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ISOLATION OF LIGHT STRUCTURES WITH ROLLING-BALL RUBBER-LAYER SYSTEM - CHARACTERISTICS AND PERFORMANCE

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ABSTRACT

The characteristics of the Rolling-Ball Rubber-Layer (RBRL) seismic isolation system are presented through results for force versus displacement, covering a range of amplitudes and varying sinusoidally with time, and through results for the acceleration and drift of the upper slab of an isolated model SDOF superstructure subjected to seismic excitations.

It is shown how these characteristics may be described approximately by equivalent linear viscoelastic parameters $K^{/}$ and $K^{//}$, or alternatively K^{*} and δ, these being functions of frequency and amplitude. This may be thought of as a frequency-domain approach. Alternatively, they may be described approximately using a non-linear time domain model, and two alternative ones are assessed here. The first has been presented previously, and a new one is presented for the first time. An objective way of comparing the accuracy of such time domain models is to compare the equivalent linear viscoelastic parameters extracted from their predictions for sinusoidal excitations, and this reveals that the new model agrees considerably better with the directly measured behaviour of the actual system.

The system is very versatile, a great range of equivalent natural frequencies and coefficients of damping being achievable through the independent choice of rubber spring and rubber rolling track layer. It is suitable for isolating light structures, and much more effective at low excitations than an equivalent sliding system would be.

INTRODUCTION

Since laminated rubber bearings are appropriate only for isolation of more massive structures, a rolling-ball rubber-layer isolation (RBRL) system was developed at TARRC to enable isolation of low-mass structures. The system comprises RBRL bearings and rubber recentering springs; these may be combined in single packages as shown in Fig.1.

Extensive experimental studies of this system have been undertaken by TARRC and collaborating research centres (Table.1), resulting in four publications on shaking table tests and two more publications restricted to laboratory characterisation of the system itself. The systems studied were diverse, involving different design natural frequencies and levels of damping.

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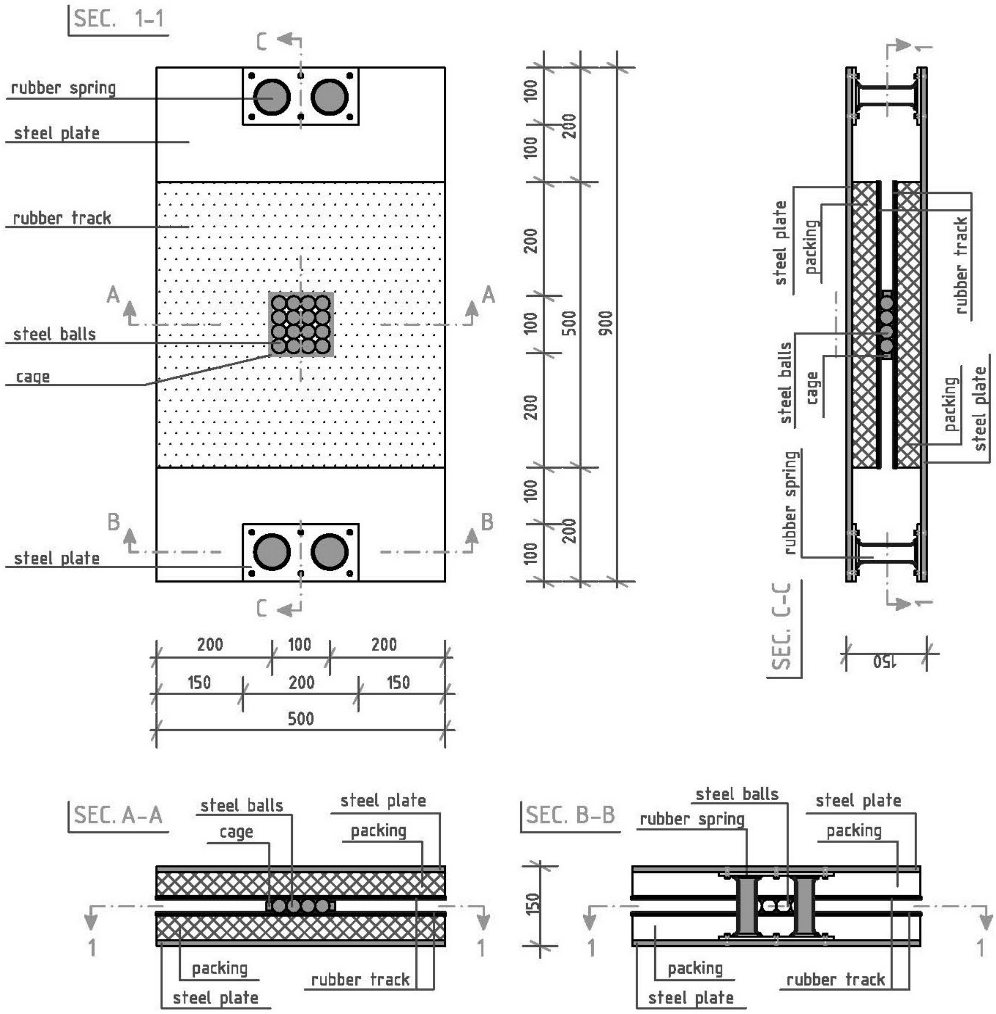


