RUBBER-BASED ENERGY DISSIPATORS FOR EARTHQUAKE PROTECTION OF STRUCTURES

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SUMMARY

The incorporation of additional damping into a structure provides a means of reducing the magnitude of the acceleration and displacement responses produced by earthquakes when the use of base-isolation is not possible or appropriate. The present work concerns the development of a rubber-based dissipator for use in a reinforced concrete frame building, though a similar device should be suitable for any type of building with a comparable interstorey stiffness. The aim is for the dampers to upgrade a standard non-seismic design so that the building responds elastically when subjected to design level earthquake inputs. The performance of the dampers developed is assessed both analytically and by pseudo-dynamic testing of a mock-up of part of the building frame. The material developed has a loss factor of about 0.4 and shows a change in the shear modulus of about a factor of three between -20 and 50^0C; this is a much lower temperature sensitivity than the principal commercial material available. The building is a 4-storey reinforced concrete office block with a total height of 13.6 metres and plan dimensions of 52.5 by 19.5 metres. Analysis showed that the response of the building could be made elastic (interstorey drift <10mm) by inserting a device with a stiffness of about 40MN/m into each external bay on the two long sides of the building. The performance of the dissipators was assessed by pseudodynamic (PsD) tests of a 2/3 scale mock-up of part of the structure. The results obtained for time-history inputs equivalent to an earthquake record for the full-size building with a peak ground acceleration of 0.31g showed that the peak interstorey drift of the mock-up was only 8mm with the devices in place. Without the devices attached the drift increased to 36mm. The PsD tests thus confirm the effectiveness of the dissipator devices in reducing seismic loads.

INTRODUCTION

Earthquake protection of important buildings, bridges, potentially hazardous industrial plants and vital equipment is of key importance both on safety and economic grounds.. One method able to reduce the displacements and accelerations imposed on a structure during an earthquake is to install auxiliary dampers within the structure. The technology is applicable both to new and existing structures. This paper is concerned with the development and evaluation of a relatively novel type of damper – one based on viscoelastic or more strictly hysteretic materials. Such devices have been used (Fujita et al, 1992) to reduce the effect of wind loading on tall buildings, and the extension of their application to seismic loading is now the subject of research and development in several centres (Aiken et al, 1990; Sause et al 1994). The devices need to experience a minimum amount of displacement during an earthquake to operate efficiently. Consequently, their use could be difficult for very stiff structures such as those containing shear walls. They are more suited to steel or reinforced concrete frame structures.

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This paper describes the dynamic and physical properties of a new rubber-based damping material with much less sensitivity to changes of temperature and less costly than those currently available commercially. Excessive temperature dependence of the device stiffness – invariably a decrease with rising temperature – not only restricts the service temperature range, but also results in a degradation of performance due to the heat generated whilst operating during an earthquake. The characteristics of prototype dampers produced using the new material are shown. A numerical evaluation of the performance of dampers based on the new material and installed in a reinforced concrete (RC) frame building is presented. The results of pseudo-dynamic (PsD) tests performed on a mock-up of part of the RC frame building are given.

MATERIAL FOR DAMPERS

The emphasis in developing the viscoelastic material was on achieving stiffness and damping which do not change excessively over a fairly wide temperature range (from -25 to 40°C) rather than on obtaining very high levels of damping. The material selection was made on the basis of the best overall performance over a range of key properties. In addition to loss factor, these are:

(a) temperature variation of shear modulus
(b) effect of strain amplitude
(c) effect of repeated cycling on modulus and damping
(d) strain history effect
(e) shear failure strain
(f) long-term stability of modulus and damping

A range of materials were assessed. Figure 1 shows the variation of the complex shear modulus (G*) and loss factor (tanδ) over a temperature range of 70°C for the compound used in the production of devices for the mock-up structure. The shear modulus varies by less than a factor of 3 over a 50°C operating temperature range. The loss factor (twice the critical damping) for this compound varies between 0.45 to 0.6 over the test temperature range. The magnitude of the changes with temperature represents a very significant improvement over the present major commercially available compound. Table 1 summarises other properties for the compound. The change of modulus with continued cycling (typified by ratio G(3)/G(10)) is fairly small after the first two cycles. The compound is quite non-linear, but this is not seen as a disadvantage in this application. There is a large margin between the shear failure strain and the strain (100%) chosen for design level inputs. The accelerated ageing results suggest reasonably stable properties over the long term.

