Modelling the Behaviour of an Earthquake Base-Isolated Building

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SYNOPSIS

Protecting a structure against earthquake excitation by supporting it on laminated elastomeric bearings has become a widely accepted practice. The ability to perform accurate simulation of the system, including FEA of the bearings, would be desirable - especially for key installations.

In this paper attempts to model the behaviour of elastomeric earthquake bearings are outlined. Attention is focused on modelling highly-filled, low-modulus, high-damping elastomeric isolator systems; comparisons are made between standard triboelastic solid model predictions and test results.

1 INTRODUCTION

Seismic base isolation systems function by supporting a building on bearings which effectively decouple the building from the strong horizontal ground accelerations occurring in earthquakes. To be effective the fundamental natural frequency of the building / bearing system must be well below the main frequencies of the earthquake. Derham & Thomas (1980), Kelly (1986), Coveney et al (1988), Coveney & Thomas (1991) and Coveney (1991). Base isolation is gaining attention worldwide for use in a wide spectrum of structures and critical facilities, including bridges, office buildings, hospitals, computing and telecommunication centres, as well as nuclear facilities.

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Today there are over 125 structures around the world which are isolated against earthquakes and the numbers have been increasing steadily in the past few years.

An international cooperation programme was initiated in September, 1988 by Argonne National Laboratory (ANL) of the USA and Shimuzu Corporation of Japan to study the response of isolated structures to real seismic events. Within the programme agreement, Shimuzu provided their test facility at Sendai and earthquake data collection while ANL supplied the isolation bearings to be installed at the test facility and performed most of the analytical simulations utilising the ANL-developed 3-D computer program, SISEC (Seismic Isolation System Evaluation Code) (Wang et al, 1991).

Two separate sets of high-damping elastomer bearings were installed in the Sendai building designed for isolation. The first set, installed in April 1989, comprised high shape factor, high shear modulus rubber bearings primarily designed for medium and large earthquakes. From April 1989 to July 1990, 37 earthquakes were recorded. Detailed responses of the test facility were analysed and reported (Wang & Gvildys 1991, Uras 1993). The second set of bearings - comprising medium shape factor, low shear modulus bearings designed for a wide range of seismic events, including small tremors - were installed in October 1990 (Wang et al 1991, Coveney et al 1993). The current paper concerns the low shear modulus bearing system. From November 1990 to March 1991 seven seismic events were observed at the test facility. Complete records of a representative earthquake, #44, were used in the current study.

2 ISOLATION BEARINGS

The bearings were cylindrical - 371 mm in diameter and 206 mm in height (Fig 1). Each bearing consisted of 12 10 mm thick layers of elastomer alternating with 3 mm thick 350 mm diameter steel inter-plates. The steel endplates were 28 mm thick. The elastomeric material used in the bearings was an experimental highly-filled but lightly-crosslinked natural rubber formulation (Coveney 1987). Such highly-filled elastomeric materials exhibit significant nonlinearity both at large and at small strains (Coveney 1988, Coveney & Ahmadi 1989, Ackerman et al 1997, Coveney et al 1997) as shown in Figure 2 (1990 data).

The nonlinear characteristics of the soft bearings are indicated in Figure 3. The stiffness (k_{Tot}) was calculated as the ratio of the amplitude of the overall force (F_0) to the displacement amplitude (x_a). The approximate damping ratio (ζ_{app}) was calculated from the area of the force-deformation loop (A)

$$\zeta_{app} = \frac{A}{2\pi F_0 x_a}. \qquad (1)$$

In spite of the relatively high level of damping of the elastomer, the creep rates were acceptably low: ~ 10% increase in deformation per 10-fold increase in time both for testpieces in simple shear and for whole bearings in compression. In contrast, the creep rate predicted from the damping using linear viscoelastic theory was much higher: ~ 33% (Coveney et al 1993). The discrepancy in the predicted and measured creep rates highlighted the limitations of viscoelastic theory for describing the behaviour of heavily-filled elastomers. The triboelastic family of models offers a possible approach to describing earthquake base isolation bearings both in terms of their overall behaviour and in terms of Finite Element Analysis of them (Turner 1988, Coveney et al 1995, Ackerman et al 1997); others have adopted a rule-based method (Ahmadi and Muhr 1996).

3 THE TEST BUILDINGS

Two test buildings, one conventionally designed and the other base-isolated, have been constructed side by side at Tohuko University in Sendai, northern Japan. The test buildings were full-size, three-story, reinforced concrete, rigid frame structures. The dimensions and construction details of the superstructure were exactly the same for both buildings. The buildings were constructed as rigid frame structures with outer walls made of lightweight concrete panels. Each building was 6m by 10m (in plan) by 9m high (9.9m including a roof parapet) with an above-ground mass of 234 tonnes.

One building had a normal foundation at basement level. The second building, designed for base isolation, had a space around its entire sub-structure to allow unrestricted movement of the building during earthquakes and was supported by 6 isolation bearings. One bearing was situated under each corner of the building and one under each of the long sides. The test buildings were completed in May 1986. Each test building was heavily instrumented with 23 horizontal and 14 vertical acclerometers, 2 horizontal displacement transducers and a thermometer.

The soil under the buildings was hard loam soil that had a shear wave velocity of 310 m/s. A site predominant frequency of 4 Hz was obtained from micro-tremor observations. Examples of ground acceleration records are shown in Figure 4 and a summary of the performances of the isolated and non-isolated buildings is shown in Figure 5 (Coveney et al, 1993).

