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MANSIDE: SHAKING TABLE TESTS OF R/C FRAMES WITH VARIOUS PASSIVE CONTROL SYSTEMS

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SUMMARY

The paper reports the results of a large experimental investigation carried out within the MANSIDE project devoted to the design, construction and testing of anti-seismic devices based on shape memory alloys (SMA). One of the main purposes of the project was the performances evaluation of the SMA based devices against conventional devices. A large number of shaking table tests were performed on eight reduced scale r/c plane frames according to the following configurations: non protected frames, frames protected with conventional devices and frames protected with SMA devices. The rational for the comparative evaluation was: (i) the non protected frames were taken as reference frames; (ii) the other frames were designed and equipped with different devices for vibration control including both seismic isolation and passive energy dissipation; (iii) the conventional systems were optimised using state of the art results and the SMA devices proportioned accordingly, (iv) different alternatives were considered for SMA devices: re-centering + dissipating devices, only dissipating or only re-centering devices, (v) masonry panels was inserted in the reference and the isolated frames to account for interactions between structural and non structural elements. The simulated seismic tests were carried out in the range 0.16 - 0.9g and statements were made quantitative through classical damage indicators. The experimental results show that major advancements, in terms of both safety and functionality, are obtained using SMA isolators; no remarkable safety increase is observed when using SMA braces in place of steel braces, but the first are preferable due to their re-centering capability. Further improvements are expected when specific design rules will be developed for the optimal exploitation of the SMA based devices.

INTRODUCTION

The systems implemented in the field of passive seismic protection are, generally, classified according two different strategies: base isolation or energy dissipation [Dolce 1994]. Both these strategies make use of specially designed devices among which the most widely used are: rubber bearings for isolation and steel braces for energy dissipation. The worldwide applications and the recent research directions devoted to the protection systems optimisation, rather than the development of updated devices, witness the achievement of high scientific and technological expertness in the field. Nevertheless, the use of “new” materials endowed with advanced capabilities, as compared to the traditional ones, can lead to significant improvements in the seismic performance of buildings both in terms of structural safety and maintenance. Apart from the same basic properties shared with more conventional materials, Shape Memory Alloys (SMA) show attractive for a number of further properties possessed. These pertain to the mechanical and functional fields as well and range from (i) tunable material characteristics, to (ii) very high fatigue and corrosion resistance and to (iii) re-centering capabilities, that are as many self-evident advantages as compared to the limited freedom in the material characteristics selection, the maintenance required and the post-earthquake interventions to which the conventional devices are subjected. SMA materials have been widely studied mainly from metallurgists and mechanical scientists, but, to date, no

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systematic investigations have been carried out, to the authors knowledge, in the structural field [Bernardini et al. 1996] to fully exploit the high potential shown by SMA materials.

The MANSIDE (Memory Alloys for New Structural vibration Isolation DEvices) project herein addressed, was carried out within the IV RT&D Framework Program of the European Union and was devoted to a comprehensive investigation, including the design, construction and testing, of SMA based anti-seismic devices [Nicoletti 1999]. Within the activities of the MANSIDE project a fundamental task was the comparative evaluation of SMA based devices against the conventional passive control systems. A large experimental campaign, aimed at evaluating the seismic performances of reduced-scale r/c frame models endowed with different protection systems, was carried out on purpose and the relevant experimental results are the main subject of the paper. Three different alternatives for the seismic ptrotection were considered: non protected (fixed base) structures, yet designed according to seismic codes, base isolated structures (either with rubber or SMA isolators) and structures endowed with dissipative bracing systems (either with steel or SMA braces). A A number of different SMA devices was devised, realised and tested: re-centering + dissipating devices, only dissipating devices, only re-centering devices. The influence of infilled masonry panels was also considered. The seismic simulations were performed using the shaking table facility at the Technical University of Athens and the structural systems underwent increasing seismic intensity up to 1g. The comparative evaluations were based on the structural response and the devices behaviour, safety and technological aspects were addressed as well.

