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EXPERIMENTAL OBSERVATIONS FROM SHAKING-TABLE TESTS ON SELECTIVE TECHNIQUES FOR REPAIR AND STRENGTHENING OF RC WALLS

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SUMMARY

It is most important that developments in new design concepts are assimilated in assessment and strengthening philosophy in order to avoid a conceptual gap between existing and new construction. Therefore, structural intervention methods must comply with capacity-design requirements, used in design of new structures, for tighter control over individual design response parameters, such as stiffness, strength and ductility. These play a vital role in the global response and failure mode of RC structures, and thus need to be individually assessed and modified in order to optimise the response of the upgraded structure. Selective repair and strengthening techniques, capable of individually affecting such design parameters, have been developed and recently tested under dynamic conditions. In this paper, a detailed description of these experiments is presented and the most relevant results and observations are discussed. These not only confirm the effectiveness of the proposed selective schemes and their feasibility for practical applications, but also further validate previously derived formulae that can be employed in design.

INTRODUCTION

The existing building stock poses a much more serious seismic safety problem when compared to safe earthquake design of new construction. Therefore, assessment followed by repair and/or strengthening assumes a role of extreme importance and priority in earthquake engineering, compared to the development of new design methods. General methods of repair to reinstate or upgrade the stiffness, strength and ductility of individual members are commonplace and will continue to play a central part in earthquake-stricken areas. However, in the context of capacity design it is imperative to reckon the effect of individual member characteristics on the response and failure mode of the overall system. Here, a desired failure mode exhibiting adequate levels of energy absorption capacity is envisaged, thus control must be exercised on the member behaviour to safeguard the achievement of the target overall response.

Therefore, local repair and retrofitting methods that result in unquantifiable effects on seismic response characteristics should be re-assessed. In contrast, selective techniques to affect, in a controlled and easy-to-monitor fashion, individual design response parameters, i.e. stiffness, strength and ductility, may provide a new framework for repair and retrofitting earthquake damaged structures to mirror ‘capacity design’ principles used for new structures.

Practical methods for selective repair and strengthening of RC structures have been developed at Imperial College [Elnashai and Salama, 1992]. In this paper, an experimental programme aiming at the assessment of the feasibility and effectiveness of such techniques under dynamic loading conditions is described. The programme consisted of a series of shaking-table tests, carried out at the Centre for Earthquake Engineering at LNEC (Lisbon, Portugal), under the auspices of the ECOEST II (European Consortium of Earthquake Shaking Tables). Eight large-scale wall models were tested up to collapse using both artificial and natural accelerograms. The proposed selective schemes were applied as both repair and upgrading measures to previously damaged or intact

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specimens, respectively. Moreover, traditional repair techniques such as reinforced concrete jacketing and epoxy-resin injection were also tested, for comparison purposes.

A discussion of the main results and observations from the tests is also included in the paper. The response of the models is investigated not only through analysis of the three design parameters, stiffness, strength and ductility, but also through assessment of other response factors such as plastic hinge length and energy dissipation, amongst others. Finally, an appraisal of the accuracy of the design expressions, derived in a previous work by Elnashai and Pinho [1998], is also included in the paper.

EXPERIMENTAL SET-UP

Test rig and instrumentation

Due to the large scale of the specimens and input limitations of the table, considerable inertia mass (20 tons) was required to approach the flexural capacity of the models [Pinho *et al.*, 1999]. However, the dimension of such mass blocks prevented their positioning at the top of the slender individual wall specimens. Hence, an alternative design, comprising a steel frame placed at the side of the table, was devised instead. In this situation, the inertia masses are connected to the models through a pinned stiff strut, as shown in Figure 1, below. The mass blocks rest on sliding bearings, made of Teflon pads coated with a lubricant to minimise friction. The models were bolted to the table at eight locations to prevent any parasitic movement during the tests.

An out-of-plane restraining system, consisting on the use of four pinned bars fixed to the table and to the loading beam (Figure 2), was also introduced to prevent deformation in the transverse direction. Such scheme proved to be successful in controlling transverse deformation whilst introducing minimum interference with the in-plane behaviour of the models [Pinho *et al.*, 1999].

