FULL SCALE TESTS OF A RC FRAME BUILDING WITH METAL SHEAR PANELS

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ABSTRACT :

In the current paper, an experimental investigation related to the use of steel and pure aluminium shear panels for seismic upgrading of existing reinforced concrete frames is presented. Based on a preliminary experimental test of the bare RC structure, the metal shear panels to be adopted have been proportioned. Such devices have been allocated within an external steel frame, whose members have been properly designed in order to sustain elastically the applied tension field actions. Then, full-scale experimental cyclic tests have been carried out on the upgraded structure, showing the significant improvement of the original building performance in terms of strength, stiffness and deformation capacity. Finally, a comparison between the adopted solutions, in terms of dissipated energy, equivalent viscous damping ratio and secant stiffness, is presented, showing the major contribution provided by the applied metsal shear panels.

KEYWORDS: Seismic upgrading, RC buildings, experimental cyclic tests, tension field mechanism, plate buckling, metal shear panels.

1. GENERAL

The upgrading of RC buildings represents a topic of significant interest in the field of seismic engineering. In the past years, Metal Shear Panels (MSPs) have been effectively used as lateral load resisting system into new and existing buildings. Nevertheless, while such devices have been largely applied for improving existing steel structures, only limited attention has been devoted to the applications within RC frames. In the latter field, the use of slender shear panels can result particularly effective, due to the combination of easy fabrication, simplicity of installation and valuable structural contribution that they are able to provide to the base structure. Such features allows the MSPs to compete with the traditional RC shear wall systems made.

On the basis of the above premises, in the current paper the proposed retrofitting strategy is investigated. In particular, two full-scale experimental cyclic tests on an existing RC structure endowed separately with steel and pure aluminium shear plates, whose design has been done according to simplified formulations, have been carried out. The obtained results have shown the important contribution provided by both typologies of MSPs for seismic retrofitting of existing RC buildings. The main outcomes of the study allow to define steel shear panels as an effective strengthening and stiffening devices, while aluminium ones can be also considered as a dissipative system in the retrofitting field.

2. THE EXPERIMENTAL ACTIVITY

2.1. The bare structure

The experimental activity is framed within the ILVA-IDEM research project (Mazzolani, 2006). A two-story RC building designed to sustain vertical loads only was first deprived of internal and cladding walls and then cut at floor levels in order to augment the number of structure to be upgraded with metallic devices.

The sub-structure selected for the insertion of MSPs is illustrated in Figure 1a with dashed lines. It is worth noticing that this sub-structure equipped with braces made of shape memory alloys had been already tested by applying transversal lateral loads. Such a test produced damages at columns ends, where cracking of the concrete and buckling of the longitudinal bars were noticeable. Then, the module was tested under cyclic lateral loads, which were applied by means of two hydraulic jacks having a capacity of 300 kN (Figure 1b), allowing the determination of both the strength and the initial stiffness. To this purpose, two steel X-bracings at the first level of the RC frame along the transversal direction were installed in order to avoid torsional structure movements during test (Figure 1c). The preceding sub-structure with the staircase acted as a reaction system for carrying out the experimental test. For this reason, it was properly strengthened by means of two steel V-bracings placed on its longitudinal sides (Figure 1a).

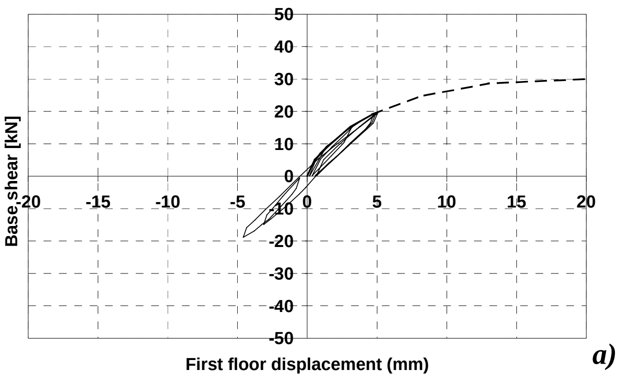

a)


b)