4 MODELLING THE BEHAVIOUR OF THE BUILDINGS SUBJECTED TO EARTHQUAKE BASE EXCITATION

Base isolation using high damping (highly filled) rubber (HDR) bearings has become a widely accepted method for earthquake protection of key buildings. However, because HDR bearings are much stiffer when subjected to small deformations than when subjected to large, performance during relatively small (but frequent) tremors can be problematic; there is a risk that base "isolation" systems may actually increase the response of the building to such seismic events. As has been previously reported, peak accelerations experienced by the Sendai building isolated by the soft HDR bearings were ~ 1/4 of the levels experienced by the, otherwise identical, non-isolated structure during small tremors (Wang et al 1993) as shown in Figure 5. Mathematical modelling of the behaviour of the non-isolated and isolated buildings has also been previously described - for which the bearings were modelled by means of a bilinear force-displacement relationship; an acceptable degree of agreement was obtained between model and experiment (Wang et al 1993). A bilinear model, rather than a viscoelastic model for example, was used in order to represent, in a simple way, the relatively rate independent damped behaviour of elastomeric materials such as HDR. The current work is directed towards examining the possibility of using a triboelastic model to represent the bearings to improve mathematical modelling further (Turner 1988, Coveney et al 1995, Ackerman et al 1997). As a first step a small testpiece of soft HDR has been subjected to deformation histories representative of those experienced in small earthquakes and the force responses compared with those predicted by a triboelastic model.

In order to obtain representative earthquake deformation histories, a structure was considered with the same mass (m) as the Sendai building (234.5×10^3 kg) supported on a (Kelvin model) linear viscous isolation system with a combined (horizontal) stiffness (k) of 2.31×10^6 N/m and damping coefficient (c) of 147×10^3 Ns/m, giving a natural frequency (f_0) of 0.5 Hz and a damping ratio (ζ) of 0.1. Measured ground acceleration histories (Fig 4) were integrated twice with respect to time and the resulting displacement history applied to the base of the idealised single-degree-of-freedom system; the corresponding deformations experienced by the idealised isolation system were then calculated.

5 MODELLING OF THE ELASTOMER

The standard triboelastic solid (STS) was used to model the behaviour of the soft high damping natural rubber (HDR) vulcanisate (Turner 1988, Coveney et al 1995, Ackerman et al (1997) and Fig 6). For a double shear testpiece of area 10^3 mm^2 and thickness 6 mm, the STS constant k_0 was set to a high value (10×10^6 N/m) and the other model constants were fitted to (normalised) dynamic stiffness (weighting of 2) and loss angle (weighting of 1) data (of 1990) for strain amplitude (γ_a) of 0.05, 0.1, 0.2, 0.3 and 0.5 (Fig 2); the following values were obtained: $k_1 = 60.2 \times 10^3$ N/m, $C_T = 1.69 \times 10^6$ N^2/m.

6 RESULTS AND DISCUSSION

A double shear testpiece (25.4 mm diameter and 6 mm thickness) of the soft HDR vulcanisate was subjected to (scaled versions of) the deformation histories described in 4. The (3 parameter) first-order triboelastic model (STS) was subjected to the same deformation histories. Experimental results and model predictions are compared in Figures 7-10; it can be seen that the model produced force histories which were similar in overall pattern to those obtained experimentally. The experimental force values were, however, higher by ~15%; the dynamic moduli (G*) of the HDR vulcanisate were then remeasured; values ~15% higher than the 1990 data were obtained, accounting for the discrepancy (Fig 11). It should be emphasised, however, that the range of shear strains studied was limited. Furthermore the 3 parameter STS model is unlikely to be suitable for modelling behaviour at shear strains significantly higher than 100%.

7 CONCLUSIONS

A, previously reported, study involving two near-identical buildings - one with a conventional foundation the other supported on elastomeric earthquake isolation bearings - has clearly demonstrated the advantage of earthquake isolation during earth tremors. Work to simulate the behaviour of buildings during earthquakes using FEA has been referred to. Work to simulate the behaviour of an experimental soft high damping natural rubber (HDR, used in earthquake isolation bearings) by means of a standard triboelastic solid (STS) model has proved successful over the range of shear strains studied. It appears that the properties of the HDR vulcanisate may have changed a little over the course of 7 years. It is anticipated that accurate modelling at shear strains significantly higher than 100% would require modifications to the STS model, but that such modifications would be relatively straightforward.

ACKNOWLEDGEMENTS

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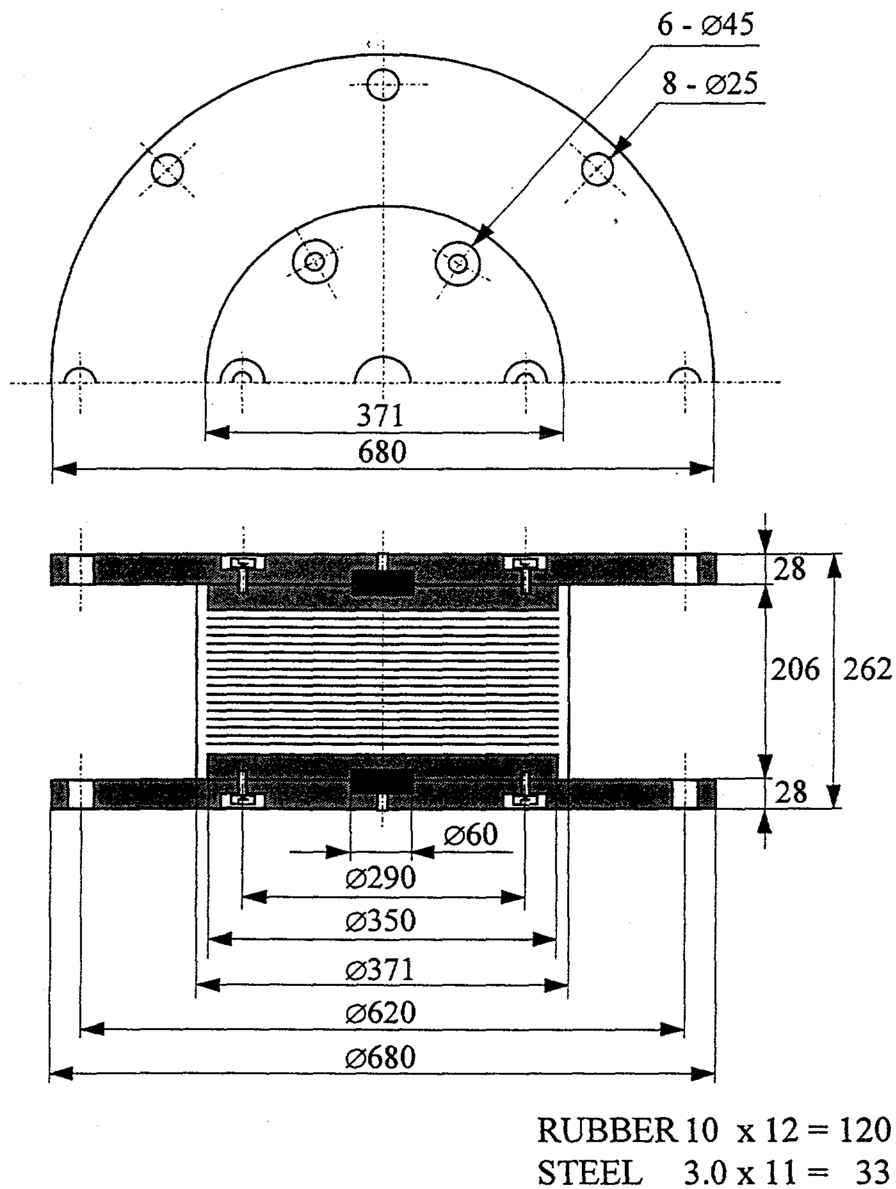