Figure 1 Combined package of RBRL bearing and recentering springs as used for REEDS and ECOEST projects

Table 1. Summary of studies done by TARRC and collaborating research centres on RBRL device

Project / Publication	**Type of tests**	**Tracks**	**Springs**	**Superstructure**
INCLUDING SHAKING TABLE TESTS				
EERC (Foti and Kelly, 1996)	monoaxial	high damping, Jakarta compound (Lab Rep 96. Compound 009-06)	steel coil, soft	flexible - model building
ENEL/ISMES/TARRC collaboration (Muhr and Bergamo, 2010)	monoaxial	high damping, probably the same of EERC	steel coil, soft	rigid - concrete slab
REEDS (Bettinali et al., 2001)	triaxial	low damping A, inside ϕ of 190 mm, high damping B outside (ball array $\phi \sim 190$mm)	rubber B, stiff (1.3Hz)	flexible - electrical substation structure
ECOEST (Guerreiro et al., 2007)	monoaxial biaxial and triaxial	low damping A, both or upper, high damping B, lower	rubber A, soft and none	rigid or flexible model building
LABORATORY BASED STUDIES				
DEGREE PROJECT (Cook et al., 1997)	monoaxial	unfilled NBR	none	none
PhD PROJECT (Muhr et al., 1997)	monoaxial	unfilled NR (two levels of curatives) and NBR	none	None

Large amounts of data were gathered, most notably on the ECOEST project, and only a summary of the findings with a few highlights has so far appeared in the literature.

In this paper further analyses of the results of the ECOEST project are presented in order to more clearly establish the behaviour of the system. An additional objective is to derive a generalised numerical description of the characteristics of the system. A model is a prerequisite for the prediction of the system behaviour, and hence necessary to quantify the efficacy of the system for seismic mitigation and achieve design objectives. Since there is considerable uncertainty regarding both the actual strong motion and the response behaviour of the structure to be protected, the need is for a robust model that is easy to fit to the measured characteristics of the system and to implement numerically, and that captures the essence of behaviour, rather than for a very elaborate model that captures every detail. We shall restrict attention here to uniaxial behaviour.

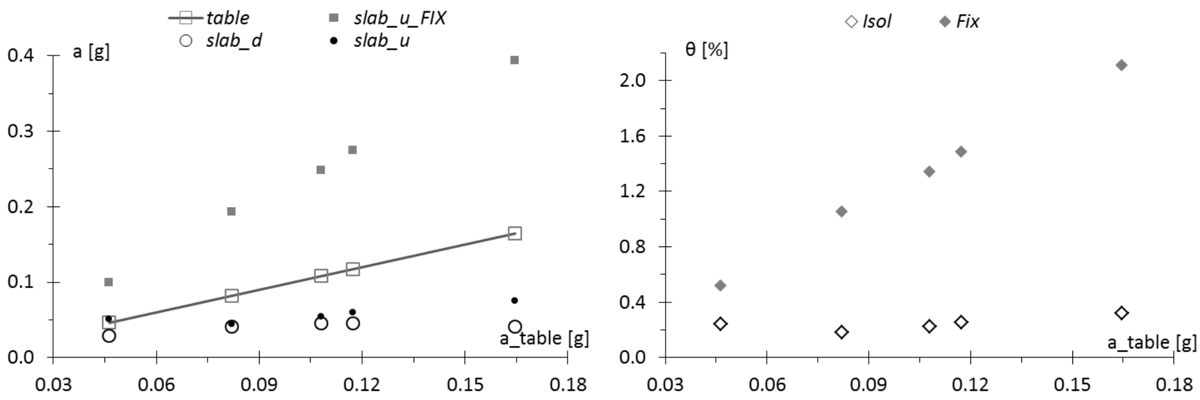
The state of the art about modelling of RBRL is limited to only two papers, by Guerreiro et al. (2007) and Muhr and Bergamo (2010). The second paper presents the equivalent linear viscoelastic parameters for very small horizontal deflections of the device, while in the first of these papers a possible specific mathematical model is given. Some considerations about this model, positive aspects and weaknesses, will be presented.