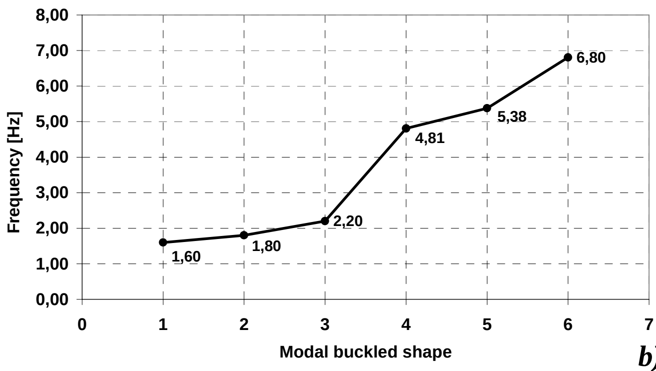

c)

Figure 1 The analyzed structure (a), the hydraulic jacks (b) and the X-bracings system (c)

The envelope curve of the experimental cyclic test has allowed to detect the maximum strength (30 kN) and the initial stiffness (4010 kNm^{-1}) offered by the bare RC structure (Figure 2a).
In a second phase, experimental dynamic analyses on the module were performed (Valente et al., 2006), in order to set-up a numerical model able to reproduce its behaviour under seismic actions. Direct impulses were been applied by means of a hammer, which was impacted at each beam-to-column joint of the two floors in the two plane directions. The dynamic response of the structure was recorded by using a modular acquisition system composed by a set of four independent four channel acquisition units. Each structural module was instrumented with both two acquisition units and an independent unit able to measure the excitation force. By the hammering tests, the modal parameters depicted in Figure 2b were drawn out.



a)



b)

Figure 2 The bare RC structure: response to lateral loads (a) and modal frequencies (b)

The knowledge of the structural dynamic properties allowed the calibration of a finite element model (Figure 3a), which has been developed by using the SAP2000 ver. 8.23 non linear numerical program (Computer and Structures, Inc., 2003) considering all members schematized as beam elements. The material properties and the loads applied on the structure are reported in (Formisano, 2006). The performed numerical analyses have provided the modal frequencies depicted in Figure 3b, where the comparison with the experimental ones is also shown.

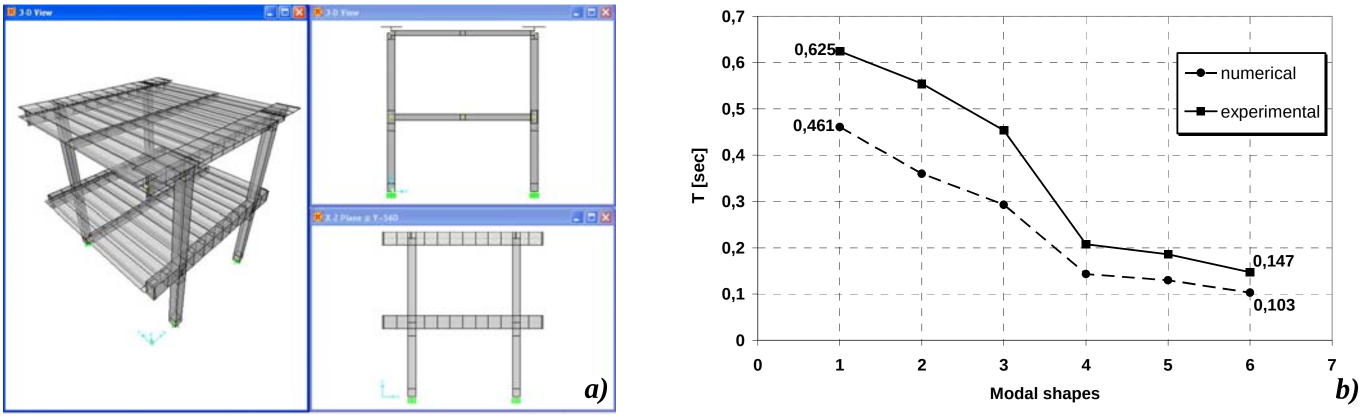


Figure 3 FEM model of the bare structure (a) and comparison in terms of modal frequencies (b)