Fig 1 Soft bearing dimensions (unit: mm)

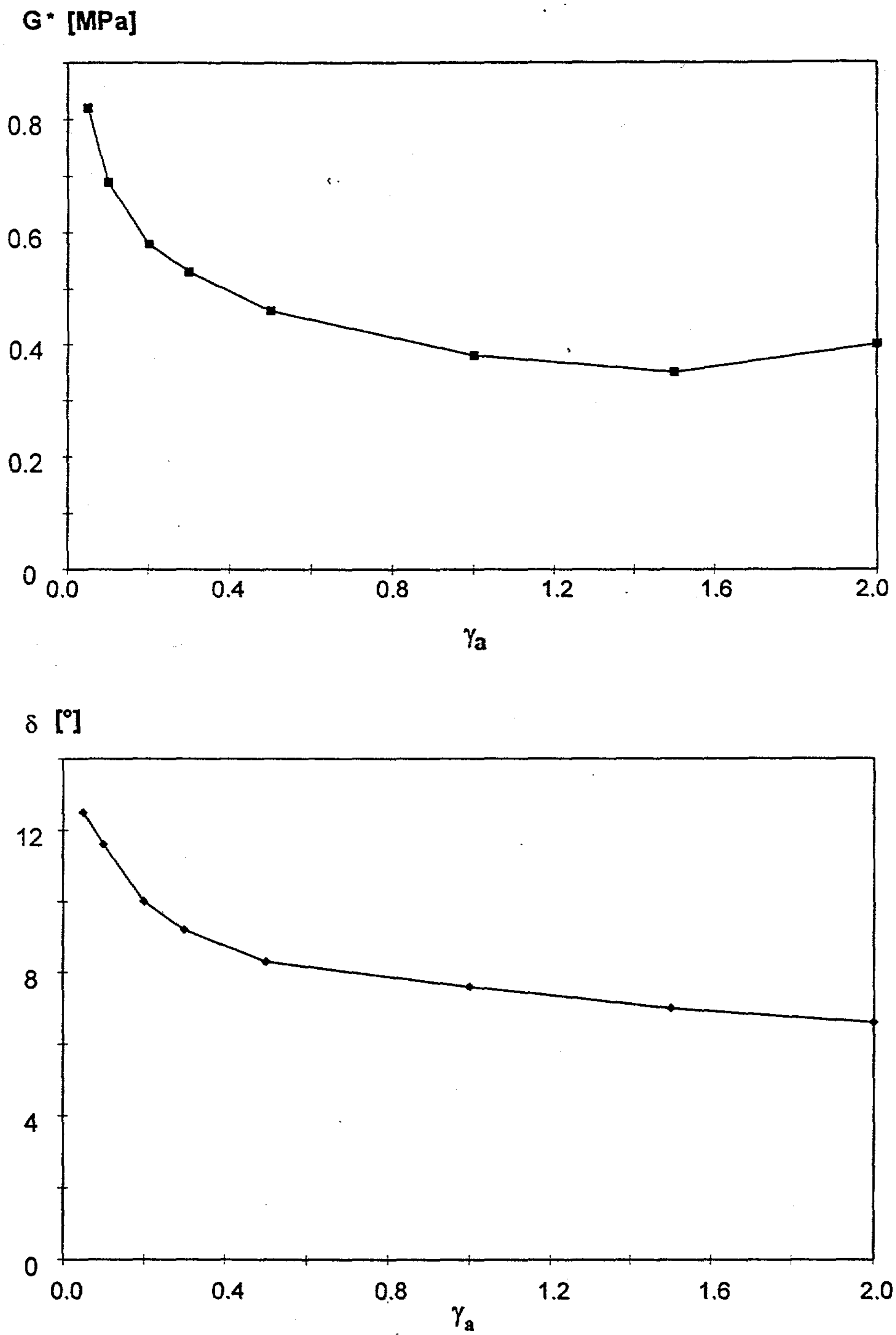


Fig 2 Dynamic simple shear modulus (G^*) and loss angle (δ), at 0.5 Hz, for fundamental Fourier component of force against strain amplitude (γ_a) for low modulus high damping NR-based elastomer (1990 data).