STRUCTURAL MODELS

Since the comparison of the performances involves the structural response, homogenous data are required for precise quantitative statements. To this end, only one structural typology was considered, even if, in principle, the structural models should be differently optimised against each specific protection system. In view of the above, the design of the models was carried out with reference to one prototype full scale r/c structure that was subsequently reduced according to 1/3 length scale factor, see figure 1. The EC8 seismic code [CEN 1994] was used for the design and among other relevant design quantities it is worth mentioning that the "low ductility" class and the behaviour factor $q = 2.5$ were adopted together with a design base acceleration of 0.25g. Note, in fact, that if an high level of ductility would be selected for non protected models, as it would indeed seem natural, then the protected models would not be well proportioned. The design was subjected to three main constraints: (i) same geometry and reinforcement for all the models, for comparison purposes, (ii) maximum dimensions of the models to exploit most of the room available on the shaking table and to prevent casting and manufacturing problems and (iii) minimum reinforcement ratio, yet compatible with the code prescriptions, to hamper the seismic effects. The beams were proportioned to have higher strength than the columns and these latter were reinforced with 4+2 ϕ 4 mm longitudinal steel bars equal to the minimum reinforcement code requirements. It should also be observed that, since some models would be base isolated and need a base beam, this was added to all models in order to get the same type of connection at the column bases (the most stressed member sections). The micro-concrete was the subject of a specific and separate study aimed at establishing the best material parameters to get a structural response as close as possible to that observed in full scale structures [Nicoletti 1999]. Further, the adopted scale factor allowed for using steel deformed bars of common production so that strenght / ductility properties of the steel complied with standard assumptions. Finally, the bond strength was also checked to guarantee a composite action between micro-concrete and rebars nominally the same as for full scale structures. Note, in fact, that changes in the bond strength can compromise the entire experimental research especially when alternate high intensity cyclic actions are one of the main concerns, as in the present case. In order to get a comprehensive comparison among the possible different structural solutions concerning seismic passive control, eight different reinforced concrete (r/c) structural models were realised and tested. They are listed in table 1.

PROTECTION SYSTEMS

Both the passive control strategies were considered in designing the protection schemes and some of the structural models were equipped with isolators and others with dissipating braces, see table 1. The protection devices were proportioned using available design methodologies for rubber isolators and steel braces. Together with these conventional solutions, innovative devices embodying SMA kernels were also considered. It is worth mentioning since now, that well grounded design criteria are presently available for conventional systems that were therefore optimised to their functions; lacking similar criteria for SMA based devices, no such optimisation was attempted and the SMA devices were simply proportioned using an appropriate scaling of the results found for the conventional devices. In view of the subsequent comparisons it is hence important to recall that the performances of the conventional systems are hardly to improve, whereas SMA based systems are expected to have significant improvements with respect to those herein reported. As concerns base isolation, the rubber bearings were designed to provide a target period of 1 sec. and 10% damping for the isolated r/c model.

Table 1: Structural models and protection systems.

Model no.	Vibration control	Devices	Design	Infill
1	NO	NO	Conventional	bare frame
2	NO	NO	Conventional	brick masonry
3	base isolation	rubber	Conventional	bare frame
4	base isolation	rubber	Conventional	brick masonry
5	energy dissipation	steel	Conventional	bare frame
6	energy dissipation	SMA	Properly devised	bare frame
7	base isolation	SMA	Properly devised	bare frame
8	base isolation	SMA	Properly devised	brick masonry

Table 2: Steel and SMA bracings parameters - K = stiffness, F_y = activation force

	steel	device	SMA	“rd”	SMA	“r”	SMA	“d”
	F_y (kN)	K (kN/mm)	F_y (kN)	K (kN/mm)	F_y (kN)	K (kN/mm)	F_y (kN)	K (kN/mm)
1st storey	19	76.5	38	61	32	37	9.5	15
2nd storey	11	48	24.5	65	20	40	7.5	16
3rd storey	4.4	34	9.5	28	7.5	21	5.5	7