A total of 22 acquisition channels, corresponding to eleven transducers (LVDT's), six optical readers (Hamamatsus), four accelerometers and one load-cell were utilised to instrument the models. At the foundation beam, three transducers (two vertical and one horizontal) were used to measure displacements at the base of the model so as to check that the latter was properly fixed to the platform. In the wall, four vertical transducers were located on each side to measure vertical displacements, which are then used to derive rotation/curvature profiles and to determine the model's flexural component of deformation. Five optical readers located at the centre of the wall and distributed throughout its height were used to measure horizontal displacements. These were placed at a distance of $h_w/8$, $h_w/4$, $h_w/2$ and h_w from the base of the wall, reflecting the need for refinement near the foundation, where inelasticity is expected to occur.

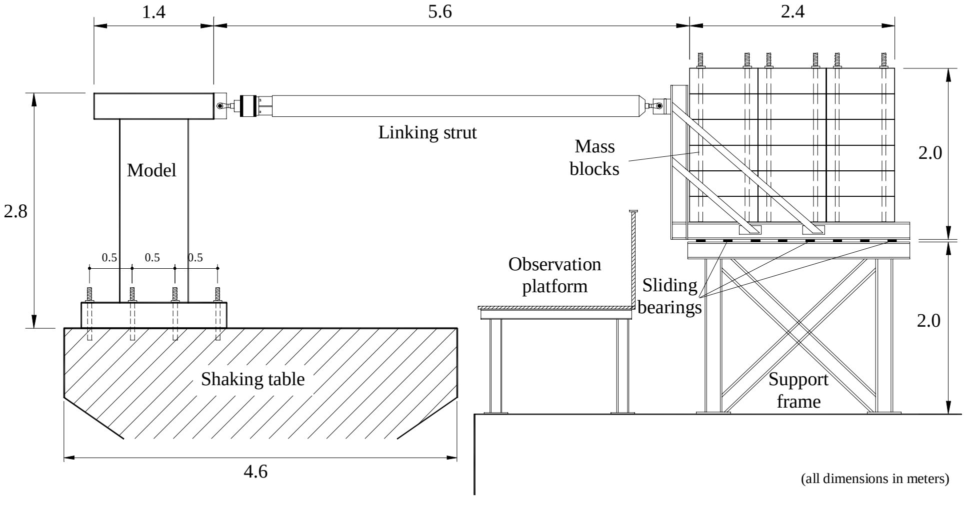


Figure 1. Test rig

Figure 2. Test specimen

The transverse (out-of-plane) displacement of the model is measured by an optical reader located on one side of the model. Also, a load cell is located in the linking strut to measure the inertia load acting on the model, and response acceleration at the top of the model is measured by an accelerometer located in the loading beam. In the platform itself, two accelerometers were attached, to record acceleration in both directions, used to check the accuracy of the input signal.

DESIGN AND CONSTRUCTION OF MODELS

Prototype and model design

The specimens used in these tests were intended to model a typical case of slender structural walls used in many reinforced concrete buildings. The prototype was therefore considered as a one-storey wall, with a height of 3.2 m and width of 1.2 m. In order to damage the models with minimum demand on table input, ductility class “L” (as defined in EC8) was considered to determine minimum dimensions and longitudinal reinforcement requirements. Regarding shear design, since the objective of the tests was to analyse the response of the models in flexure, the prototype was designed using EC8 Class “H” rules for shear detailing.

To obtain the model characteristics, a geometric scaling factor of 1.5 was applied to scale down the dimensions and reinforcement detailing of the prototype, resulting in a model with the characteristics shown in Figure 3. The use of large-scale models enabled the utilisation of normal concrete and reinforcement bars, with no need for any special provisions. The concrete material used was specified as C20/25, representative of older design structures, (requiring strengthening) whilst the reinforcement steel was specified as of class S400.

The dimensions of the loading beam were defined in accordance with the characteristics of the load-transfer mechanism, resulting in a cross-section area of $300\times300\ \text{mm}^2$. Minimum reinforcement detailing, for construction purposes only, was adopted. As for the foundation, its length and width were determined to allow the use of eight fixing points to the table, where the existing grid is $0.5\times0.5\ \text{m}^2$. The height was determined to provide sufficient protection against punching shear failure.

The flexural reinforcement of the foundation was designed using an estimated overturning moment of 220 kNm, corresponding to an horizontal force of 103 kN at the top of the model. This level of horizontal load is associated to the expected capacity of the model repaired with reinforced concrete jacketing, anticipated to be the strongest model to be tested.