BEHAVIOUR FOR SMALL EXCITATIONS: COMPARISON OF RBRL AND SLIDING ISOLATION SYSTEMS

The model superstructure in the ECOEST project (Guerreiro et al., 2007) consisted of two concrete slabs which could either be clamped together (mass down configuration) or separated by four M16 studs 500 mm long, to give a first mode fixed base response at ~2.5 Hz (mass up configuration).

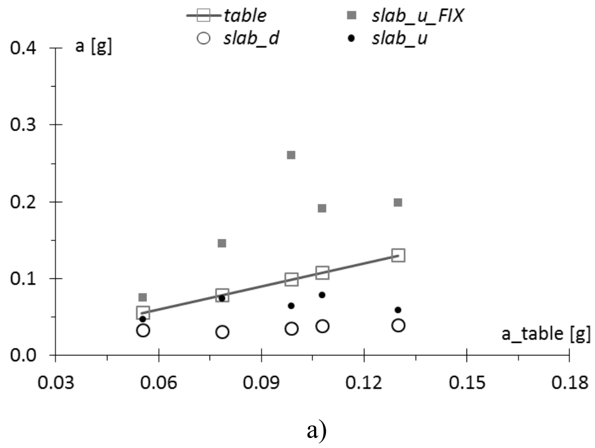
ECOEST data for the "mass-up" configuration isolated on the RBRL system, subjected to a range of time histories, for peak accelerations of the shaking table, lower and upper slab, and for the drift between the slabs, were compared to results from OpenSees simulations of the "fixed-base" case. The time histories were truncated in this exercise such that steady-state rolling of the balls did not occur, but they merely rocked in the "pits" formed in the rubber tracks due to creep in the rubber for the period under static load. The maximum displacement of the lower mass relative to the table for this to be so was taken in this exercise to be 5 mm. The measured table accelerations were used in the Opensees simulations, rather than the command time histories, to make the comparison as close as possible. The fixed-base case represents also the behaviour of a sliding isolation system, for excitations insufficient to overcome the static friction.

The earthquakes considered were: EC8(02), EC8(05), Faial, NorthridgePCKC and Tolmezzo. Figs.2-3 show the results only for the last two of these real accelerograms, which are scaled to get a range of peak ground accelerations (PGA), but for all the earthquakes analysed the conclusions are the



a) b)

Figure 2. a) Slab down("*d*")-up("*u*") accelerations *a[g]* and b) drifts *θ [%]* between the two slabs versus peak table acceleration from ECOEST results, for the isolated-base case, compared with the simulated fixed-base case ("*Fix*") (≈ sliding isolator for small seismic intensity), for NorthridgePCKC different-scaled earthquakes



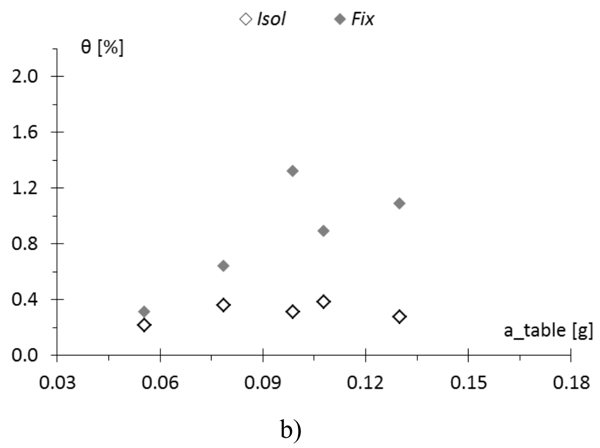


Figure 3. a) Slab down("*d*")-up("*u*") accelerations *a[g]* and b) drifts *θ [%]* between the two slabs versus peak table acceleration from ECOEST results, for the isolated-base case, compared with the simulated fixed-base case ("*Fix*") (≈ sliding isolator for small seismic intensity), for Tolmezzo different-scaled earthquakes

same: the compliance and damping at small excitations has the great advantage of both changing the mode shape and suppressing excitation of the vibration modes of the isolated structure even for small seismic intensities, in contrast to the case of sliding bearings below their threshold force.