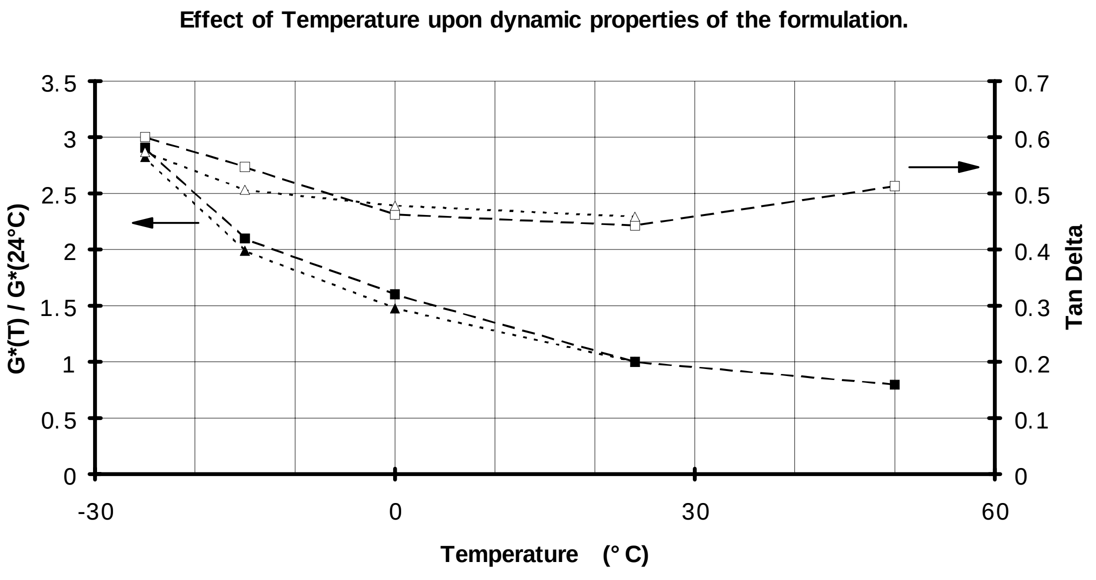


Figure 1. The effect of temperature on the dynamic properties of the high damping compound for prototype devices. Dynamic shear modulus normalized with respect to modulus at 24^{O}C. Triangles are for 100% strain and squares are for 50% strain. Measurements at 1Hz - 3rd cycle

Table 1. Dynamic and physical properties of the compound used in the manufacture of the dissipators

G(3)/G(10)*	G(10%)/G(100%)**	Shear failure†	G(MPa) ‡	
		strain %	unaged	aged
1.07	4.64	450	0.76	0.86

Tanδ‡		Tensile strength (MPa)		Elongation at break (%)	
unaged	aged	unaged	aged	unaged	aged
0.52	0.50	606	7.5	640	630

* Number in brackets gives the strain cycle number - Modulus values are quoted at 100% shear strain and at 0.1Hz

** Shear strain given in brackets. Third cycle data at 0.1Hz

† Testpiece pulled at 100% strain/s

‡ Dynamic properties quoted at 100% shear strain and 1Hz

DEVICE CHARACTERISTICS

The design chosen for the viscoelastic damper (VED) is shown schematically in Figure 2. It consists of a single layer of rubber bonded between steel plates. The design strain in the rubber is intended to be about 100% in simple shear. For the PsD test devices the rubber layer is 7mm thick and has a plan dimension of 240x170mm; the layer is bonded to metal end-plates 330x330x15mm thick.