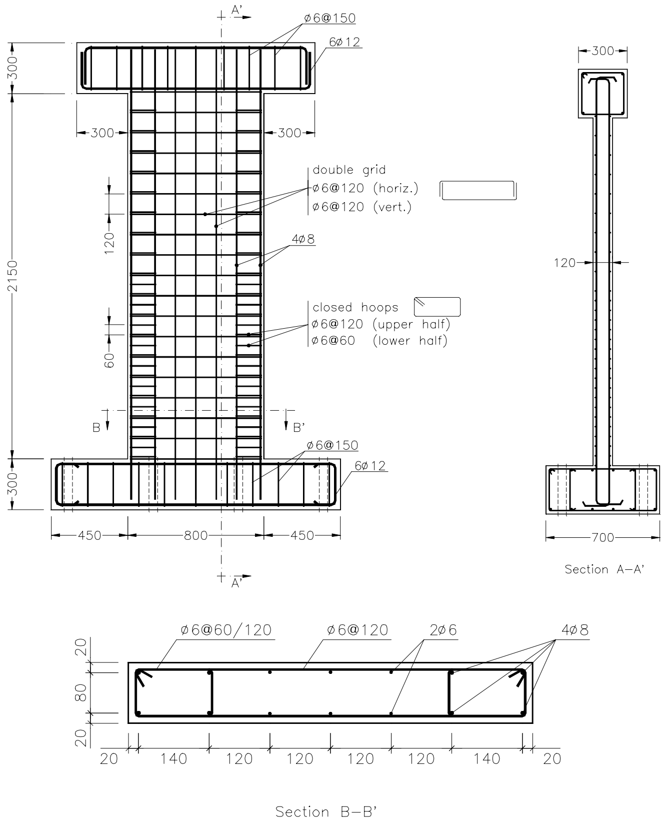


Figure 3. Dimensions and detailing of test specimens

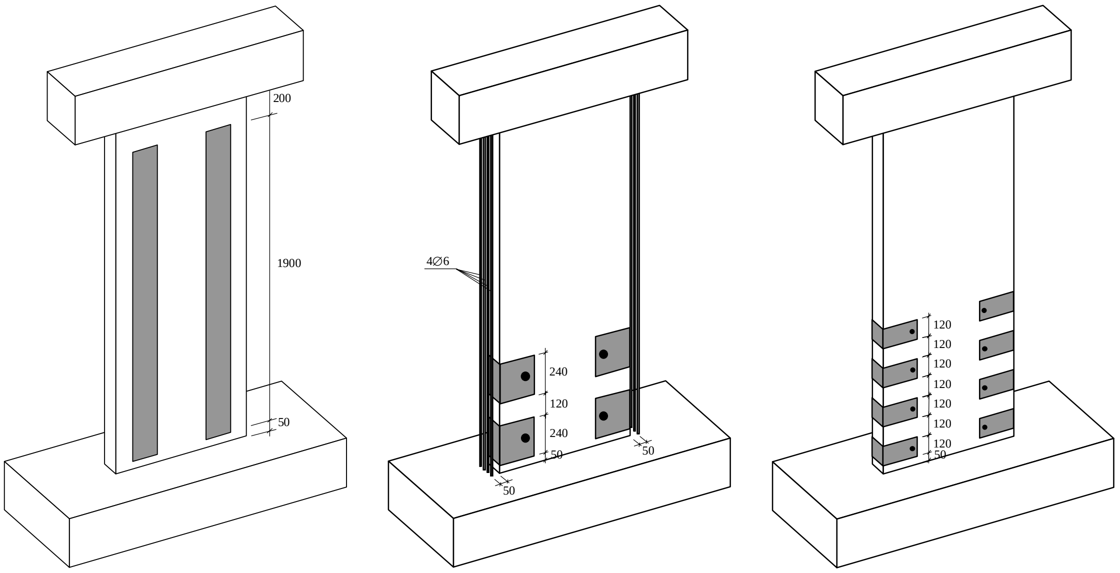
Design of retrofitted models

Detailed description of the rationale of the proposed intervention schemes is beyond the scope of this short paper. The reader should refer to the work by Elnashai and Pinho [1998] for more in-depth explanations of the format and application of the proposed selective schemes, described below. In addition, the characteristics of the intervention schemes described below (dimension of plates, location, material properties, etc.), were determined by making use of previously derived design expressions, also presented in the aforementioned work, and by running detailed numerical simulations. A thorough description of such design procedure can be found elsewhere [Pinho *et al.*, 1999].