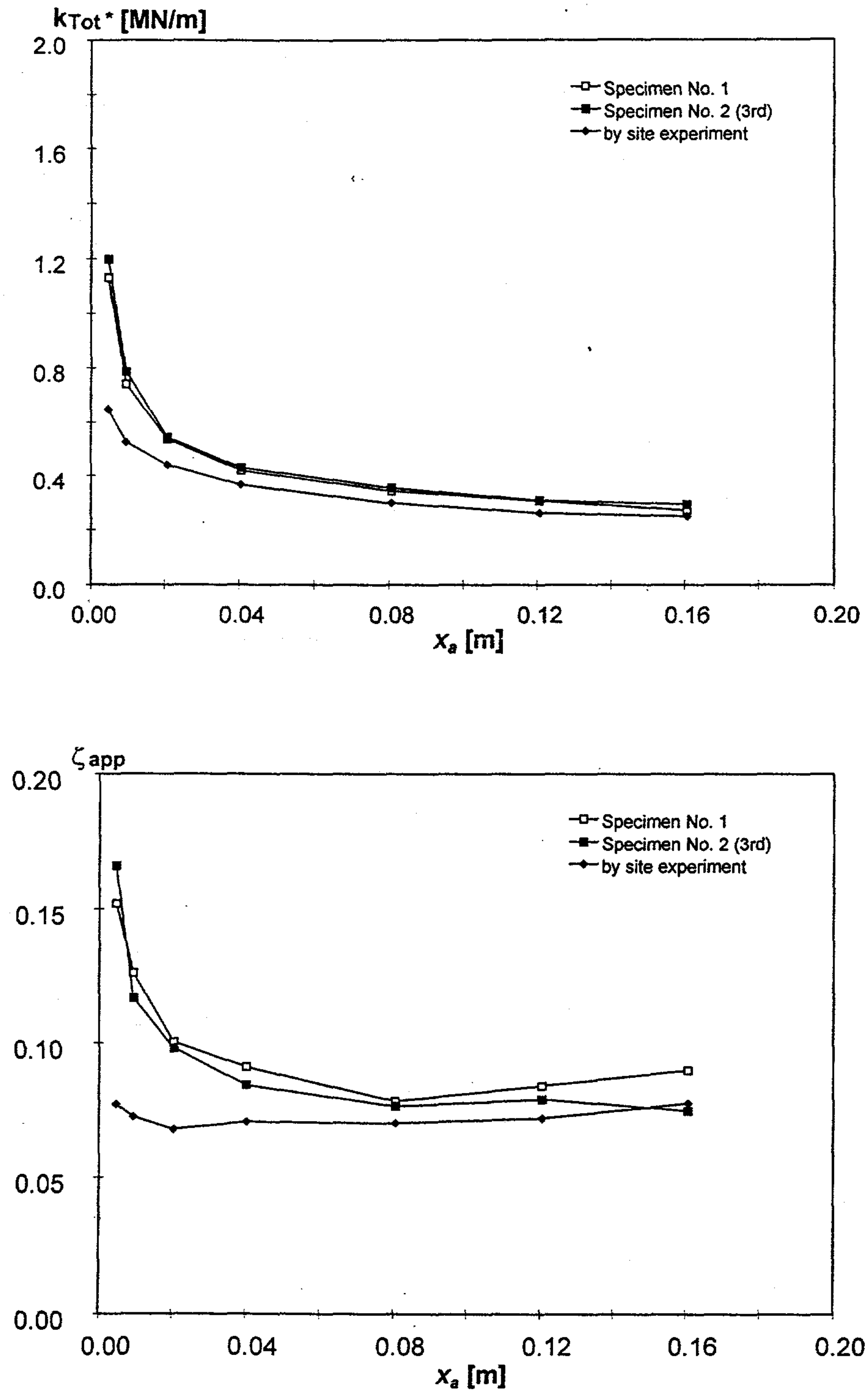


Fig 3 Dynamic stiffness (k_{Tot}) and approximate damping ratio (ζ_{app}) against displacement amplitude (x_a) for low modulus high damping earthquake base isolation bearings

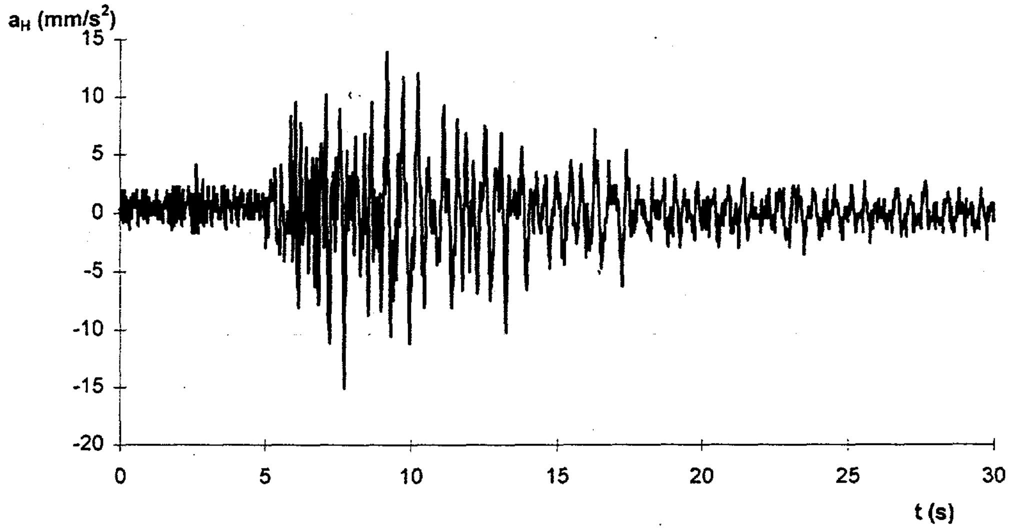


Fig 4 (a) Horizontal ground acceleration (a_H) against-time (t): longitudinal direction (EQ44)