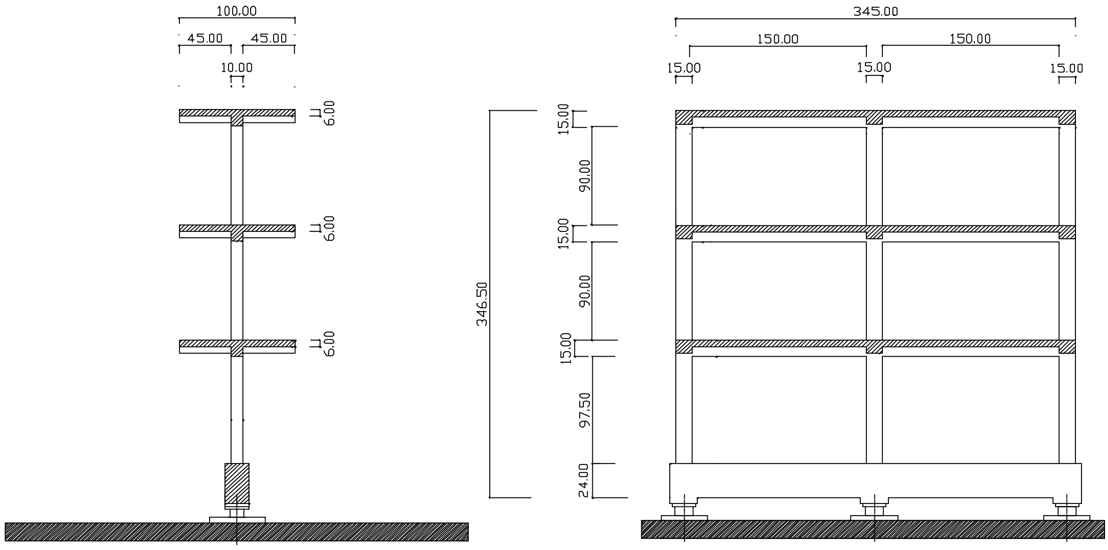


Figure 1: Layout of the r/c structural models

As concerns energy dissipation, the constitutive parameters of the steel braces were designed using the numerical procedure suggested in [Braga et al. 1991]to minimise a multiobjective function that comprises the inter-storey drifts, the ductility demands and the residual displacements. As concerns the SMA devices, a number of different devices were considered either for the base isolation or the energy dissipation case in order to get a deeper understanding into their actual capabilities and to decide upon the best exploitation of the SMA properties and the kernel geometry. The differentiation was made possible through an appropriate conception of these devices whose response is made up by the joint contribution of different SMA kernels each of which specialised to a particular action [Dolce et al. 1999]. Three different SMA devices were considered: one complete device (“rd” = re-centering + dissipating) and two partial devices (“d” = only dissipating devices or “r” = only re-centering devices). The design parameters of the steel and SMA braces are given in table 2 according to an idealised elastic-plastic behaviour; it is worth noticing that they are equal, within practical limits, to the actual experimental response of the devices [Cardone et al. 1999].