DESCRIPTION OF THE RBRL SYSTEM USING EQUIVALENT LINEAR VISCOELASTIC PARAMETERS ($K^{/}$ $K^{//}$)

The force-deflection behaviour of the RBRL system is controlled by rubber properties, either through the rubber springs, which predominantly provide the restoring force, or through the rubber layers on the tracks, which provide energy dissipation but also, for small oscillations, contribute to the restoring force. The resulting overall behaviour is thus non linear and originates from viscoelasticity, so it is natural to consider a description in terms of equivalent linearised viscoelastic parameters.

The viscoelastic parameters we shall use are the storage and loss stiffnesses, $K^{/}$ and $K^{//}$, respectively, defined as the in- and out-of-phase amplitudes of steady-state harmonic force required to impose a harmonic displacement of unit amplitude:

$$\begin{aligned} x(t) &= \tilde{x} \cdot \sin(\omega t) \\ f(t) &= \tilde{x} \cdot (K^{/} \sin(\omega t) + K^{//} \cos(\omega t)) \end{aligned} \tag{1}$$

Sometimes the complex stiffness $K^{*} = \sqrt{K^{/2} + K^{//2}}$ and loss factor $\tan\delta = K^{//} / K^{/}$ are used instead.

If we consider a Kelvin model (spring k and dashpot c in parallel) then we have:

$$\begin{aligned} x(t) &= \tilde{x} \cdot \sin(\omega t) \\ f(t) &= \tilde{x} \cdot (k \sin(\omega t) + c\omega \cos(\omega t)) \end{aligned} \tag{2}$$

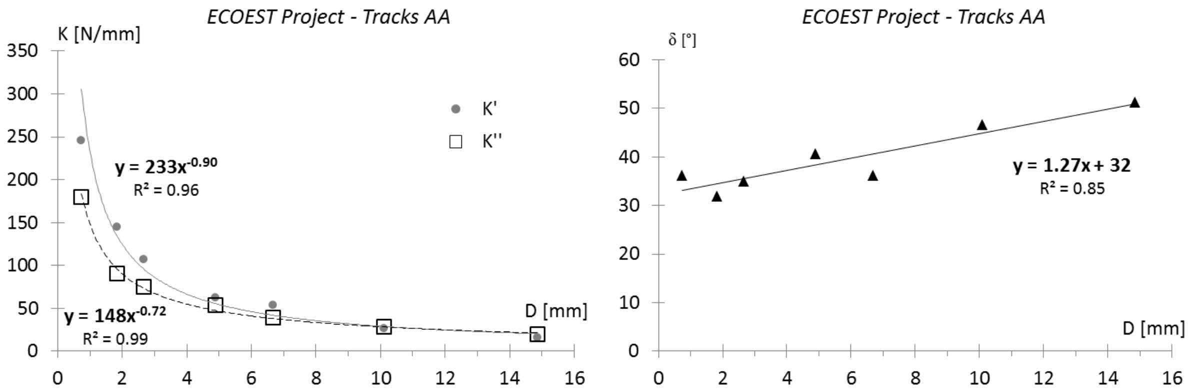
so it is apparent that $k \equiv K^{/}$ and $c \equiv K^{//}/\omega$. This implies that if $K^{/}$ and $K^{//}$ are independent of frequency then the equivalent Kelvin parameter c is inversely proportional to frequency. For a typical rubber a better approximation of the behaviour is found to be that $K^{/}$ and $K^{//}$ are both linearly dependent on $\ln(\omega)$, so that they do have a weak frequency dependence which may be neglected for limited ranges. We shall refer to the frequency ω_{ch} at which $K^{/}$ and $K^{//}$ are measured as the characterisation frequency, and the frequency ω at which (say) the Kelvin model is used to be the application frequency. The coefficient of critical damping of a mass m mounted on a Kelvin model is:

$$\zeta = \frac{c}{2m\nu} \equiv \frac{1}{2}\tan\delta \frac{\nu}{\omega} \quad \text{where} \quad \nu = \sqrt{k/m} \quad \text{is the undamped natural frequency} \tag{3}$$

Seismic isolation systems are generally excited at their natural frequency, so we have $\zeta \approx 1/2 \cdot \tan\delta$ and, for an equivalent Kelvin model for an isolation system, $c = \tan\delta \cdot K' / \nu$.