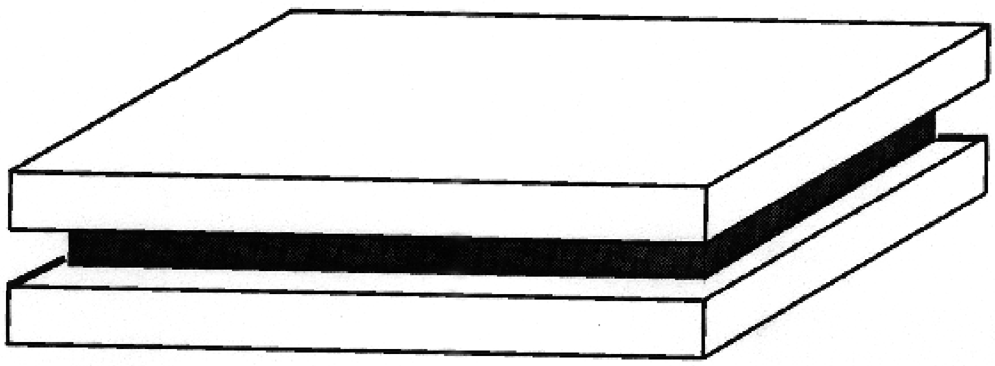


Figure 2: Schematic View of VED Devic

The dampers have been tested in a double shear configuration over a range of frequencies and amplitudes. Figure 3 shows the dynamic stiffness and loss factor; the tests spanned strain amplitudes of 10 to 100% at a frequency of 0.1Hz. The effect of repeated cycling is indicated by the difference between the two dashed lines for the 1st and 3rd cycle. Further cycling produced little change in the dynamic properties. The changes in dynamic properties produced by varying the frequency over two orders of magnitude are modest (see Table 2).

Table 2: Effect of frequency on VED device stiffness and loss factor

Frequency HZ	Stiffness kN/mm	Loss factor
0.01	3.1	0.35
0.1	3.4	0.35
1	4.1	0.34

Strain amplitude 50% Tenth cycle data.

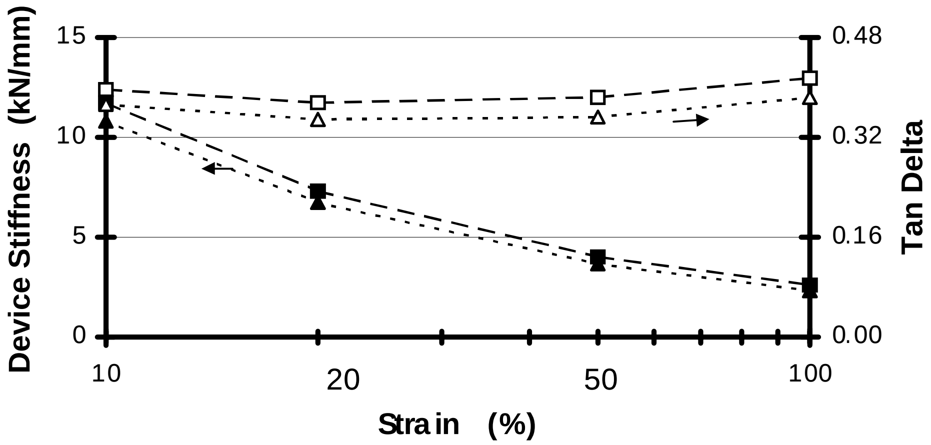


Figure 3. Effect of strain amplitude in the rubber on the dynamic stiffness and loss factor of the devices for the mock-up structure. Squares are for 1st cycle data and triangles are for 3rd cycle data.

NUMERICAL EVALUATION OF PERFORMANCE IN RC FRAME BUILDING

The building is an office block to be located in a non-seismic area and has therefore been designed assuming there will be no seismic action. Its fundamental natural frequency lies within the peak range of the response spectra for typical severe earthquakes. Consequently, it would be subjected to much stronger acceleration levels than the ground during an earthquake. The aim of this study is for the viscoelastic dampers to upgrade this standard non-seismic design such that the building responds elastically when subjected to earthquake levels specified by EuroCode 8 (for medium soils) (peak ground acceleration 0.3g).

The building is composed of ground floor and two upper floors. The roof is supported by a slab. The total height of the building is 17.70m, the ground floor level being 1.50m above the foundation level. The total length and width of the building are 53.60 and 20.60m respectively. The height of each storey is 4m. Spacing between columns along the longitudinal direction is 7.1m; distances between the four columns along the transverse direction are 6.0, 7.5 and 6.0m. Beams supporting the slabs join the columns only along the longitudinal axis. There are three types of column along the facades; the C1 columns have a section of 0.4m by 0.76m (with the longest dimension perpendicular to the facade); in the centre of the building the C2 columns have a square section of typical length 0.40m; in the corners, the C3 columns have an L-section with arms of length 0.75m and thickness of 0.40m. There are two types of beams; the outer beams have a width of 0.23m and height 0.75m; the corresponding figures for the central beams are respectively 0.3m and 0.75m. The slab thickness is 0.2m.