As it can be observed from the above figure, the numerical curve is different from the experimental one, with discrepancies ranging from 26% (1st mode) to 30% (6th mode). Such a difference is due to the structural members degradation (Figures 4a and b), which reduces the module stiffness, modifying its dynamic response. As a consequence, in order to account for the effect of the cracking, the numerical model has been set-up according to a bending and shear stiffness of beams and columns suitably reduced. In particular, appropriate stiffness reduction factors have been proposed aiming at fitting the experimental results. Such factors are very similar to the ones introduced by the new technical Italian code (Ministerial Decree 14/01, 2008), with the only exception to consider a reduced bending stiffness for columns equal to 0.4EI instead of 0.5EI. The new achieved numerical results in terms of vibration periods are plotted in Figure 4c, where a very good correspondence with the experimental ones can be noticed.

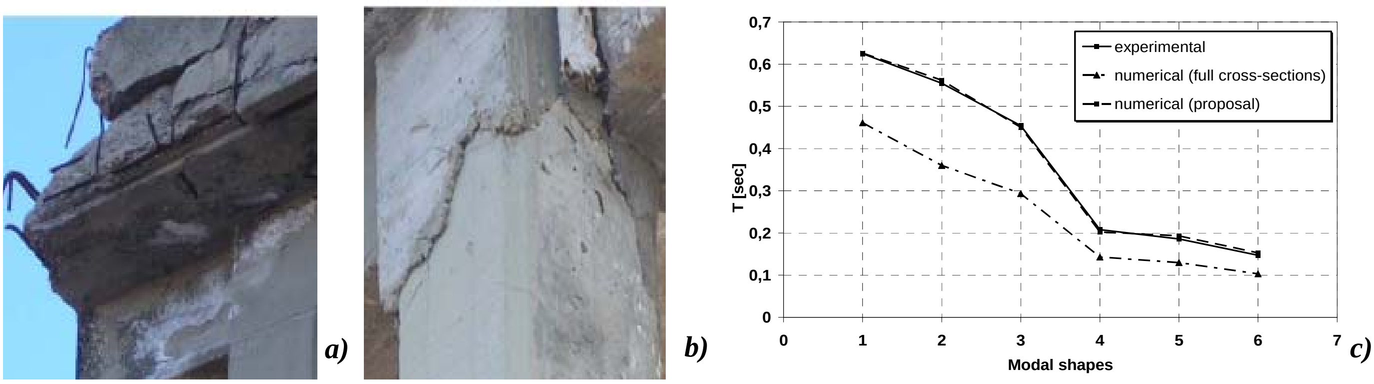


Figure 4 Beam (a) and column (b) degradation and experimental - numerical comparison in terms of vibration periods (c)

2.2. The retrofitted structure

2.2.1 Selection of shear panels

Based on the performance offered by the bare RC structure, the contribution required to metal shear panels in terms of both strength (V_p) and stiffness (K_p) for seismic retrofitting purpose has been determined on the basis of the ATC 40 design procedure (1996), which is framed within the performance based design methodology. Indications about the applied methodology are largely illustrated in (Mistakidis et al., 2007).

Two metallic materials have been selected for shear panels, namely the DX56D steel and the EN-AW 1050A aluminium alloy, the former being defined in the UNI EN 10142 Italian code (1992) and the latter currently known with the name of pure aluminium. The material mechanical properties of the used steel have been preventively estimated by means of a tensile test, providing yield and ultimate stress values equal to 300 and 340 MPa, respectively, and ultimate strain larger than 30%. On the other hand, the pure aluminium has conventional yielding stress and ultimate stress of 21.3 and 80 MPa, respectively, the latter corresponding to an ultimate strain of 45%.