Different configurations of the intervention schemes were envisaged to provide an insight into the influence of design-parameters of each technique on the response of the retrofitted model. Therefore, a total of eleven tests on eight models were envisaged. Three of the models were tested twice, being firstly tested as bare intact specimens and then re-tested after being repaired. In this manner, the response characteristics of intact specimens, necessary for comparison with retrofitted models behaviour, was appraised. The remaining five models were upgraded before being tested up to collapse.

Stiffness-only intervention schemes were tested as both upgrading and repair techniques, using models SW4 (Figure 4a) and SW3R, respectively. In the former, the objective was to achieve an 80% increase in member stiffness whilst for the latter, reinstatement of the initial stiffness of the damaged specimen was sought. In both applications, Fe430 external steel plates with a thickness of 2 mm were utilised.

For the case of strength-only intervention (models SW5 and SW7), two tests were envisaged, with similar external reinforcement detailing but different values for the design slackness of the re-bars. The increase in flexural capacity envisaged for both models was 25%. This represents the type of augment required for upgrading of members initially designed without capacity design considerations, i.e., without application of overstrength factors. The latter may reach values of 1.25 if DC "H" is considered, thus justifying the proposed capacity increase target. In addition, model SW7 was also upgraded in terms of ductility thus providing an insight into the feasibility of combining different selective intervention types (Figure 4b).



(a) (b) (c)

Figure 4. Selective intervention: (a) SW4; (b) SW7 and (c) SW6

Regarding the case of ductility-only intervention (models SW6, SW7 and SW8), three tests were envisaged using intact models without internal ductility detailing. These targeted at the evaluation of the influence of the two crucial parameters for this intervention; height and spacing of the confinement plates. Thus three distinct configurations were employed, whereby three different values of ratio between plate spacing and plate height ($s_p/h_p=1$, $s_p/h_p=0.5$ and $s_p/h_p=0$) were adopted. The thickness of the plates, on the other hand, was kept constant at 2 mm. Model SW6 ($s_p/h_p=1$), is schematically represented in Figure 4c.

In addition, two of the most widely used repair/strengthening techniques, i.e. reinforced concrete jacketing and epoxy-resin injection, were also tested in the current research programme. Epoxy-resin was injected in a cracked model (SW6R) to assess the effectiveness of this method in reinstating stiffness. Reinforced concrete jacketing was applied in model SW1R, adopting the minimum dimensions required for practical execution, together with concrete and steel materials similar to those used in the intact specimens. In this way, by maintaining both the dimensions of the jacket and the material properties to minimum values, it is possible to demonstrate that the inherent characteristics of such repair method are the cause for the significant changes usually observed.

Construction of models

As mentioned earlier, a private contractor, STAP, carried out the repair and strengthening works on the models. The work was mainly carried out by one technician, with few exceptions where the presence of two workers was required. There were no particular complications or difficulties with the application of the selective techniques, which were considered by the contractor as being of straightforward application.

It is also noteworthy that the total cost (labour and material) associated to the application of each selective technique was on average five times below the cost of the reinforced concrete jacketing, as described elsewhere [Pinho *et al.*, 1999]. This shows that not only the techniques are practical and feasible, but they are also economical. Moreover, the results of the tests, shown below, confirm that they are indeed efficient.

Input motion

Due to the features of the shaking table, and the characteristics of the models response, a combination of artificial and natural records was found to be most suitable to achieve the objectives of the tests. Both records possessed similar peak velocities, reaching the limit of the shaking table capacity (23 cm/s). They also exhibited response spectra with corner periods enclosing the range of expected periods of vibration of the model (0.2-0.6s), to guarantee maximum amplification of motion.

However, the two input motions differed significantly in terms of acceleration time-history. Whilst, the artificial record is characterised by a ‘synthetically’ rich frequency content, containing a high number of peaks, the natural record possessed fewer but stronger pulses. As a result, and taking into account the aforementioned velocity restraint, the artificial accelerogram has a smaller peak acceleration (0.18g) than the natural accelerogram (0.33g). Consequently, the latter induced higher values of response acceleration, whilst the former imposed higher energy levels [Pinho *et al.*, 1999]. Therefore, a mixture of both records was utilised providing a combination of isolated strong pulses from the natural record with the lower but more ‘repetitive’ artificial input motion. The tests were performed in stages, with the input motion being successively scaled up, so as to ensure a gradual degradation of the properties of the test specimens, maximising in this way the amount of useful information gathered through the experiment.