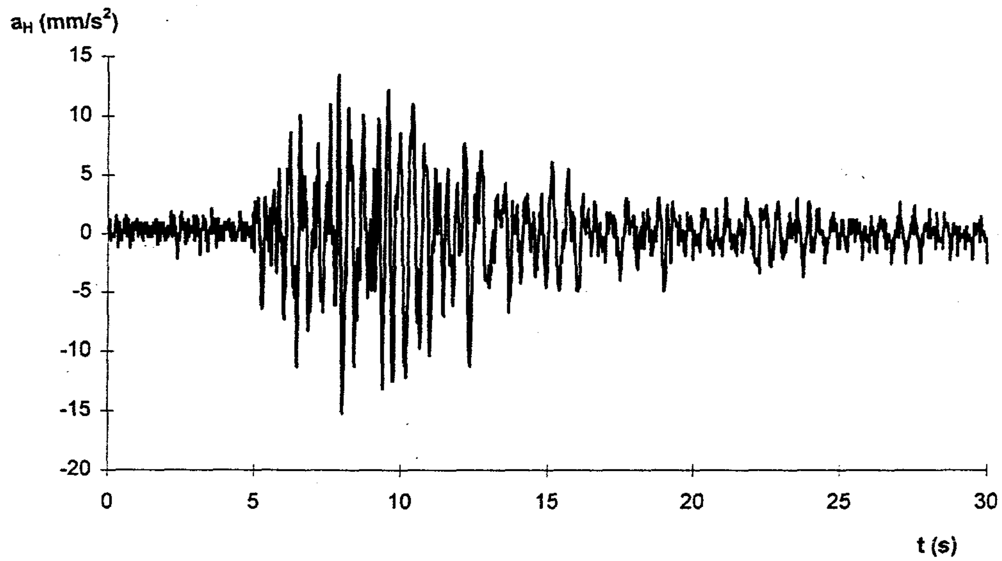
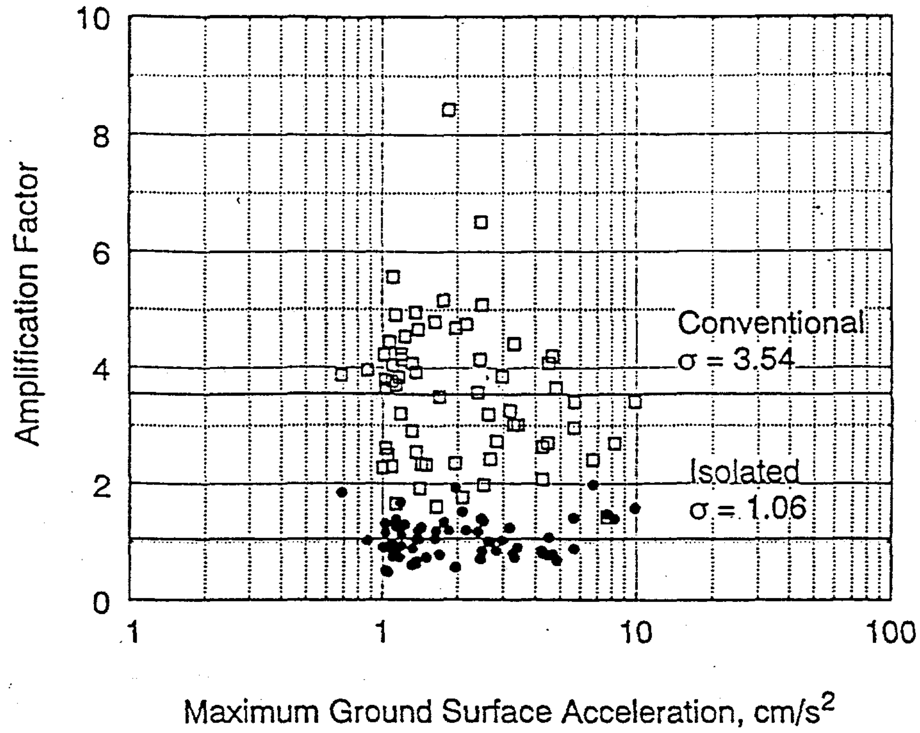
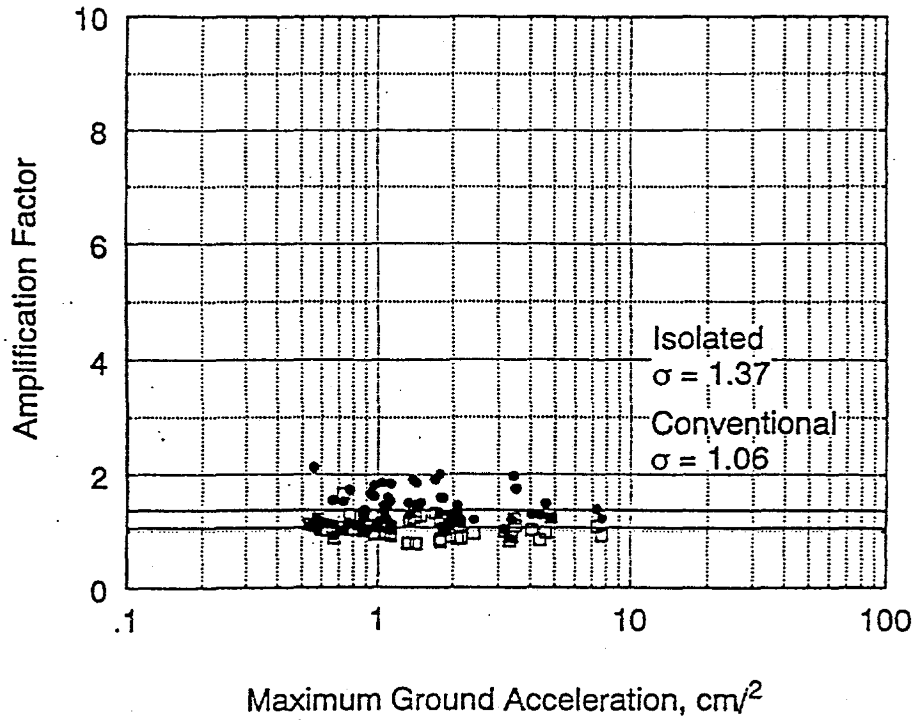


Fig 4 (b) Horizontal ground acceleration (a_H) against time (t): transverse direction (EQ44)



(a) Horizontal (longitudinal)



(b) Vertical

Fig 5 Comparison of peak accelerations for isolated and non-isolated (conventional) Sendai buildings