Based on the analytic simplified formulations given by Sabouri-Ghomi et al. (2003) and Berman and Bruneau (2003), the panel design has been carried out by using the the following relationships:

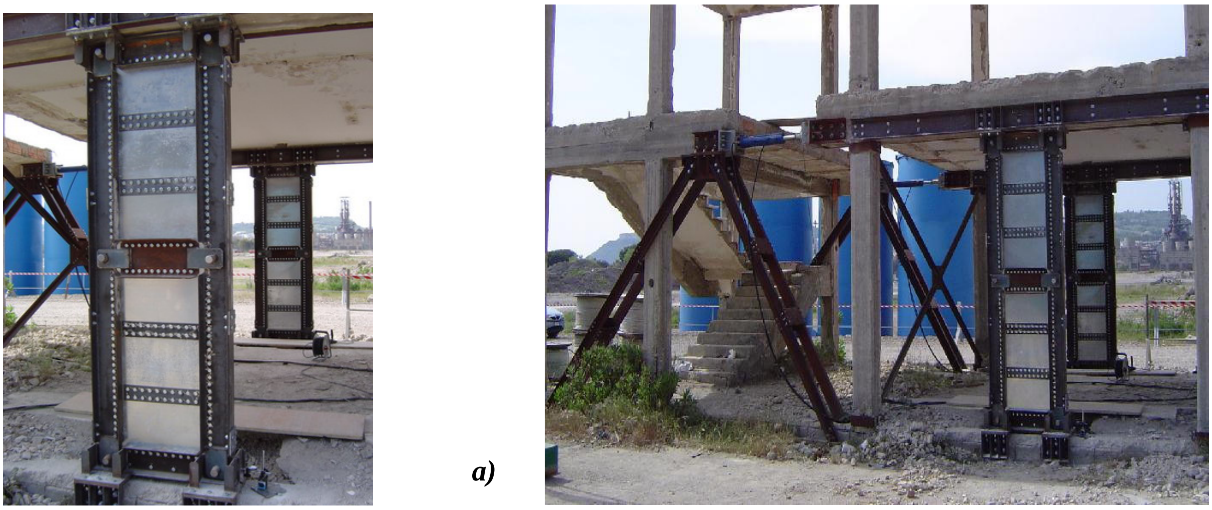
$$V_p = \frac{1}{2} f_y t\, b \sin 2\alpha \tag{2.1}$$

$$K_p = \frac{E}{4} \frac{b \cdot t}{d} \tag{2.2}$$

where *b*, *d*, *t* are the panel width, depth and thickness, respectively; *E* and f_y are the Young modulus and the yielding (conventional elastic limit) stress of the used metallic material, V_p = 192 kN, K_p = 11500 kNm^{-1} and α is the inclination angle of the tension field.

Considering that the whole depth (*d*) of the shear wall is equal to the inter-storey height of the analysed RC frame minus the steel beam depth (400 mm), therefore of 2400 mm, and that 1.15 and 5 mm thick plates have been assumed when steel and aluminium have been considered, respectively, the system width (*b*) has been calculated according to eqs. (1) and (2).

From the performed design, it resulted that the panel dimensions are governed by strength rather than stiffness, leading to a width of 600 mm. Since the shape ratio *b/d* of panels was of 0.25, that is minor than the lower limit (0.8) suggested by the Canadian code (CSA, 2001) aiming at having the complete panel plasticization, intermediate stiffeners under form of 500x100x4 mm plates have been applied. As a consequence the whole shear wall has been subdivided into six sub-parts bolted connected to an external steel frame composed by UPN 180 profiles with an intermediate UPN 240 beam. The shear walls have been installed within both longitudinal sides of the first story of the structure. This required the reinforcing of both the first level beams and the foundation beams by means of UPN 220 members and class 8.8 M16 bolts. The final view of the intervention is illustrated in Figures 5a and b, where steel and aluminium panels are visible, respectively.



a) ***b)***

Figure 5 Steel (a) and aluminium (b) shear walls inserted into the RC frame structure

2.2.2 Test results

In the final analysis phase, the effectiveness of the proposed upgrading intervention has been proved by the execution of two experimental cyclic tests, which have been carried out according to the loading history depicted in Figure 6. The lateral load was applied to the reinforced structure by using hydraulic jacks, which were able to apply tensile and compression actions equal to 200 and 300 kN, respectively. In the experimental tests, the load was increased of 20 kN for each cycle up to the last one, where the load increment was equal to 60 kN. All loading cycles have been symmetric up to the attainment of 200 kN; hence only the compression load has been increased up to 300 kN.

