame, whilst figure 4 illustrates the anchorage details of the joints.

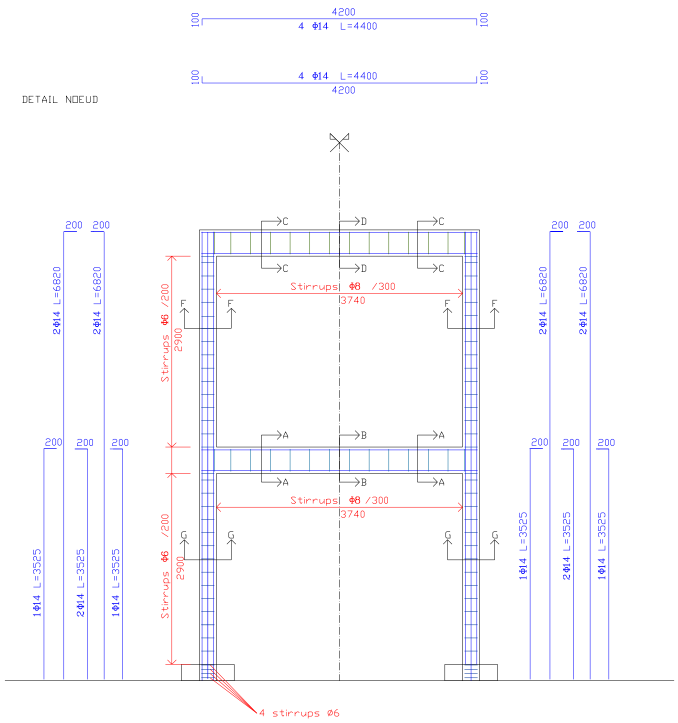

Figure 3: Steel reinforcement of beams and columns

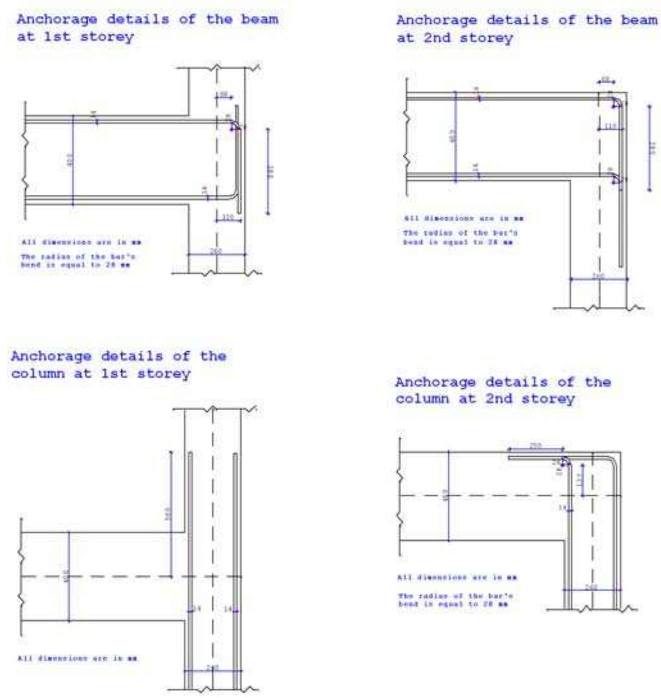

Figure 4: Anchorage details of nodes

Figure 5 shows a view of the reinforcement typical of a joint in the 1st level. All longitudinal reinforcement bars were continuous without any lap splices. The specimen was cast at the CEA laboratory using steel formwork, specially designed and manufactured for the specific project (concrete compressive strength: 20 MPa). This formwork permitted the casting of one floor of the specimen (4 columns, 4 beams and 1 slab) each time. The specimen was cast in 2 phases. Figure 6 shows a view of the frame after casting.

Figure 5: Reinforcement of a 1st level node

Figure 6: Frame after casting

The frame was anchored on the AZALEE shaking table through a specially manufactured steel box at the base of each column (Figure 7). The vertical bars of the columns were welded on the base plate of the box aiming at fully fixed support conditions. Eight horizontal steel bars, four in each direction, were bolted on the sides of the steel box to increase its rigidity.