A simplified 2D model was used to estimate the response of the structure when subjected to a synthetic time-history record formed by averaging a number of synthetic accelerograms each complying with the response spectrum defined in EuroCode 8 (medium soil). The natural frequencies of the structure before the introduction of the devices were calculated to be 1.81 and 5.56Hz. The devices were modelled as a combination of a linear spring (k) and a dashpot (c) in parallel. The following relationship between the in-phase (k') and out of phase (k'') stiffnesses of the device was used:-

$$\tan\delta = \frac{k''}{k'} = \frac{c\omega}{k}$$

$\omega = 2\pi f$, where f, the fundamental natural frequency of the structure along its long axis, equals 1.81Hz.

Figures 4 and 5 respectively show, as a function of total device stiffness per floor, the peak acceleration at the roof of the structure and the peak interstorey drift between the second and first floors. The three sets of results are for $\tan\delta$ = 0, 0.5 and 0.8. The value of 0.5 represents the target loss factor for the high damping compound at shear strain amplitude of 100%. Figure 4 illustrates the effectiveness of added damping in reducing the top floor acceleration levels. It is interesting to note that raising the interstorey stiffness of the structure from

500kN/mm (for the unmodified structure) to 1040kN/mm reduces the peak accelerations at the top of the building from 16m/s^2 to 9m/s^2. Introducing viscoelastic dampers with loss factor of 0.5, however, reduces the peak acceleration further to 5.5m/s^2. The effect on the interstorey drift of raising the loss factor from 0.5 to 0.8 is less significant (see Figure 5). In order to achieve an elastic response (ie. 10mm interstorey deflection) the stiffness of the devices for each floor should be about 540kN/mm when their loss factor is 0.5. Therefore, the total stiffness of the devices on each floor should be of the order of the interstorey stiffness of the structure. Installation of 14 units per floor (one in each external bay of the structure along its long axis), each of stiffness 40kN/mm would achieve the required stiffness. Each unit could consist of a pair of devices each about six times stiffer than the prototypes tested for Figure 3. This could be achieved by increasing the plan dimensions of the rubber layer to about 500mm square.

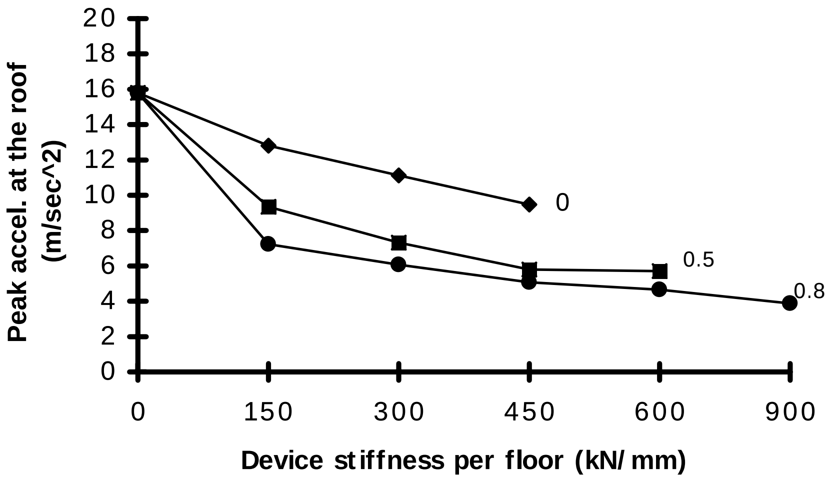


Figure 4. The effect of introducing viscoelastic dampers on the peak acceleration response at the roof of the RC frame building. The number against each curve represents the loss factor assumed in the analysis.