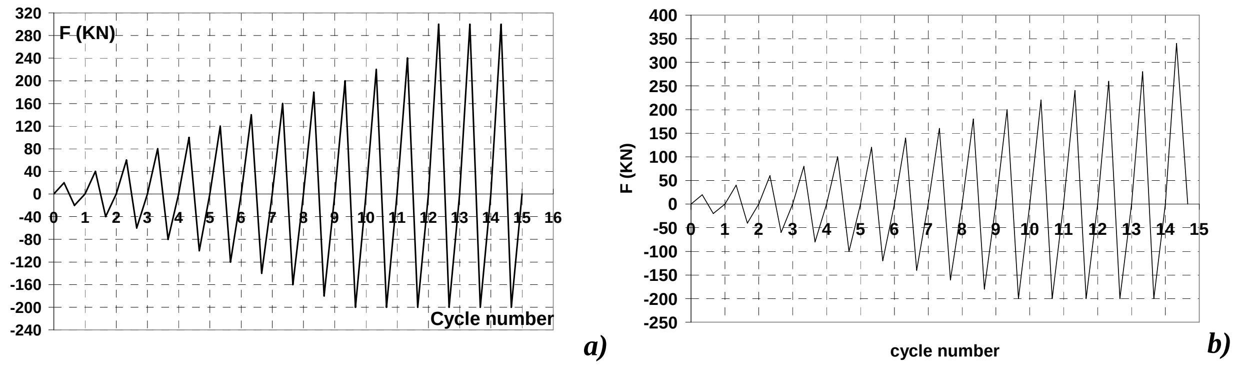


Figure 6 Loading protocol used in the test for steel (a) and aluminium (b) shear panels

In the experimental test several measurement devices (continuous transducers) have been employed in order to acquire the following absolute displacements (Figure 7):
- first level floor on both sides of the structure (P3);
- reinforcing steel beam (P4);
- shear wall stiffeners (P5- P7-P8) and intermediate
- UPN 240 beam (P6);
- foundation of shear panel (P9).

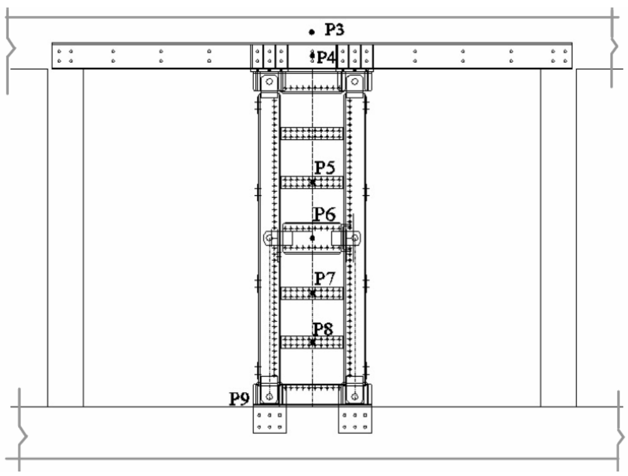
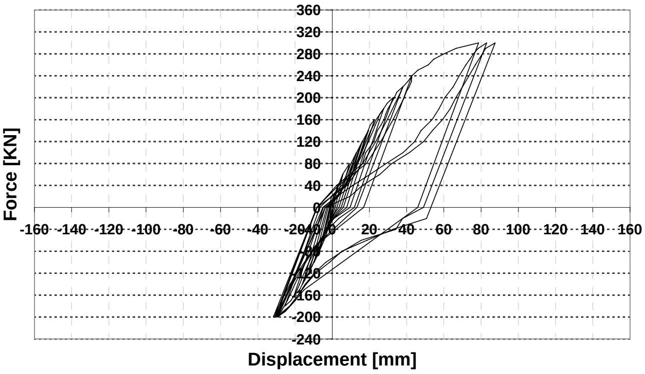
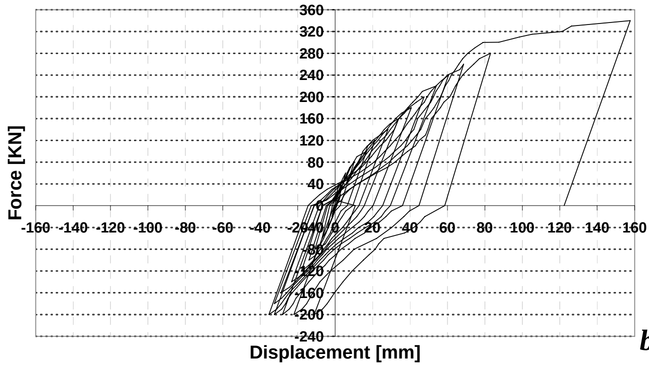