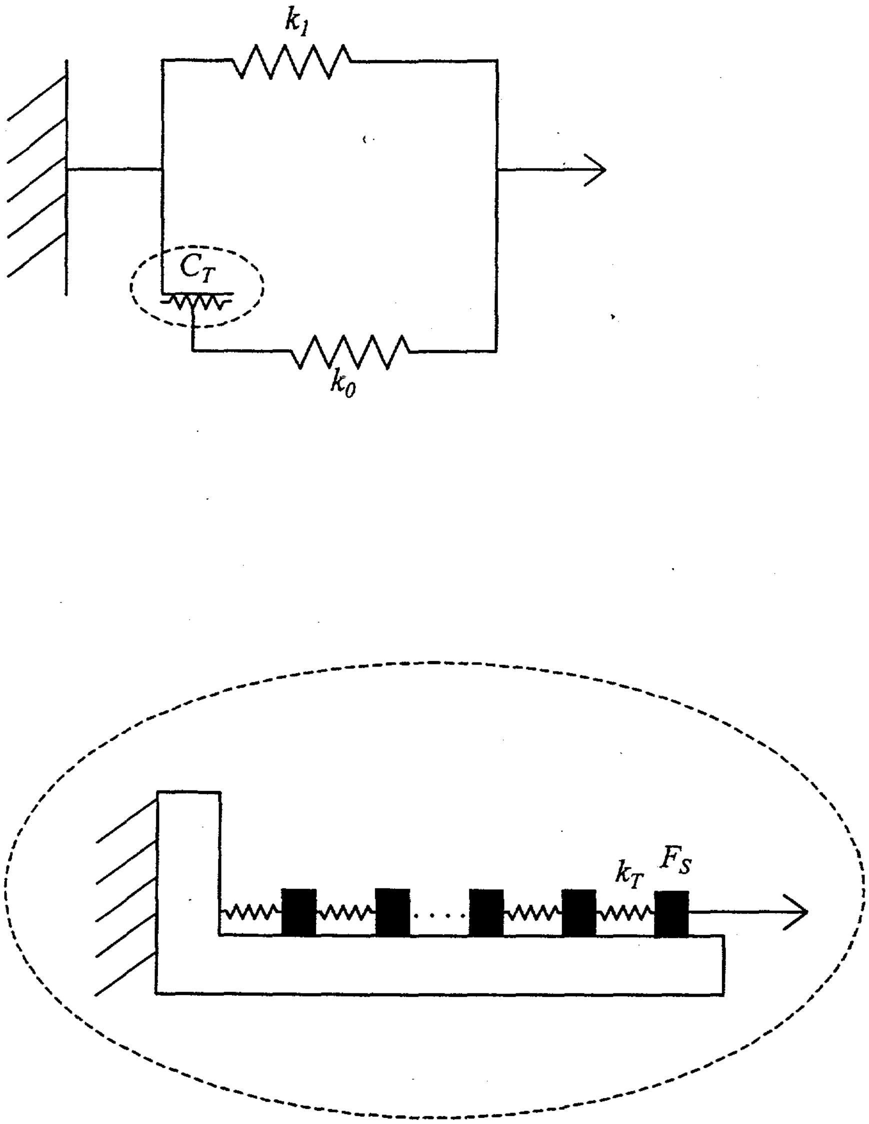


Fig 6 Standard triboelastic solid

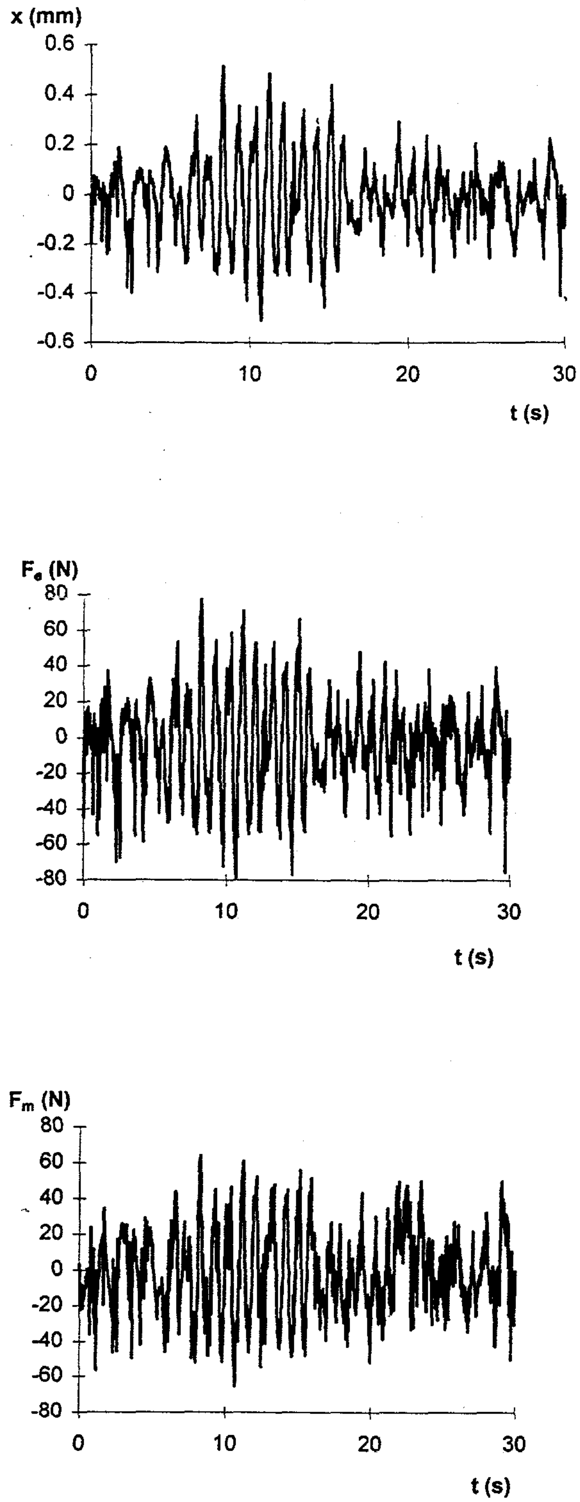


Fig 7 Applied displacement history (x), longitudinal (10%), experimental (F_e) and model (F_m) force response for soft high damping natural rubber