TESTS PERFORMED

Each structural model was subjected to a series of simulated earthquakes using the shaking table facility at the Technical University of Athens (NTUA). The generic series is composed by eight tests that share the same base motion but have increasing seismic intensities up to the operation table limits or the model collapse. The seismic motion was simulated using a pseudo-stationary spectrum compatible acceleration profile that that was selected according to the following criteria: (i) best spectrum matching for results homogeneity and (ii) minimum residual velocity and displacement to avoid the transfer of unwanted impulses into the structural models because of sudden stops of the table. The reference spectrum was the elastic normalised spectrum provided by the EC8 code for soil type B [CEN 1994] and the duration of the scaled accelerogram was set to 11 sec. with a stationary portion of 7 sec. The sequence of seismic intensities was: a/g = 0.08 - 0.16 - 0.24 - 0.36 - 0.48 - 0.60 - 0.78 - 1.00. The in-plane structural response was monitored using one accelerometer and one displacement transducer per storey including the base beam and the table, whereas the response of the devices was characterised in terms of the force – displacement behaviour. Additional accelerometers were used to check rocking effects and to detect possible out-of-plane responses of the structural models. It turned out that both these two effects were small and they were hence neglected. A separate study was necessary to make effective the comparisons among the measured responses; in fact, the dynamic interaction between the table and the supported model caused the actual accelerogram provided by the table to differ from the ideal input accelerogram both in frequency content and peak acceleration. The said changes were mainly related to the very different stiffnesses shown by the structural models since they strongly depend on the infill presence or on the protection devices embodied in the model. It was found an average de-amplification of the peak values of about 12% with respect to the nominal peak table accelerations and some energy suction in the low period range that do not significantly altered the results. Finally and before entering the discussion of the results it is worth mentioning some comments helpful in their interpretation. The complete "rd" SMA devices are constituted by 24 ϕ 1 re-centering wires and 16 ϕ 1 dissipating wires, whereas the partial only recentering "r" or only dissipating "d" SMA devices are obtained by the former by simply eliminating one of the two types of wires [Dolce et al. 1999] so that the "r" or "d" SMA devices are generally endowed with lower activation forces and stiffnesses than the complete devices, table 2. The structural models 6 to 8 were tested with all the three above SMA devices in sequence according to the following programme: the "rd" devices were installed first ant the models tested up to 0.36g (reference design peak acceleration in view of the table de-aplification), then the "rd" devices were removed and the "r" or "d" devices were installed in turn and the tests repeated at 0.36g, finally the "rd" devices were re-installed and the complete programme carried out for increasing seismic intensity, re-starting from 0.36g, up to the maximum seismic intensity. This was possible due to the excellent behaviour of the SMA devices in protecting the structural models, however in order to be consistent with the tests programme, the "rd" SMA devices will be termed "rd,a" or "rd,b" depending on whether reference is made to the results of the first or second installation.

RESULTS AND COMPARATIVE ANALYSIS

The main target of any protection systems is the reduction of the structural vibrations so that, consequently, possible damages are prevented or at least limited. It is therefore a damage measure the best indicator to be used when the performances of different devices have to be compared. Such a measure is effective for safety purposes, but should be integrated by other measures devoted to quantify the service life and the maintenance conditions of the structure and the embodied devices. In mechanical terms, the service life can be measured by the number of earthquakes the device can sustain; whereas the maintenance conditions can be measured by the capability of the device to recover the initial or pre-earthquake configuration. In the comparative evaluation both the above damage and performance indicators were considered. The response (de)ampification, given by the ratio between the storey and the base acceleration, and the inter-storey drift were used as damage indicators, as they are recorded by the monitoring system without any further computation. Forces and displacements in the devices were used as performance indicators to provide information on the stress level and the high cycle fatigue resistance required to the materials. Residual displacements were related to the post-earthquake interventions necessary for maintenance purposes. In the following a general overview of the shaking table test results is given where the experimental results are complemented by the corresponding numerical results obtained by as may numerical simulations. The finite element models used were validated against the above tests and a further separate series of controlled tests on the functional kernels and on the complete devices [Valente et al. 1999].

Energy Dissipation Devices

The results in terms of inter-storey displacements are given in figure 2 and 3. Figure 2 compares the experimental and numerical results for the "rd,b" case, where, for conciseness, the inter-storey displacements have been limited to the first storey that is also the most representative since, for all the considered models, the maximum drifts turn out to be confined between the base beam and the first floor. Figure 2a shows that the rate of drift increase along with the seismic intensity is almost uniform stating for an as much regular increase rate of work of the SMA braces the effectively protect the structure. The same regular trend is observed for the numerical solution that is however slighlty more flexible and hence overestimates the interstorey drifts.