Figure 7: Steel foundation box

3. FRP STRENGTHENING

The strengthening design was undertaken in collaboration between Ecoleader researchers and an industrial partner (Freyssinet – France). The industrial partner applied the strengthening after the last seismic test (0.4g) on the bare frame. Before applying the FRP, resin was injected into the main cracks of the joints (Figure 8). After injection and polymerization of the resin, surfaces were prepared and FRP was applied (Figure 9). The top (60 cm) and bottom (90cm) of each column were confined with one layer of CFRP. Joints were enhanced in flexure and shear using one layer of CFRP. Beams were not strengthened at all, following the main idea of transferring the plastic hinges into the beams. The Carbon FRP characteristics (according to the industrial partner) were the following:

Young modulus: 105 GPa, guaranteed stress in tension: 1700 MPa, Design tensile strength: 913 MPa, layer thickness: 0.48 mm and anchorage length 20 cm.

Figure 8: Injection of resin into crack

Figure 9: FRP retrofitting

Figure 10: Retrofitted frame on AZALEE shaking table

4. SHAKING TABLE TESTS

4.1 Test program and instrumentation

Tests were performed on the 6 DOF AZALEE shaking table of the "Seismic Mechanic Study" laboratory of CEA Saclay (France) (Figure 11). The maximum payload is 100 tons. The square base plate is 6 m wide. Eight hydraulic jacks (4 for horizontal and 4 for vertical excitations) are connected to the plate. Each jack has a maximum force of 1000 KN. Four static pneumatic supports are placed under the plate to support the weight of the table and the specimen. The maximum displacement range is 250 mm for the two horizontal axes and 200 mm for the vertical axis.

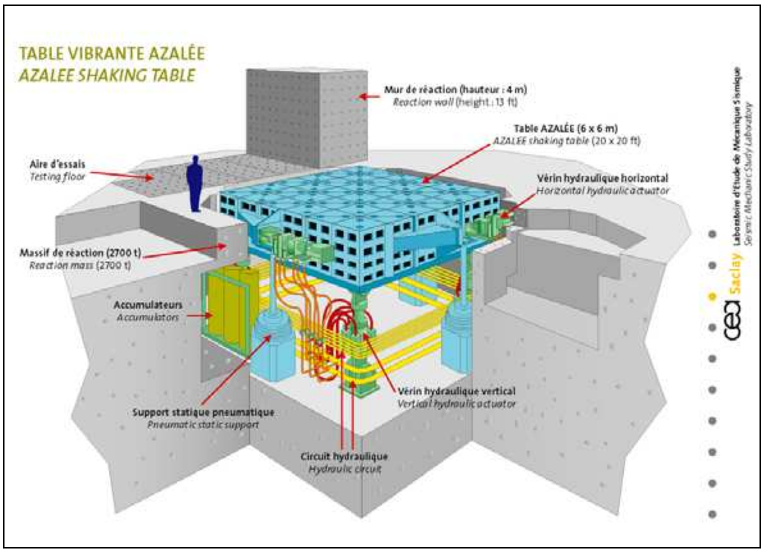

Figure 11: AZALEE shaking table

The test program was performed in two steps:

- Bare frame:
  5 mono-axial seismic tests with increasing PGA levels from up 0.07 g to 0.38 g,
- Retroffited frame:
  6 mono-axial seismic tests with increasing PGA levels from 0.05 g up to 0.50 g and 5 sine sweep tests with increasing acceleration from 0.06 g up to 0.19 g.

Each seismic test was preceded and followed by a mono axial white noise test, with a frequency range from 0.5 Hz to 50 Hz, with low acceleration level (0.1g max), to measure the natural frequencies of the frame. Natural frequencies of the bare frame were measured before and after retrofitting.

The reference spectrum was derived from Eurocode 8, corresponding to soil C (Figure 12). An artificial seismic signal of duration 20 seconds was calculated from this spectrum.