Figure 7 Measurement transducers used in the experimental tests

The main result of the experimental tests performed on steel devices in terms of applied force versus first level displacement of the structure is shown in Figure 8a, whereas the application made on aluminium plates has shown the curve depicted in Figure 8b. More information on the experimental activity are available in Formisano et al. (2007).
From the test results achieved on steel panels it is noticed that the retrofitted structure attains a maximum load of 300 kN for a displacement amplitude of 85 mm, which corresponds to an inter-storey drift equal to about 3.5%. Besides, the hysteretic cycles of the loaded structure are strongly affected by pinching phenomena, which do not allow to achieve a fully dissipative system behaviour. Therefore, according to the initial forecasts of the performed study, the used steel panels can be considered as strengthening and stiffening devices only for retrofitting operations.
In the experimental test the retrofitted structure attains a maximum load of 340 kN for a displacement amplitude of 158 mm, which corresponds to an inter-storey drift equal to about 6.5%. Besides, the hysteretic cycles of the compound RC frame - aluminium panels structure appear to be significantly more dissipative than the ones achieved in the previous experimental test, they allowing to exploit the plastic features of the used material.



a)



b)

Figure 8 Lateral response of the RC structure retrofitted with steel (a) and pure aluminium (b) shear panels

A global view of the deformed shape of steel and aluminium panel devices during the significant test phases and at the end of the loading process is shown in Figures 9 a and b, respectively. In both cases the initial presence of buckling waves in the terminal panel fields determines a reduction of the system stiffness between the loading phases and the unloading ones. This occurs in a less pronounced way when aluminium panels are used due to their *b/t* plate ratio higher than the steel one. Nevertheless, when significant displacements are attained, permanent waves characterising the full development of the tension field mechanism were apparent into each sub-panel of each used metallic material.

a)

b)

Figure 8 Development of the tension field mechanism into steel (a) and pure aluminium (b) shear panels

3. COMPARISON OF THE OBTAINED EXPERIMENTAL RESULTS

The obtained experimental results have been compared in terms of both monotonic and cyclic behaviour. With reference to the first aspect, the comparison is performed by considering the envelope experimental curves (Figure 10a). From these curves it can be observed that the response of the retrofitted structures is significantly improved, showing an increase of both initial stiffness (2.5 and 2 times with steel and aluminium panels, respectively) and ultimate strength (10 and 11.5 times with steel and aluminium panels, respectively). Also the deformation capacity of the structure appears to be very large, without the involvement of any brittle collapse mode up to a deformation amplitude corresponding to an inter-storey drift greater than 3.5% and 6.5% when steel and aluminium panels have been used, respectively.
On the other hand, with reference to the cyclic behaviour of the strengthened structures, a first effective comparison between results can be performed by superposing the hysteretic loops achieved from experimental tests (Figure 10b).
From the comparison it is apparent that hysteretic cycles obtained using aluminium panels are decidedly larger, evidencing a better dissipative behaviour with respect to the steel ones.
Such a condition occurs for two main reasons: 1) for the same applied load the displacement of the structure strengthened with aluminium panels is greater in comparison to the one of the structure endowed with steel plates; 2) the slenderness of shear panels is smaller in case of aluminium.
In addition, the experimental data have been processed in terms of secant shear stiffness (K_{sec}) and equivalent viscous damping ratio (ν_{eq}) and compared. The comparison has been performed only with reference to the hysteresis cycles

characterized by the same force levels detected in both tests (see Figure 1).