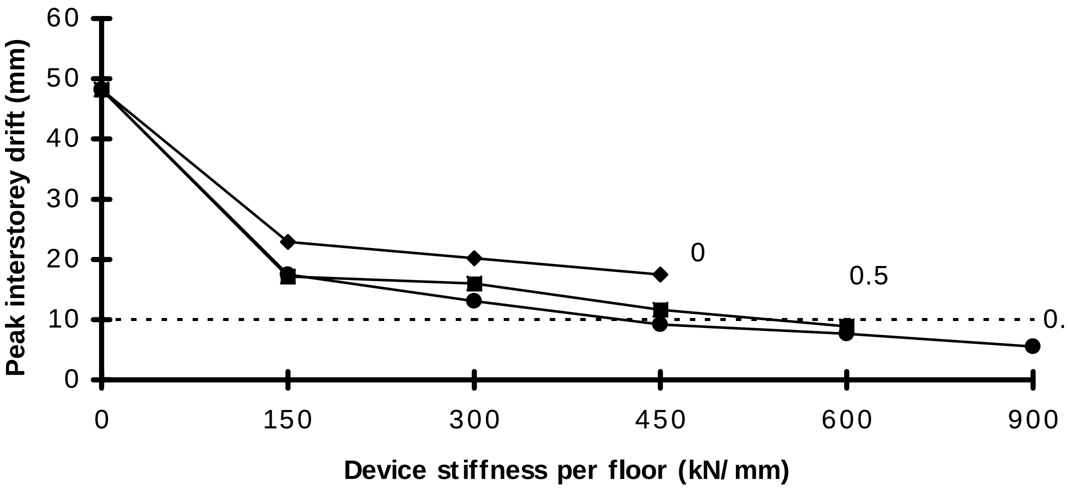


Figure 5. The effect of introducing viscoelastic dampers on the peak interstorey drift at the first floor (ie. between second mass and first mass) of the reinforced concrete framed building. ----- elastic limit for drift The number against each curve represents the loss factor assumed in the analysis.

It is clear that devices can be installed to restrict drift to elastic levels during the reference seismic input. Most of the reduction in the response, particularly regarding the drift, comes from the added stiffness to the structure. Moderate levels of damping lead to further reductions, but there appears to be little further advantage beyond a device loss factor of 0.5.

PSEUDO-DYNAMIC TESTS OF RC-FRAME MOCK-UP

A two-storey mock-up of part of the reinforced concrete office building was designed and constructed for testing at JRC, Ispra, Italy. The mock-up (10m long, 4m wide and 5.2m high) (Figure 6) represents a portion of the building scaled by 2/3 in dimension and consists of two bays of 5m in the direction of testing and of one bay across its width (see Figure 4). The mock-up represented a non-seismic design. The aim was to upgrade it by installation of the dampers so that the frame responded elastically to the design level earthquake.