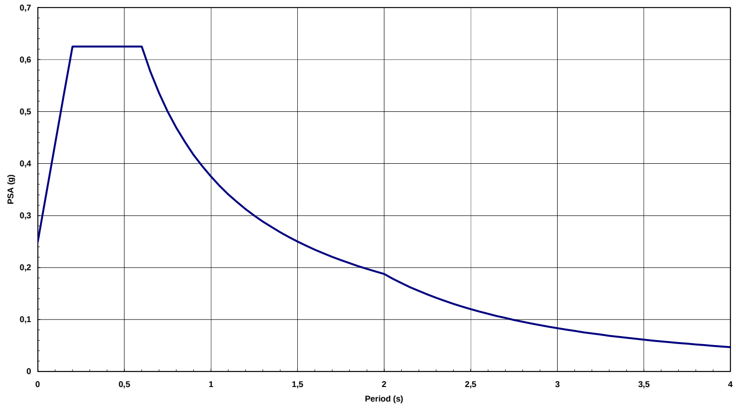

Figure 12: Reference spectrum

During the tests, the global behaviour of the frame was monitored by 15 accelerometers and 6 displacement transducers. Sixteen strain gauges were bonded before concrete casting on several longitudinal bars of columns and beams, at the 1st level on the frame. Table 1 presents the target and actually measured maximum acceleration values of all tests (chronological sequence).

Table 1: Target and measured PGA values in all the seismic tests.

	Bare frame	Retrofitted frame (seismic tests)		Retrofitted frame (sine sweep tests)
Target PGA (g)	0.05	0.05	**Target Accel (g)**	0.04
Measured PGA (g)	0.07	0.065	**Measured Accel (g)**	0.06
Target PGA (g)	0.10	-	**Target Accel (g)**	0.08
Measured PGA (g)	0.12	-	**Measured Accel (g)**	0.09
Target PGA (g)	0.20	0.20	**Target Accel (g)**	0.10
Measured PGA (g)	0.21	0.21	**Measured Accel (g)**	0.11
Target PGA (g)	0.30	-	**Target Accel (g)**	-
Measured PGA (g)	0.29	-	**Measured Accel (g)**	-
Target PGA (g)	0.40	0.40	**Target Accel (g)**	0.40
Measured PGA (g)	0.38	0.39	**Measured Accel (g)**	0.39
Target PGA (g)	-	0.50	**Target Accel (g)**	0.50
Measured PGA (g)	-	0.50	**Measured Accel (g)**	0.50
Target PGA (g)	-	0.40	**Target Accel (g)**	0.40
Measured PGA (g)	-	0.38	**Measured Accel (g)**	0.38

4.2 Main test results

4.2.1 Damage report

Bare frame:
No damage was observed after the first two seismic tests. First visible cracks appeared during the 0,2 g seismic test on the joints of the 1st level (diagonal shear cracks) and under the joints of the 2nd level (horizontal cracks). Some new horizontal cracks appeared over the joints of the 1st level, on the columns and at the base of column 4 during the 0.3g seismic test. Finally, during the last seismic test (0.4 g), new cracks appeared on column 1 between the base and the 1st slab. At the base of column 4, spalling of concrete was observed. Figures 13 to 15 show views of cracks after this first series of seismic tests.

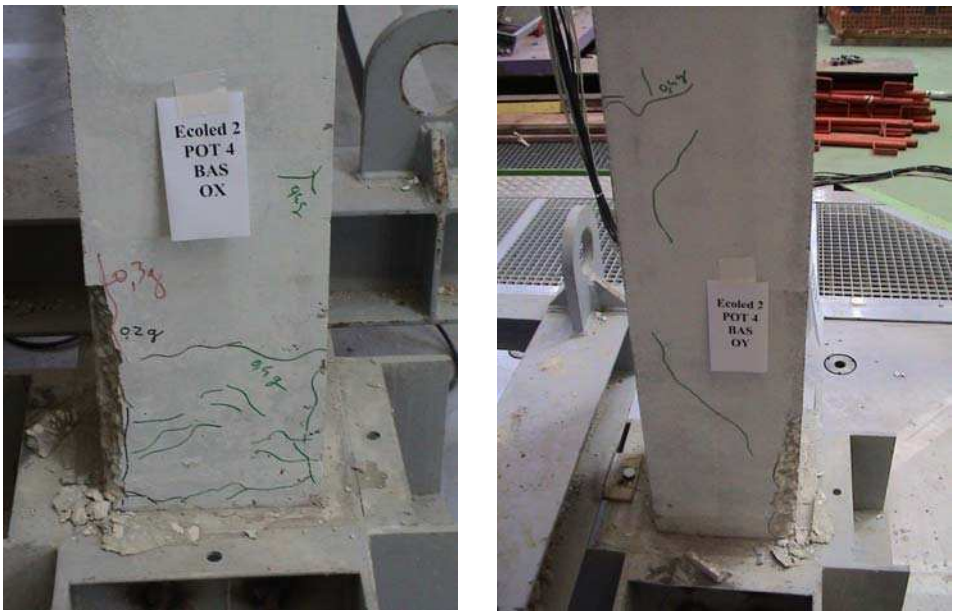

Figure 13: Views of the cracks and the bottom of the columns of the mockup after the first series of tests without strengthening