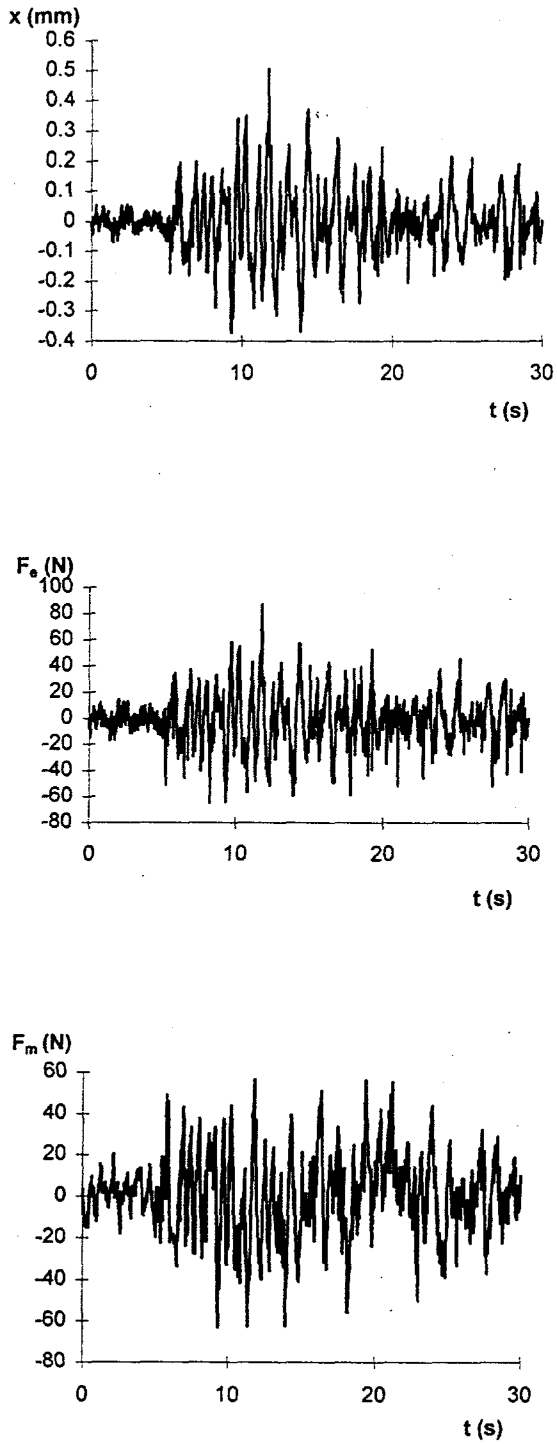


Fig 8 Applied displacement history (x), transverse (10%), experimental (F_e) and model (F_m) force response for soft high damping natural rubber

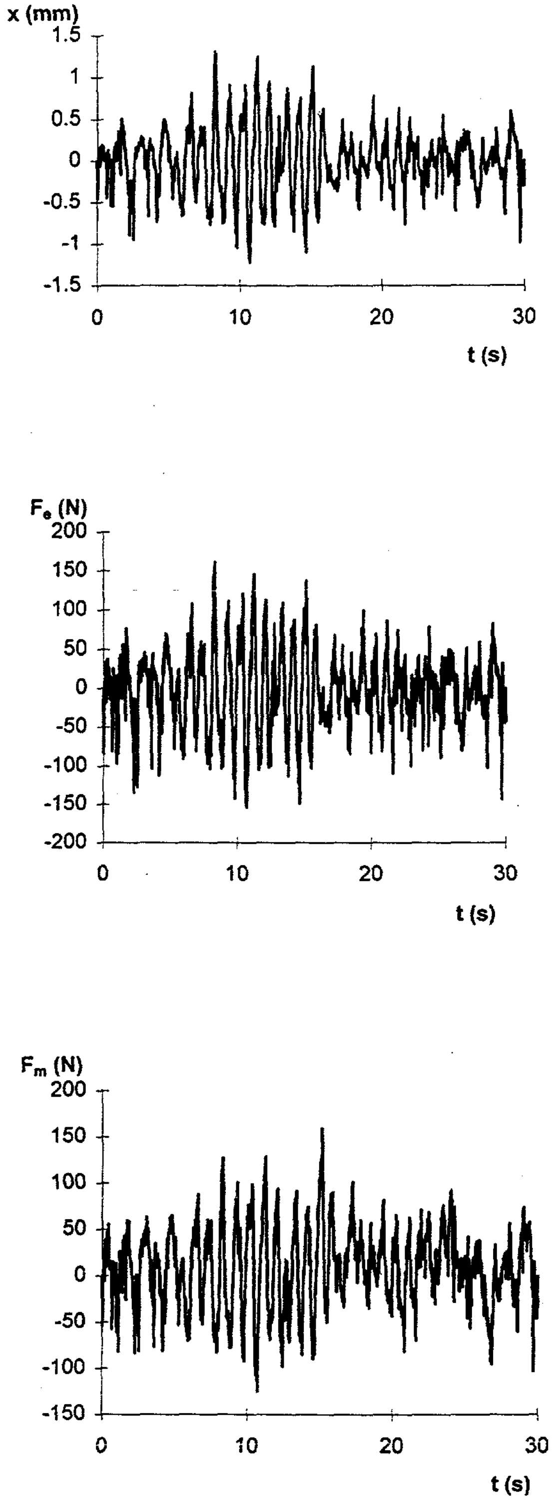


Fig 9 Applied displacement history (x), longitudinal (25%), experimental (F_e) and model (F_m) force response for soft high damping natural rubber