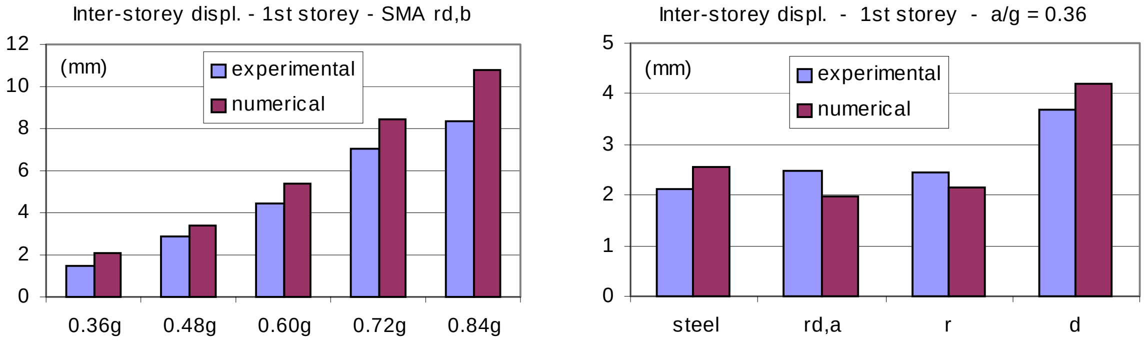
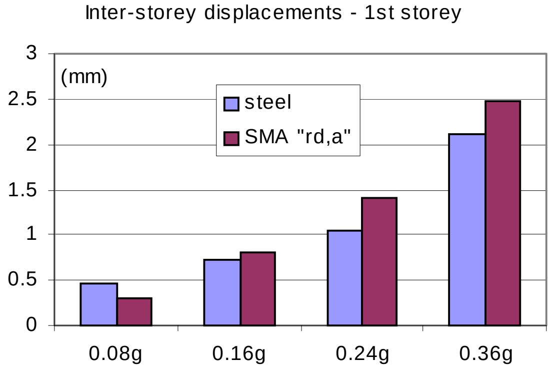


Figure 2: SMA bracings – experimental vs. numerical results



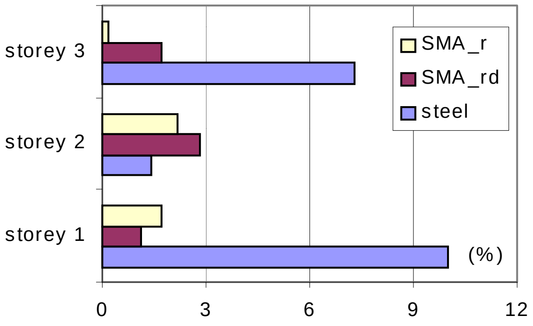


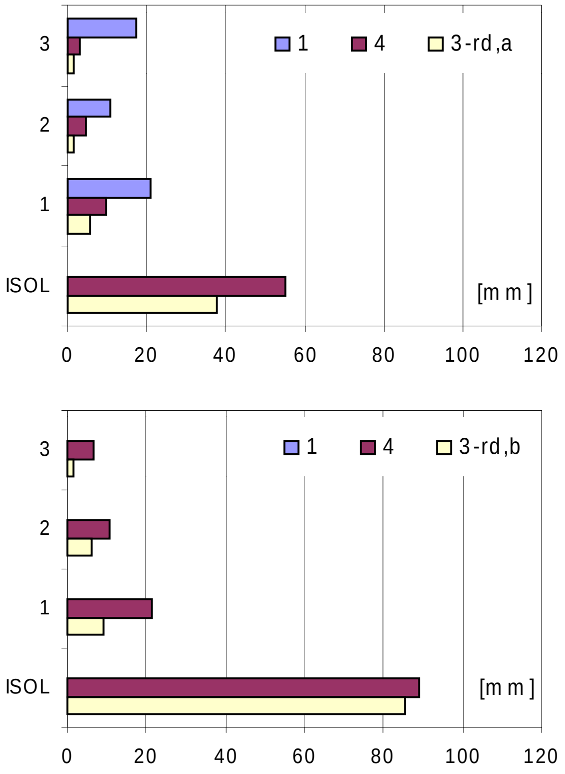
Figure 3: Steel vs. SMA bracings

Figure 4: Inter-storey residual displ. (a = 0.36g)

This higher flexibility is no longer observable in figure 2b where different solutions are compared for a given seismic intensity equal to 0.36g. At least for this case the steel braces and the SMA with re-centering capability seems equally effective. Only the dissipating SMA device, "d" label, shows large drifts, however this can be attributed to the lower activation force and stiffness of this particular solution, see table 2. Figure 3 shows the comparison between the steel and the SMA devices, case "rd,a", for the low seismic intensities. The comparison would lead to conclude that steel braces are preferable because of reduced drifts as compared to SMA braces, however the differences are very small from a practical point of view and are completely overcome by the superior performances of the SMA braces as concerns the re-centering capabilities. This aspect is shown in figure 4 where the residual inter-storey displacements, expressed in percent with respect to the peak inter-storey displacement, are shown. The bar graph shows non negligible residual straining in the steel devices and hence in the frame members, the same do not happen for the SMA braces that are capable to virtually annihilating residual stresses and are hence preferable when also functionality is claimed.