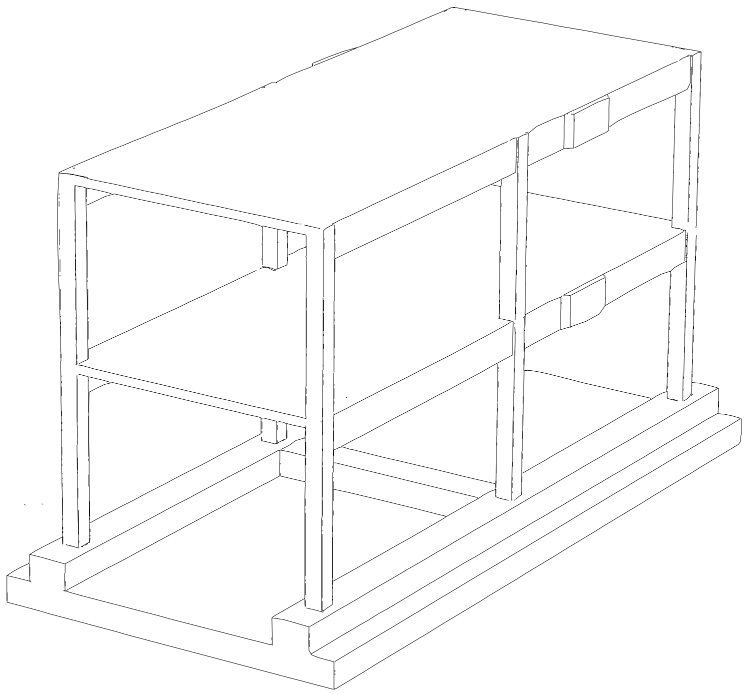


Figure 6: Isolmetric view of the mock-up structure

With time-dependent loading, three independent scale factors may be selected, namely, mass M, length L, and time T. The other scale factors can be derived according to the principles of dimensional analysis. In PsD testing, forces and displacements are applied and measured, and the test is carried out in pseudo time. Therefore, the principal aim of testing scaled models is to achieve a reduction in size (length scaled) of the specimen to suit the available laboratory space (as is the case here), or to reduce the load (force scaled) to a level below the maximum capacity of the actuators. Thus, the only scale factors of interest are length and force. The scale factors for the other quantities (time and mass) are of less concern since these are used only in the numerical calculations. The stress identity is preserved by loading each floor of the model with masses to reach the necessary vertical forces and the accelerogram will be scaled in accordance with the scale adopted for the test model. This can be achieved by increasing the acceleration amplitude by 3/2 and scaling down the time by 2/3.

The VE dampers are installed as pairs with the viscoelastic material being deformed in shear. Thus there are 16 devices (8 pairs), one pair in each bay along the two longitudinal facades. The stiffness of the dampers (~3kN/mm for each) was determined by preliminary analysis of the mock-up plus devices taking into account the loss factor (~0.4) at the design strain (100% shear). The moving central plate is fixed to the top of K-bracing and external steel plates, bolted to the side plates of the VE devices, are anchored to the RC structure at the base of the columns (Figure 7). The bracing and its joints were designed to be stiff compared with the devices to ensure that the deformation of the frame appeared mostly across the rubber layers. In the design of the bracing system particular care has been given to prevent any instability in the struts, and to avoid any differential displacements in the joints at the base of the frame and in the bolted connections since these could give extra energy dissipation. The system has been designed such that the bracing can be completely disconnected from the mock-up structure thus enabling the testing of the unbraced frame.

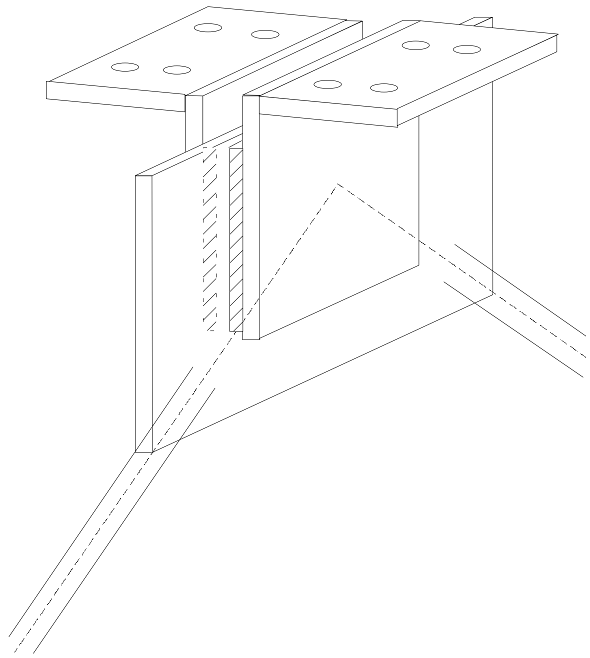


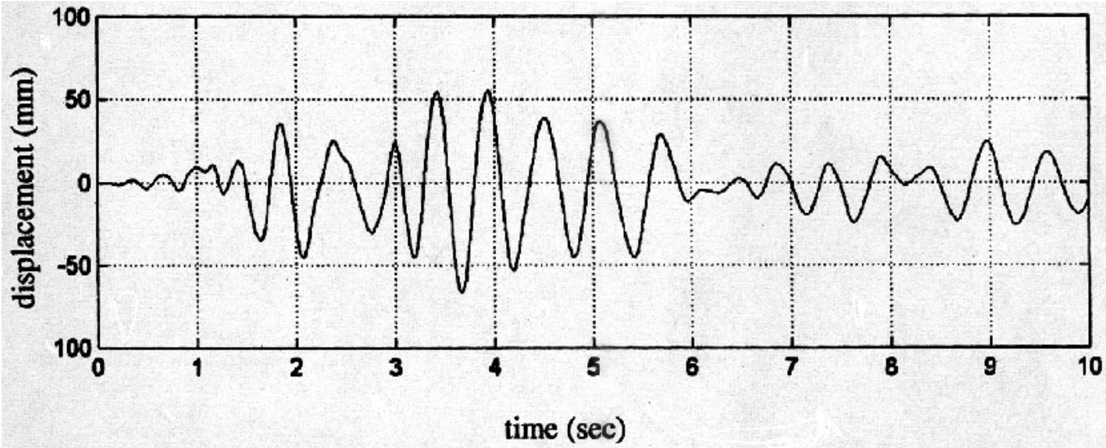
Figure 7: Details of the attachment of the VED to structure and K-bracing