Finally, it is important to note that a scaling time factor was not applied to the input motion, as required for full dynamic similitude (adopting length, stress and velocity as the fundamental scaling parameters, as suggested by Elnashai *et al.*, 1988). For the purpose of the present investigation, partial similitude sufficed since the outcome of the application of the novel techniques was assessed by comparison to a ‘control’ model, rather than to the prototype.

EXPERIMENTAL RESULTS

In Table 1, a summary of the dynamic characteristics of each model after testing is given. Although, as mentioned earlier, many other response parameters were evaluated [Pinho *et al.*, 1999], the contents of Table 1 do constitute a succinct and informative summary of the response of each specimen. These are used to support the observations and conclusions described below regarding the effectiveness of the intervention schemes tested.

Stiffness-only intervention (SW3R and SW4)

Results in Table 1 show that the application of external steel plates in model SW3R was indeed successful in reinstating the initial (yield) stiffness of the intact model (SW3) since both models present an initial stiffness value of approximately 7 kN/mm. It is also observed that no significant change in the flexural strength and displacement capacity occurred, as was envisaged.

Regarding model SW4, where an 80% stiffness increase was sought, values in Table 1 indicate a ratio between upgraded and original stiffness of the order of 1.7. This represents a 6% deviation from the initial design, attesting to the accuracy of the design expressions derived in previous work. Moreover, similarly to SW3R, no changes in ductility supply were observed (similar drift at failure between intact specimen, SW1, and upgraded model, SW4) and only minor drop (5%) in flexural capacity was registered. This might be related to variability in steel properties, and not necessarily related to the intervention scheme itself.

Table 1. Summary of dynamic characteristics of each model after testing

Model	Initial stiffness (kN/mm)	Flexural capacity (kN)	Drift at failure (%)	Final state
SW1	5.5	58	1.1	failure
SW1R	17.0	109	3.3*	failure
SW2	4.2	45	1.1	failure
SW3	7.2	56	-	cracking
SW3R	7.1	59	1.1	failure
SW4	12.0	53	1.1	failure
SW5	8.3	67	1.5	failure
SW6	8.6	53	0.9	onset of failure
SW6R	5.1	53	0.9	failure
SW7	9.7	72	4.2*	failure
SW8	14.1	66	0.9	failure

* model taken to collapse under monotonic loading

Strength-only intervention (SW5 and SW7)

In Figure 5a, the hysteresis envelope of the control model (SW3) and the upgraded specimen (SW5) is depicted. It is evident that the proposed scheme efficiently increases strength without changing the initial stiffness of the element. Moreover, considering the values indicated in Table 1 above, the original/upgraded strength ratio is estimated as being 1.20, resulting in a difference of 3% to the initial design value. The results confirm the accuracy of the developed design expressions.

Regarding the behaviour of model SW7, the application of a mixed intervention combining strength and ductility resulted in an increase in both parameters, as observed in Table 1. This confirms the efficiency of both schemes, even when used in combination. However, the analytically predicted 25% increase in strength was in this case largely surpassed since the significant improvement in the deformation capacity of the model was not taken into account at the design stage.

Ductility-only intervention (SW6, SW7 and SW8)