Base Isolation Devices

In this case the comparisons are richer due to the presence of infilled frames besides the bare ones. The inter-storey displacements recorded for the nominal 0.36g and 0.6g earthquake-like shaking are plotted as bar graphs in figures 5 and 6 for the bare (models 1, 3 and 4) and infilled frames (models 2, 5 and 6) respectively. Recall that 0.36g is taken as reference since it approximately corresponds to the design level, while 0.60g corresponds to the collapse level of model 1 (that is therefore not reported in the relevant figure); note further the lack of horizontal bars for the fixed base models 1 and 2 in correspondence to the "ISOL" label that identifies the relative table-to-frame displacement, i.e. the displacement that the isolators should absorb. The comparison between figures 5 and 6 shows the beneficial effect of the infilled masonry, in fact the damage is kept within acceptable limits (approx. 1%) even for 0.6g when the bare frame is collapsed. The effectiveness of the isolation, either for rubber or SMA isolators, is then more evident in the case of bare frames; these latter, in fact, experienced peak acceleration higher than 0.6g without apparent damage. Note that the SMA isolator is capable to reduce by a factor of two the interstorey displacements and this happens also in the case of the infilled frames. As concerns the devices, the analysis of the figures points out the reduced displacements demand for the SMA isolators as compared to the rubber isolators, this aspect is of some importance when considering functional aspects concerning the building equipment and provisions for the device housing to accommodate movements.



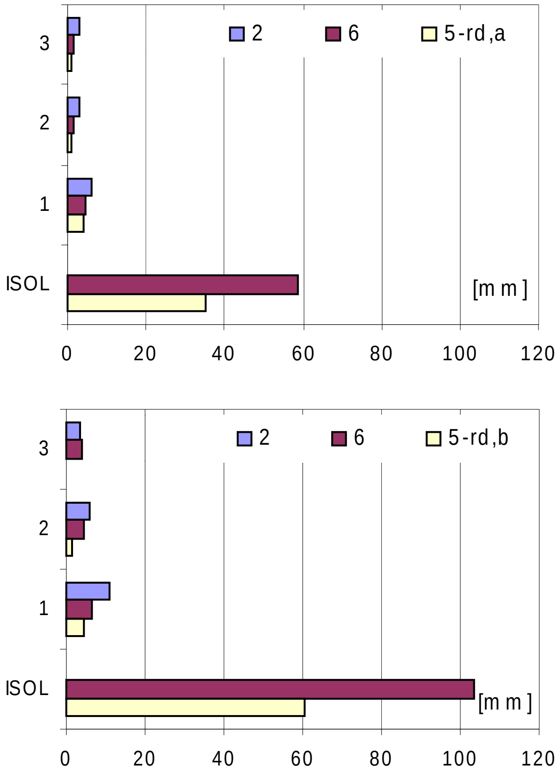


Figure 5: Inter-storey displ. - Bare frames (a) 0.36g, (b) 0.60g

Figure 6: Inter-storey displ. - Infilled frames (a) 0.36g, (b) 0.60g

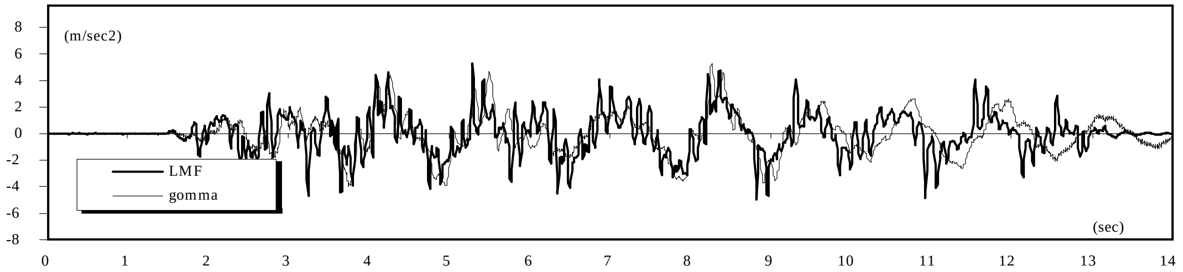


Figure 7: Base isolated frames – 3rd storey acceleration time histories (a = 0.6g)