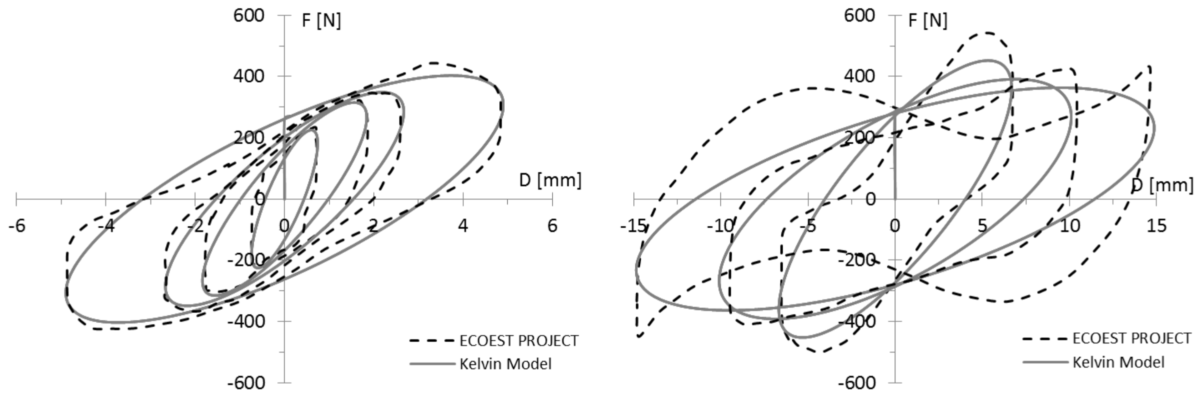
Calculation methods for the equivalent viscoelastic parameters have been presented by Ahmadi and Muhr (1997). Here, the Harmonic Method is used, which corresponds to calculation of the Fourier components of the periodic force at the fundamental frequency ω. The parameters may be converted to the equivalent Kelvin model, if a time domain model is needed, provided the frequencies of the responses to be predicted are within a factor of 10 or so of that at which K' and K'' were characterised. A more sophisticated viscoelastic model consisting of a spectrum of Maxwell elements is required to capture the linear dependence of K' and K'' on $\ln(\omega)$, as discussed for example by Ahmadi and Muhr (2008; 2011).

Results for K' and K'' for tests on the rolling tracks AA obtained performing shaking table tests at 5 Hz on a rigid mass placed on the RBRL isolators with the recentering springs, in the ECOEST project, are given in Fig.4. It is evident that the parameters depend on the amplitude of motion, showing the properties are non-linear, despite the equivalent linearization. This, however, does not prevent the parameters being useful, as discussed by Ahmadi and Muhr (2011). Firstly, they can be used to provide a time-domain Kelvin model for seismic response; iterations are required in which the peak amplitude is predicted by the model, from which fresh values of K' and K'' can be calculated and hence the Kelvin model updated and rerun to update the prediction of amplitude. Convergence is usually found to be very rapid, e.g. only 2 or 3 iterations are required to reach a peak amplitude consistent with that used to determine K' and K''. Secondly, the equivalent viscoelastic parameters enable different non-linear time-domain models for the system to be compared quantitatively and objectively with the real behaviour, by comparing directly measured parameters with those extracted –



a) b)

Figure 4. Equivalent linear viscoelastic parameters obtained from ECOEST sinusoidal tests at 5Hz: a) K' K'', b) δ



a) b)

Figure 5. Force-displacement loops obtained for AA tracks during the ECOEST project and compared with equivalent linear viscoelastic representations a) amplitudes up to 5 mm b) amplitudes up to 15 mm

using the same Harmonic Method – from hysteresis loops simulated using the models. The parameters themselves correspond to representations of the hysteresis loops as ellipses, as illustrated in Fig.5. This figure compares results for force directly obtained from the mass acceleration using Newton's second law, plotted against the relative displacement measured across the isolation system, with loops plotted for a Kelvin representation of the equivalent viscoelastic parameters over a range of amplitudes.

GUERREIRO MODEL

The results from the ECOEST project were summarised by Guerreiro et al. (2007), and a time-domain model was presented to describe the 1D force-deflection behaviour, which for convenience we shall refer to as the Guerreiro model. The basis of the model is presented in Fig.6. It consists of a rubber spring, having a small degree of nonlinearity (Fig.6a), in parallel with a friction force (Fig.6b), characteristic of steady-state rolling and associated with all deflections, and a special behaviour for displacements from the initial state of reference less than 15 mm to capture the effect associated with indentations developed by the balls in the rubber track under static load (Fig.6c).