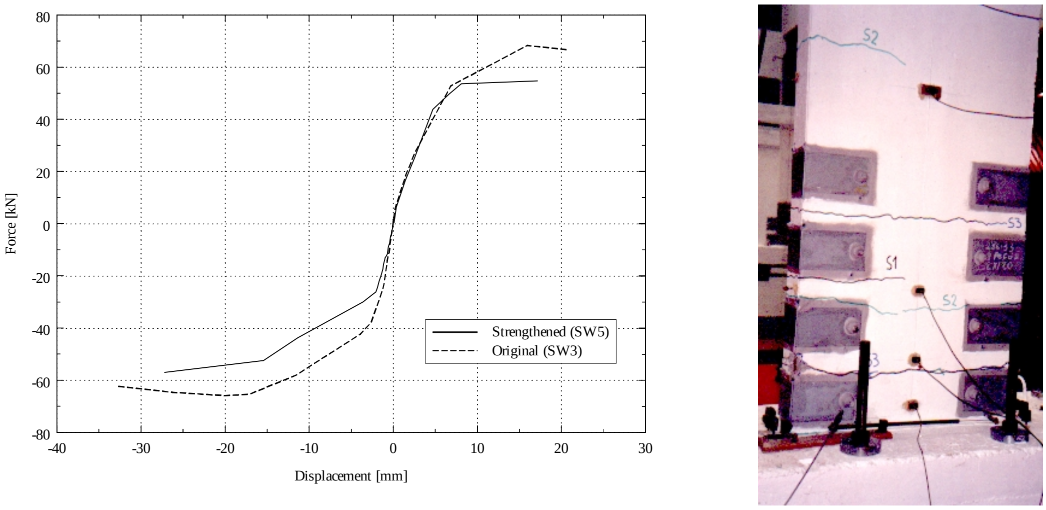
In Table 1, the significant ductility improvement introduced by the retrofitting scheme in model SW7 is observed, with failure occurring at a displacement of 4.2, as opposed to 1.1 in the control model. However, it is also observed in Table 1 that the ductility of models SW6 and SW8 was less than that of the original model, where internal confinement was used. Such behaviour was indeed expected and arises from the characteristics of plate spacing-to-plate height ratio adopted in the retrofitted models.

In model SW6, the spacing used (equal to the height of the plates) proved excessive, thus an effective confinement situation was not achieved (as had been predicted by the design expressions, Pinho *et al.*, 1999). Regarding model SW8, the reverse effect was observed instead, since in this model the plates were intentionally designed without any gap between them. Consequently, the continuous U-shape plates did not allow propagation of damage throughout the model to occur, and a ductile failure mode could not be attained.

Concerning model SW7, the improvement in deformation capacity was significant, with a four-fold increase in ultimate displacement compared to the control model. This seems to indicate that a ratio between plate spacing and plate height in the vicinity of 0.5 renders the proposed scheme efficient in the selective increase of member ductility. In addition, to avoid unfavourable increases in stiffness, smaller plates, as used in model SW6 (Figure 5b), should be used to allow crack spreading thus minimising the effect on stiffness.

Conventional interventions (SW1R and SW6R)

As can be observed in Table 1, the use of minimum dimensions for the reinforced concrete jacketing did not prevent substantial changes in all response parameters of the model. On the contrary, initial stiffness and ductility were changed by a factor of three whilst flexural capacity was doubled. Therefore, if the objective of



(a) (b)

Figure 5. (a) Hysteresis envelope of SW3 and SW5 models; (b) Damage pattern on model SW6

intervention is centred on fine-tuning of structural response by controlled adjustment of individual member behaviour, then such intervention approaches are inappropriate. In fact, application of this repair technique may lead to stiffness irregularities or perturb the sequence of plastic hinge formation, thus jeopardising the whole retrofitting process.

Epoxy-resin injection was applied to model SW6R, with the objective of reinstating the initial yield stiffness. The values of initial stiffness indicated in Table 1 for the intact and repaired models clearly show that this method failed to meet its target, since the stiffness of the repaired model is considerably lower than that of the initial model. During the test, it became evident that a weak-zone developed in the vicinity of the repaired crack with local damage concentration at that section. Such results highlight the advantages in the use of external steel plates to ‘sew’ opened cracks instead of (or in addition to) ‘gluing’ these back together.

CONCLUSIONS

The outcome of this extensive experimental programme was a positive one. Firstly, the feedback from the contractor who applied the proposed innovative repair schemes was reassuring. The technicians found the selective schemes to be of relatively simple application (usually simpler than other more conventional methods employed in practical applications). The innovative schemes were also economical, as confirmed by the final breakdown of costs. With regard to the technical significance of the results, they served the following essential purposes:

- confirmation of the effectiveness of the techniques under dynamic conditions, using models and intervention schemes of significantly different proportions to the ones used in previous experimental programmes;
- validation of the design expressions under dynamic loading, with differences between predicted and measured properties not exceeding 6%;
- development of further design/application guidelines for the techniques concerning location of external plates, spacing between plates, height of plates and procedure for application.

Further tests are presently being carried out to investigate the feasibility and effectiveness of application of selective intervention methods in repair and strengthening of multi-storey buildings. For this purpose, two four-storey, three-bay, full-scale RC frames are being tested under pseudo-dynamic conditions at the JRC in Ispra (Italy).

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