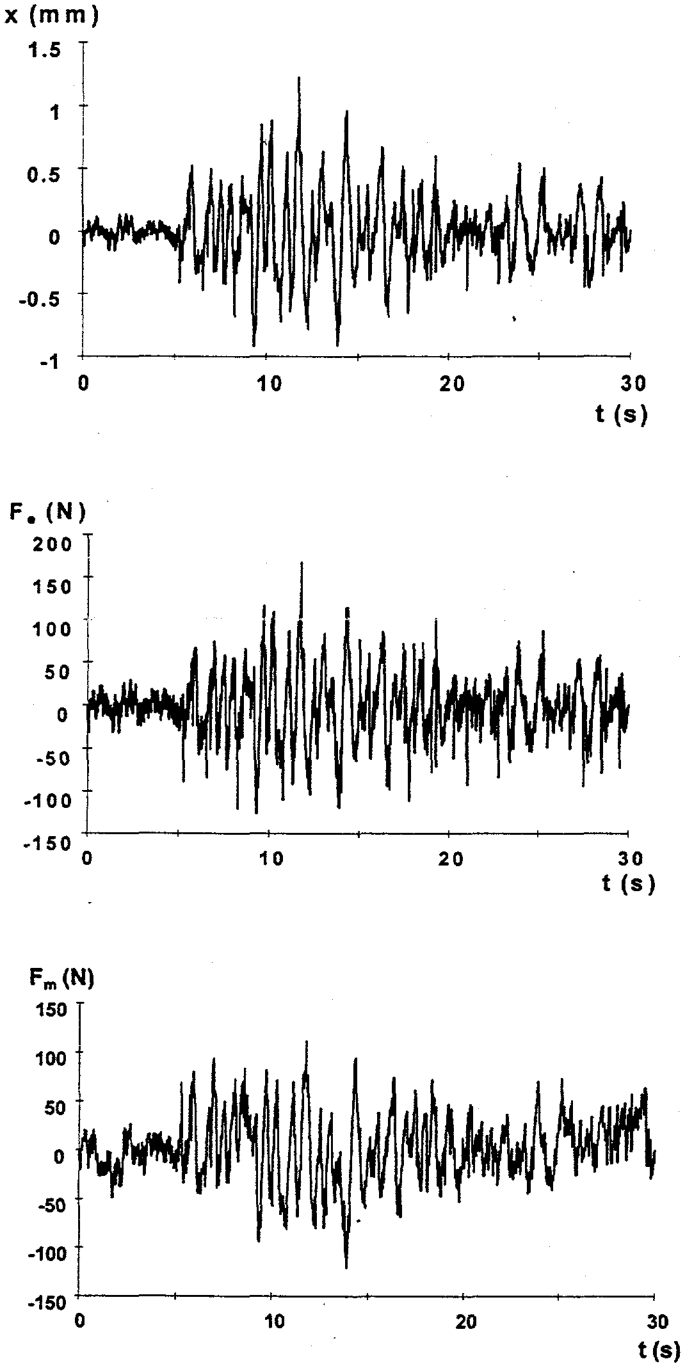


Fig 10 Applied displacement history (x), transverse (25%), experimental (F_e) and model (F_m) force response for soft high damping natural rubber

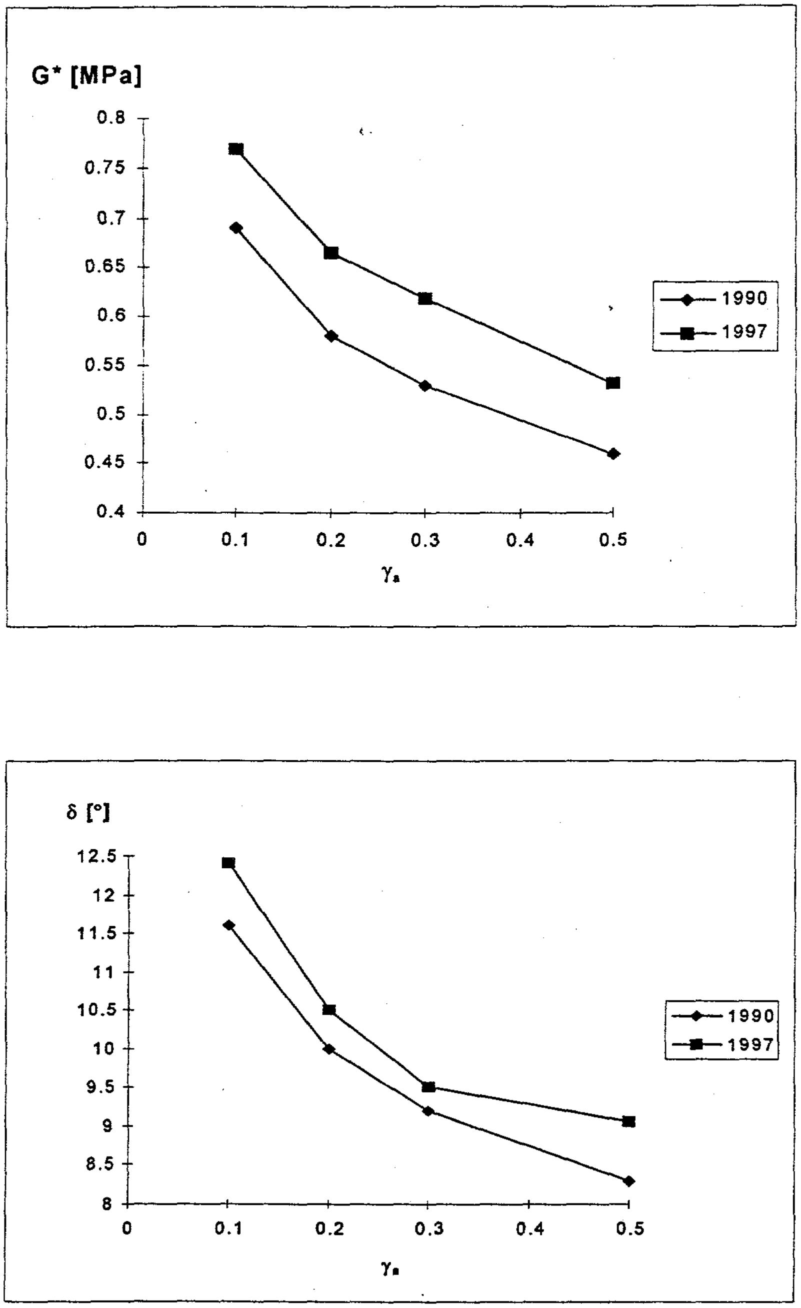


Fig 11 Dynamic simple shear modulus (G*) and loss angle (δ), at 0.5 Hz, for fundamental Fourier component of force against strain amplitude (γ_a) for low modulus high damping NR-based elastomer (1990 and 1997 data)