As shown by Guerreiro et al. (2007), the Guerreiro model gives reasonably good predictions of response in moderately large seismic events, for which the RBRL system experiences excursions large enough to involve steady-state rolling. Here we report a new comparison for the NorthridgePCKC earthquake. Fig.7 compares predictions of the model with results from the ECOEST

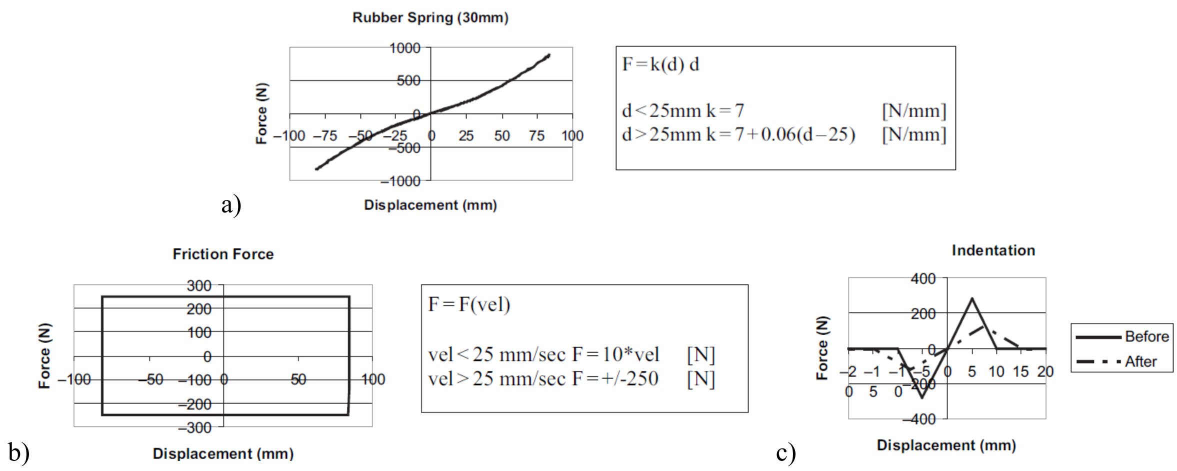


Figure 6. a) Rubber spring analytical model, b) track surface friction model, c) analytical model of the indentation effects, by Guerreiro et al. (2007).

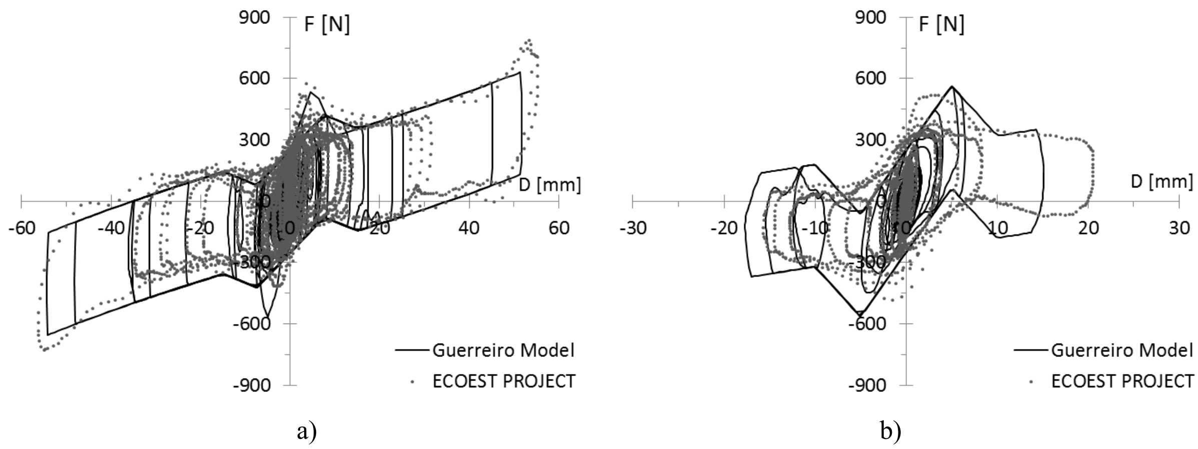


Figure 7. Comparison of directly measured and modelled force-displacement plots for NorthridgePCKC
a) 0 dB, b) −12 dB