Moreover, to better appreciate the comparisons, it is also important to note that the shear strain in the rubber isolator approaches the design limit $\gamma = 150\%$ at 0.36g and exceeds 250% at 0.6g. This progressive rubber straining is responsible for increasing hardening in the device and reduces the effectiveness of the isolation system. This feature explains the non negligible inter-storey displacement at 0.36g and the strong increase at 0.6g. Of course, this problem is not shown by the SMA isolator that can be designed according to "any" required displacement by simply adjusting the wires length and hence allows for a better control of the forces transmitted to the super-structure. To better appreciate this point, the force – displacement diagrams obtained by the numerical models are given in figure 8a,b for the case a/g = 0.6, where the stiffness increase is apparent for the rubber isolator. The numerical data were preferred because of their stability; however the excellent numerical fitting against the experimental data is shown in figure 8c for the more complex case of the SMA isolator. Figure 8c refers to a controlled test on a single device and has been chosen to point out a basic difference between the behaviour of the pure SMA isolator and the complete installed device, see figure 8a and 8c. The different behaviour is due to the presence of a supplemental bearing device necessary, in field applications, to transmit the vertical loads; the bearing contributes to some energy dissipation through the friction developed between its sliding plates and an estimate of its contribution is given by the sharp force decrease at any load reversal. Finally, figure 7 shows the comparison between the 3rd storey acceleration time histories of the rubber and SMA isolators, case "rd,b", for the intensity 0.6g. When considering the peak acceleration it is noted that the amplification factor is close to one in both cases; on the other hand, when considering the acceleration profile the average oscillations are similar in the two cases, but it happens to be more regular for the rubber isolator than for the SMA isolator where a sequence of pulses superposed to the fundamental vibration mode is observed. This is due to the operating conditions of the SMA device that causes impacts between two counteracting movable elements at each load reversal. This feature can certainly be ameliorated in revised versions of the SMA devices. A final important point concerns the free vibrations at the end of the earthquake shaking that happens approx. at 13 sec. in figure 7. The SMA isolator correctly stops the vibrations, whereas the rubber isolator shows persistent vibrations of large amplitude.