Figure 14: Views of the cracks and the first slab level of the mockup after the first series of tests without strengthening

Figure 15: Views of the cracks at the first slab level of the mockup after the first series of tests without strengthening

Retrofitted frame:
No damage appeared after the first seismic test at PGA 0.05g. Some FRP debonding was detected by manual tapping of the FRP at the base of the columns of the first floor after the test with PGA 0.2g. No further damage was detected until the end of the test with PGA 0.4g. After the test with PGA 0.5g, new cracks appeared on the beams and on the columns. The FRP sheets provided in the joints appeared to have debonded partially from the beams, as shown in figures 16 and 17. From this and other evidence from the strain gages readings, it was concluded that the plastic hinges were moved away from the columns and into the beams.

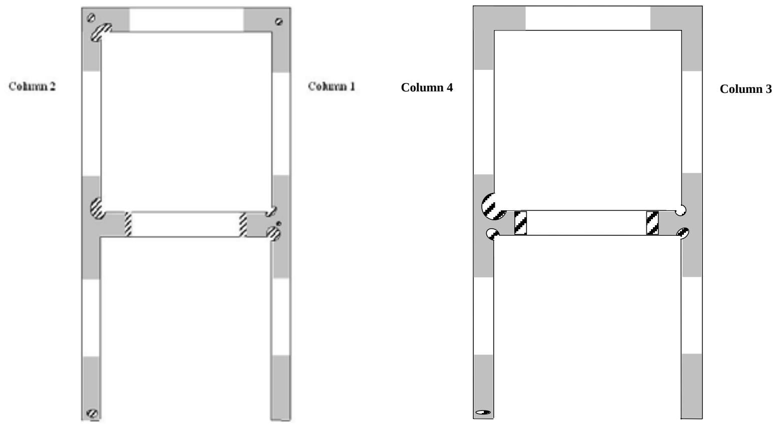

Figure 16: Debonded areas of FRP after 0,5 g seismic test – (Front-back elevations)

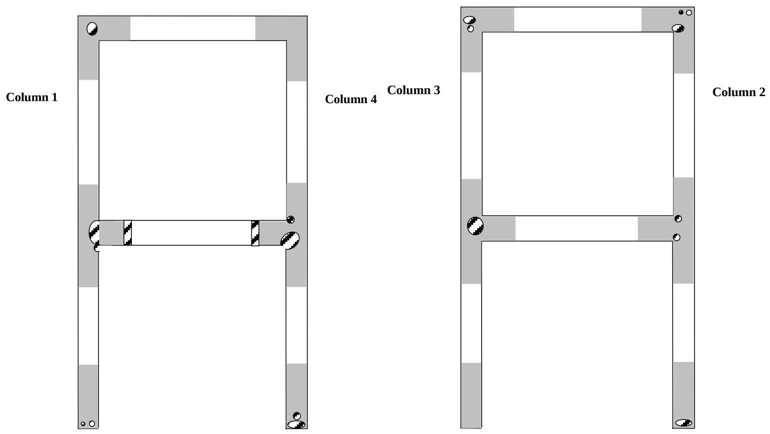

Figure 17: Debonded areas of FRP after 0,5 g seismic test – (Side elevations)

4.2.2 Natural frequencies

Table 2 shows the values of the first two natural frequencies of the bare frame measured before and after each seismic test. It is obvious that the 1st natural frequency of the specimen decreases as the acceleration increases due to the building's stiffness deterioration. It should be noted that the first frequency after the first serious motion of 0.1g decreased by 30%. This degradation in stiffness is associated with the cracking of the concrete sections. After the last test with a GPA of 0.4g, the frame was damaged substantially and a sway mechanism was achieved.