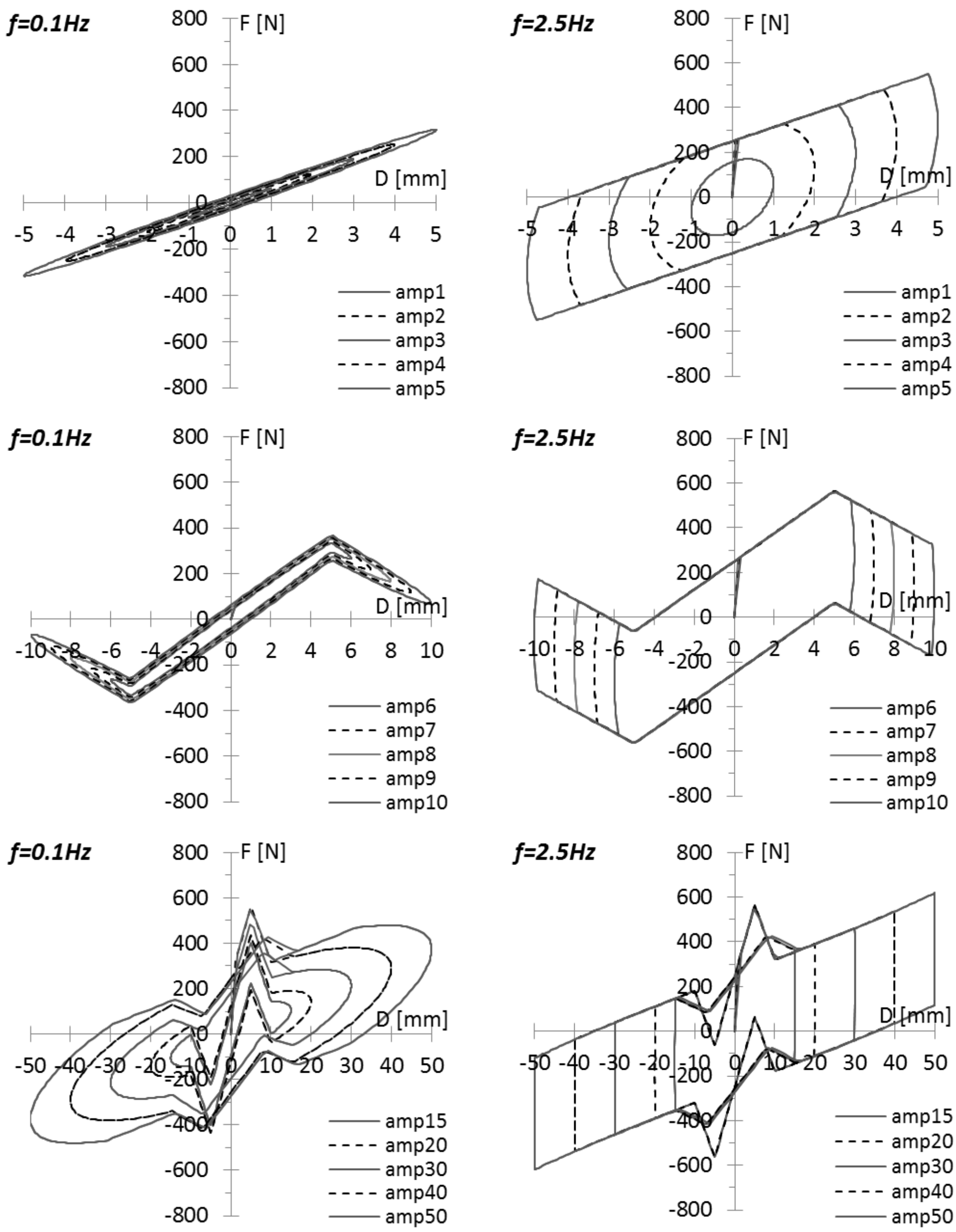


Figure 8. Force-displacement loops from the Guerreiro model for selected amplitudes and frequencies

project for the acceleration obtained for the case of isolated base: “mass-up” configuration (2 DOF) for the time histories NorthridgePCKC not scaled (0 dB) and scaled with (-12 dB). For Fig.7a the amplitude is generally relatively high and the model works well, but for Fig.7b amplitude is smaller and the model is less good.

To illustrate the performance of that model, a parametric sinusoidal analysis was performed, from which the values of the equivalent viscoelastic parameters were calculated. The analyses covered amplitudes from 1 mm to 20 mm, in steps of 1mm, and then up to 50 mm in steps of 5 mm, and the frequencies 0.1, 0.5, 1.0, 2.5 and 5.0 Hz. Fig.8 gives selected sinusoidal force-displacement loops obtained from the analyses and Fig.9 gives $K^{/}$ and $K^{//}$ values as functions of amplitude for all the amplitudes and frequencies analysed.