For the evaluation of the performance of the VE dampers, PsD experiments were carried out on the mock-up with and without anti-seismic devices. The input motion corresponded to artificially generated earthquakes specified by EuroCode 8 and representative of medium soil conditions. The level of the earthquake corresponded to 0.3g PGA for the full-size building. In order to allow for the strain rate effects associated with the VEDs, the forces measured in these during the PsD testing were scaled up by 49% at every integration step. The scaling factor was obtained from tests on the devices over a range of strain rates.

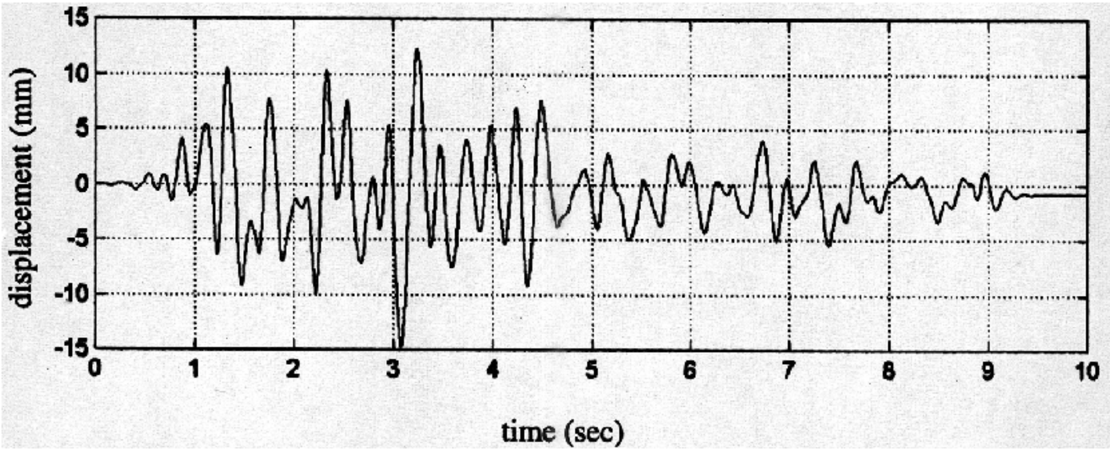
The displacement-time history for the second-storey of the mock-up is shown in Figure 8. The peak displacement is seen to be reduced by about 80%. Much of the decrease is attributable to the increase in stiffness (by a factor of 4) produced by incorporation of the devices. The peak inter-storey drift of the mock-up with the devices in place was 8mm compared with 36mm without the devices. The inter-storey drift at the design level earthquake (0.3g PGA) remained within the elastic deformation range.

The overall peak forces in the protected frame are similar to those in the bare frame. A high proportion of the force (55%) in the protected frame, however, is borne by the devices. The added stiffness raised the natural frequency of the mock-up from 1.7Hz to 3.5 – 5Hz (the figure depending upon amplitude because of the non-linearity introduced by the devices). The energy content of the seismic input was much higher at the higher frequencies and this explains the similarity in the peak forces induced in the bare and protected frame. Without the high damping obtained with the devices, the increased stiffness of the protected frame would have led to higher force levels.

The installation of VED successfully transformed the non-seismic design RC frame to one able to restrict the response to the design level earthquake to elastic deformations.



Bare Frame



Protected Frame

Figure 8: Displacement response of second storey of mock-up to EC8 – medium soil acceleration time-history (0.3g PGA)

CONCLUSION

A viscoelastic damper with stiffness and damping relatively insensitive to temperature has been developed. Analysis shows that such dampers could be used to upgrade a non-seismic design reinforced concrete frame building so that it responds elastically to peak acceleration of 0.3g. The performance of the dampers has been confirmed by pseudo-dynamic tests on a 2/3-scale mock-up of part of the building.

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