Table 2: Natural frequencies of the bare frame – Seismic tests

	1st natural frequency (Hz)	**2nd natural frequency (Hz)**
Before tests	1.90	5.60
After the test PGA target 0,05 g	1.66	4.88
After the test PGA target 0,10 g	1.36	4.30
After the test PGA target 0,20 g	1.07	3.60
After the test PGA target 0.30 g	0.88	2.64
After the test PGA target 0.40 g	0.68	2.54

Figure 18 below, shows the results of the frequency measurements.

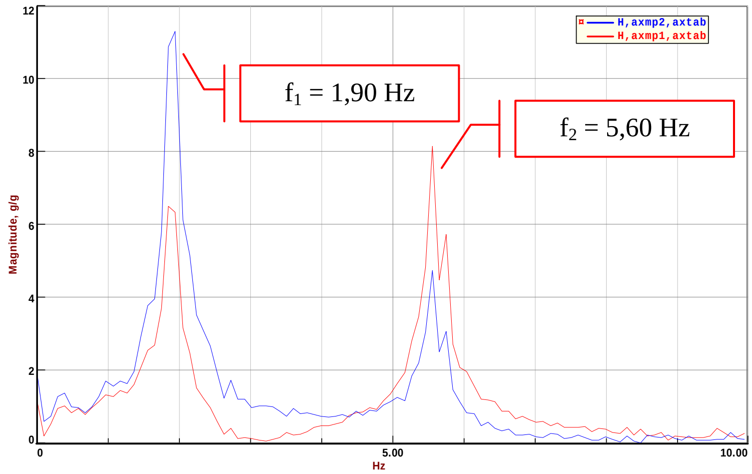

Figure 18: Natural frequency measurements –Bare frame before seismic tests

Table 3 shows the values of the first two natural frequencies of the retrofitted frame measured before and after each seismic test. The 1st frequency of the retrofitted specimen is around the 70% of the initial value of the bare frame, indicating that the stiffness has been restored to a satisfactory level. Comparing the values at 0.4g, the retrofitted frame behaves substantially better, showing energy dissipation enhancement as the plastic hinges were created in the beams. Even at the high PGA of 0.5g, the frame responded better as for PGA of 0.3g for the bare frame, but with a much better ductility.

Table 3: Natural frequencies of the retrofitted frame – Seismic tests

Tests	**1st natural frequency (Hz)**	**2nd natural frequency (Hz)**
After retrofitting	1.37	4.30
After the test PGA target 0,05 g	1.27	4.20
After the test PGA target 0,20 g	1.07	3.61
After the test PGA target 0.40 g	0.98	3.32
After the test PGA target 0.50 g	0.88	3.00

After performing the 0.5g acceleration test, the shaking table displacements limits were reached. Considering that the target displacement was not achieved yet, it was decided to perform sine sweep excitations with frequencies close to the natural frequency of the structure. Following this specific strategy, larger amounts of energy could be applied to the frame, using only a small percentage of the shaking table displacement capabilities. Table 4 reports the values of the first two natural frequencies of the retrofitted frame measured before and after each sine sweep test. It is clear that even with an increasing acceleration only increased displacements were achieved with little overall degradation in stiffness.

Table 4: Natural frequencies of the retrofitted frame – Sine sweep tests

Tests	**1st natural frequency (Hz)**	**2nd natural frequency (Hz)**
After retrofitting	1.37	4.30
After 0,04 g sine sweep test	0.78	3.02
After 0,08 g sine sweep test	0.78	3.00
After 0,10 g sine sweep test	0.78	2.93
After 0,12 g sine sweep test	0.78	3.02
After 0,14 g sine sweep test	0.78	2.93
After 0,18 g sine sweep test	0.68	2.73

5. CONCLUSIONS

A two-storey full scale RC frame designed to old European standards was tested and damaged on a shake table. A sway mechanism was created, with some damage in the joints. The damage was repaired and the frame was strengthened with a small amount of CFRP in the region of the joints and column hinges. After retesting the frame, it was found that this minimal strengthening was sufficient to restore the stiffness of the frame and enhance its strength and deformation capacity by shifting the plastic hinges into the beams. Further analytical work was done and this is presented in separate papers.

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