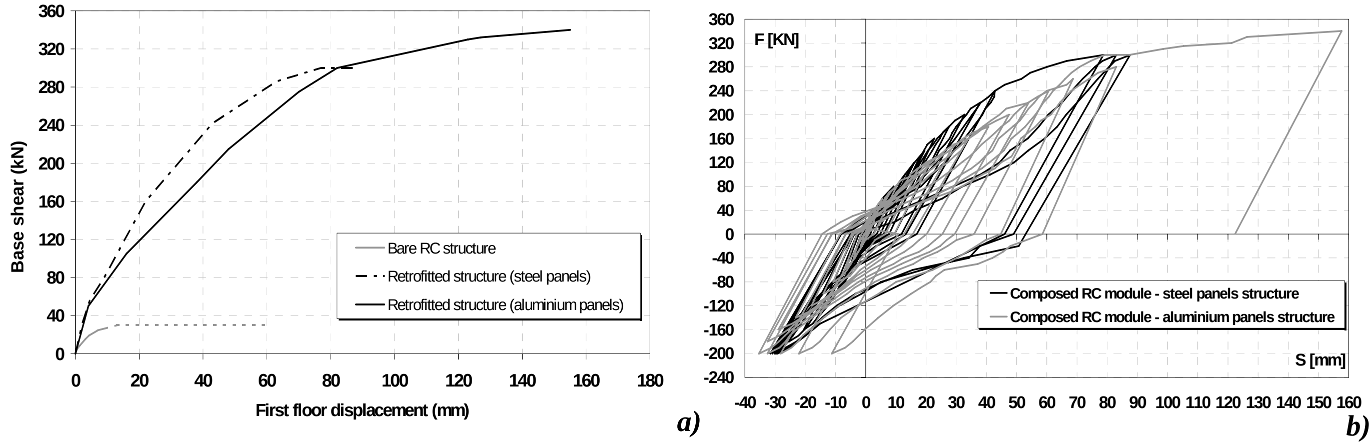


Figure 10 Comparison of results in terms of envelope curves (a) and hysteresis cycles (b)