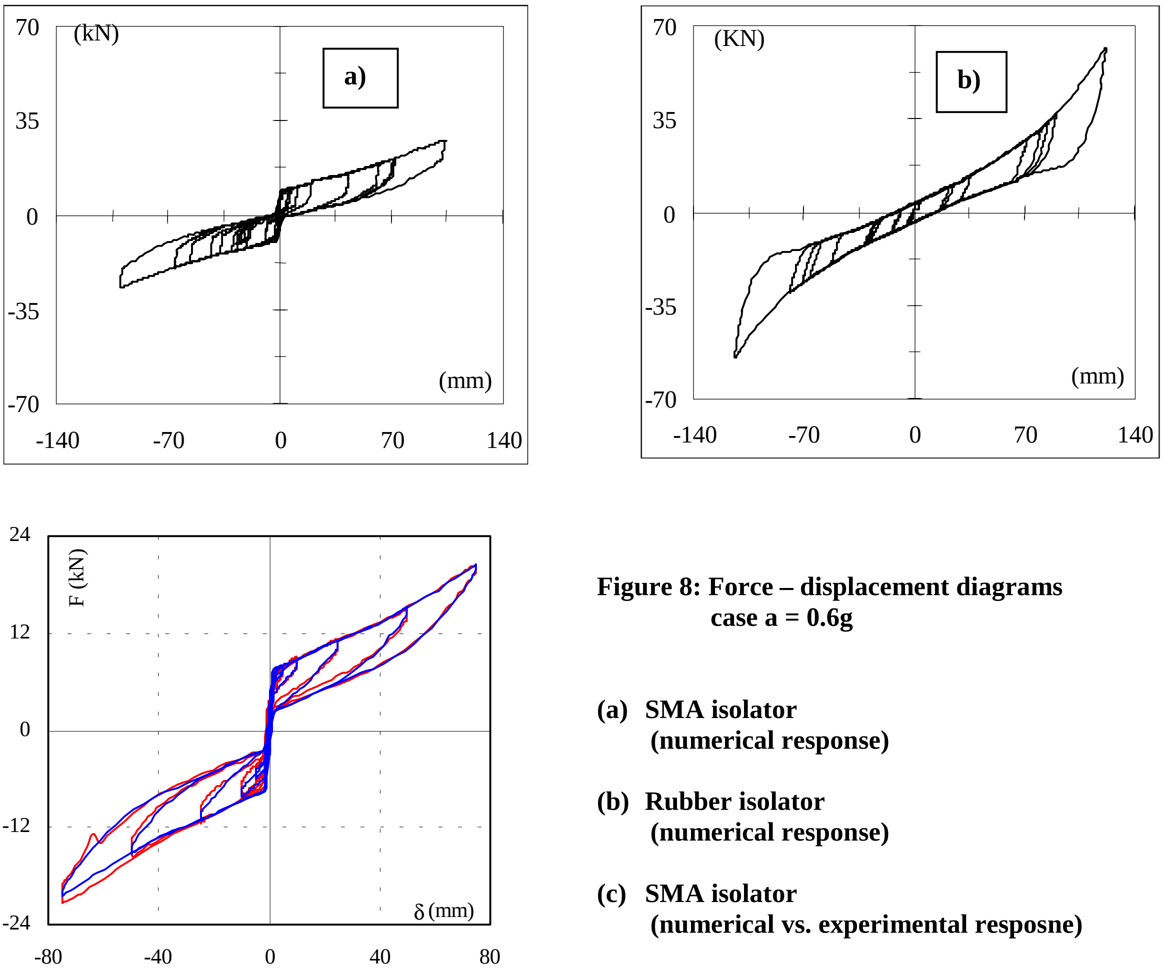


Figure 8: Force – displacement diagrams
case a = 0.6g

(a) SMA isolator
(numerical response)

(b) Rubber isolator
(numerical response)

(c) SMA isolator
(numerical vs. experimental resposne)

CONCLUSIONS

The paper reports the results of a large experimental investigation aimed at furnishing a comparative validation of innovative SMA-based devices against conventional anti-seismic devices. To this end, eight different reduced scale r/c plane frames tested using the shaking table testing facility at NTUA of Athens. The r/c frames, both bare and infilled, included: non protected frames, yet designed according to seismic codes, conventionally protected frames and frames protected with innovative SMA devices. Both the base isolation and the energy dissipation strategies were addressed and the conventional devices employed were respectively rubber isolators and steel braces. The innovative devices were tested considering different alternatives: re-centering + dissipating devices, only dissipating devices, only re-centering devices. This was done to decide upon the best exploitation of the SMA material properties and geometry and to gain a deeper understanding into their actual behaviour. The SMA kernels of the devices were properly designed to act within small adjustments either as isolators or braces. The structural models either non protected or equipped with conventional or innovative devices were tested for increasing earthquake like excitations in the range 0.16g to 1.00g or until model failure occurred. The experimental outcomes were used to evaluate the devices performances in terms of safety and functionality. Only a small selection of the total amount of data collected has been reported in the paper with the primary target to give an overview of the main results. The comparative evaluations demonstrated the general superior performances of the SMA devices with respect to the conventional devices and this appears particularly true in the case of base isolation where consistent increase of safety can be obtained. The same cannot be stated for the dissipating braces where the SMA and steel devices provide for the same safety degree, however SMA devices remains preferable because of the re-centering capability possessed. Finally it deserves to be recalled that the conventional devices were optimised to their functions, whereas the SMA devices were not because of the lacking of specific design criteria. As a consequence, the performances of the conventional devices appear hardly to improve, whereas the SMA based systems are susceptible to improve significantly their already excellent qualities.

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