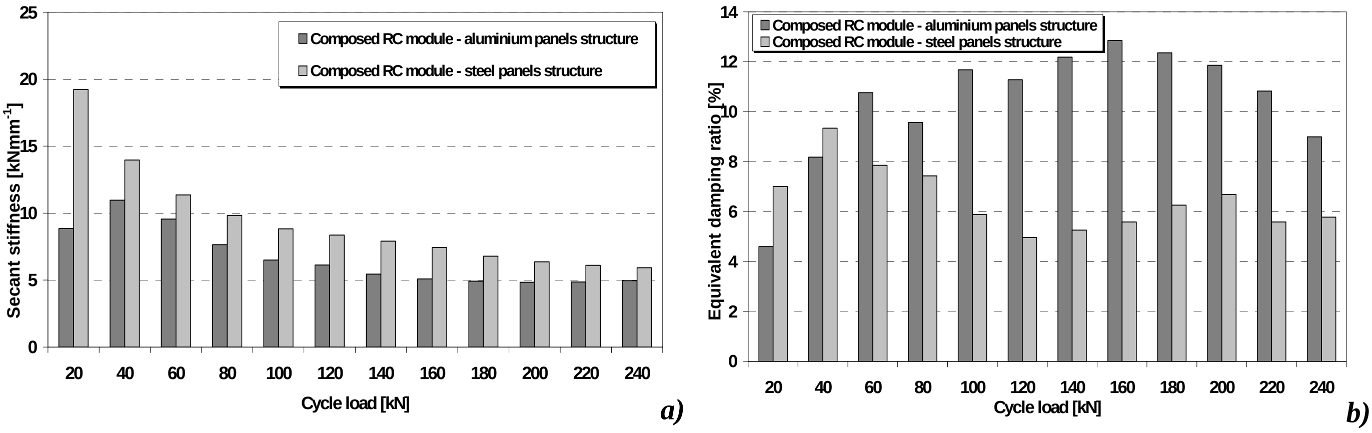


Figure 11 Comparison of results in terms of secant stiffness (a) and equivalent viscous damping ratio (b)

By observing the trend assumed by K_{sec} during tests it is noticed that in the initial test phase, up to a total force of 40 kN, the global stiffness of the RC module retrofitted with steel panels increases due to the limited activation of the tension field mechanism into plate fields. Later on, it rapidly decreases as the applied deformation amplitude increases. On the other hand, the trend assumed by this parameter for the RC module equipped with aluminium is well represented by a non linear decreasing curve with values always higher than the one retrofitted with steel plates. For this reason pure aluminium shear panels are effective in stiffening the bare RC structure. Nevertheless, in the current case, the reduction of shear stiffness K_{sec} is more remarkable than the one exhibited by steel shear panels, showing the better attitude of the latter devices to be applied as stiffening rather than dissipative devices for seismic retrofitting interventions.

With reference to the damping properties it is noticed that the retrofitted structures have a different average equivalent viscous damping ratio, which is equal to 6.7% and 10% with steel and pure aluminium, respectively. When steel panels are adopted, the maximum damping ratio values are attained both in the initial and final phases of the loading process and presents a strong reduction for intermediate amplitude cycles, whereas with the use of aluminium devices the peak value (12.85 %) occurred in the middle test phase, when a displacement of 57 mm is applied, presenting a reduction of values for loads both greater and lower than 160 kN. In particular, such a reduction is more significant for displacements smaller than 57 mm. This is due to the fact that in the final phase of the loading process the energy dissipation capacity of the structure retrofitted with aluminium panels increases. In conclusion, on the basis of the above considerations, it is possible to declare that pure aluminium shear panels result to have damping properties more remarkable than steel panels ones, which are preferably used as stiffening devices of existing RC structures, due to the higher ultimate strain of the base material.

4. CONCLUDING REMARKS

In the current paper the use of metal shear panels as seismic retrofitting systems of existing RC structure has been analysed. The preliminary experimental tests on the bare RC frame allowed to detect both the strength and stiffness of the base structure for the application of the design methodology and the calibration of a finite element model. In particular, to correctly interpret the structural response of the system, a modification of the reductive factor considered by the new Italian code for taking into account the reduced stiffness of degraded columns has been proposed. Then, the geometry of metal shear panels has been selected according to both existing simplified relationships and the provisions of the Canadian code. On the basis of the panel structural configurations obtained from this design phase, two experimental tests have been carried out on the RC module retrofitted with either steel shear walls or pure aluminium shear panels. The experimental results confirmed the effectiveness of the used retrofitting systems due to the significant improvement of the original structure behaviour in terms of strength (10 and 11.5 times with steel and aluminium panels, respectively), stiffness (2.5 and 2 times with steel and aluminium panels, respectively) and deformation capacity (3.5% and 6.5% inter-storey drift with steel and aluminium panels, respectively). Finally, it should be observed that the dissipation capacity of the structure retrofitted with aluminium shear panels is more satisfactory than the one endowed with steel plates, mainly due to the excellent features of the adopted aluminium alloy. For this reason, steel shear panels should be considered as strengthening and stiffening devices, whereas the pure aluminium shear panels are also able to improve the energy dissipation capability of the structure. In the whole, the proposed systems appear very effective for the seismic upgrading of existing RC frames characterised by significant structural deficiencies.

ACKNOWLEDGEMENTS

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