It is evident that there is a very high frequency dependence of the behaviour of the Guerreiro model for small amplitudes, substantially with regard to the dissipation of energy (see Fig.9b), which would not be expected to be the case for a system based on rubber. In addition, the shape of the loops at moderate amplitudes does not bear even much qualitative resemblance to the experimental loops, shown in Fig.5. We would like to emphasize that the most frequent earthquakes are characterized by a

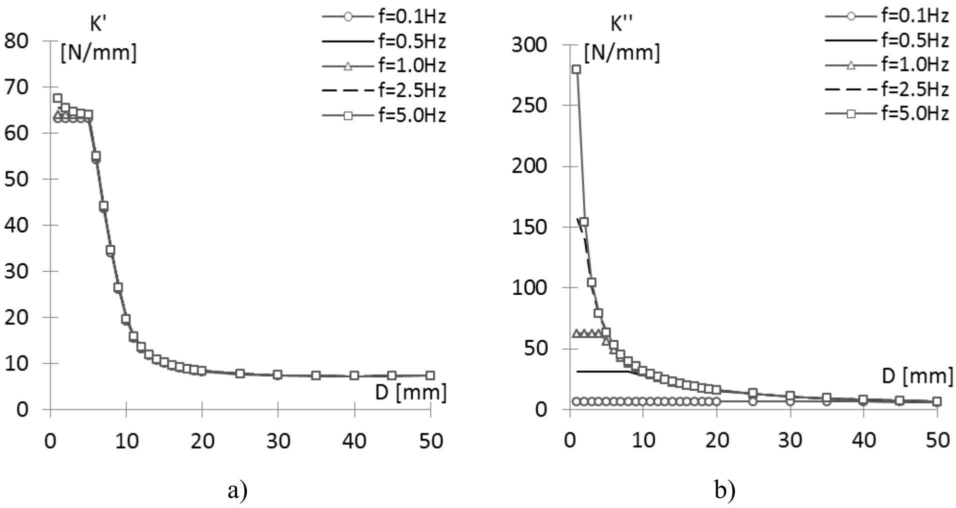


Figure 9. a) $K^{/}$, b) $K^{//}$ from the Guerreiro model for all the amplitudes and frequencies analysed

"small displacement response": so the design (SLU) spectra is not the only for which good performance of the anti-seismic device is required (at least for the protection of sensible lightweight structures, such as artefacts, statues and sensitive industrial or medical equipment).

Although the Guerreiro model works quite well for high amplitudes (see Fig.7a), it was decided to evolve a more realistic uniaxial model, to better capture the low and moderate amplitude behaviour, before attempting generalisation to the biaxial case. A new simpler and no-updating model could be also useful in the design process to speedily get the best isolation solution.

NEW UNIAXIAL MODEL FOR RBRL SYSTEM

The intention was to devise a model that would be efficient to program and to run in simulation software, hence ideally not involving any internal parameters that call for updating during analyses. The model uses a viscoelastic framework for describing the restoring force and energy dissipation in accord with their origins in rubber, and should ideally be straightforward to generalise in a natural way to the biaxial case. Fig.10 gives a schematic diagram of the model. A simple characteristic is provided for the rubber spring. The resistance to steady rolling over the rubber tracks is, as for the Guerreiro model, considered to be a constant force, and is introduced in series with the Kelvin model that represents the amplitude-dependent behaviour for small deflections, caused by the indentations formed by the balls in the rubber track due to the time under static load. Although this model is simple and does not call for updating of parameters, it has to be used iteratively for a time-history analysis to capture the real behaviour for small amplitudes. The value of the Kelvin model parameters (k_1, c_1) are changed in accord with the new values of $K^{/}$ and $K^{//}$ obtained by interpolating equations given in Fig.4a for the new amplitude value resulting from the previous run of the model.

The model is simple to calibrate, because the three behaviours - recentering spring, pit and steady-state rolling - are independently represented. The values of the equivalent viscoelastic parameters for the recentering rubber springs, $K^{/}_2 = 8$ Nmm^{-1} and $K^{//}_2 = 0.4$ Nmm^{-1}, and the fuse force, $f = 250$ N, are directly obtained by experimental results performed in the ECOEST project. The "f" (fuse) parameter could be obtained also from the theory about rolling friction coefficient for the rolling on a finite thickness layer of rubber (Muhr et al., 1997). "$K^{/}_1$" and "$K^{//}_1$", equivalent viscoelastic parameters for the behaviour in the pit, are obtained in accord with Eq.(4) considering that $K^{/}$ and $K^{//}$, from the ECOEST results reported before, are related to the global behaviour of the RBRL device together with the recentering rubber springs.

Once the equivalent viscoelastic parameters are known ($K^{/}_1$, $K^{//}_1$, $K^{/}_2$, $K^{//}_2$), the relative Kelvin parameters (k_1, c_1, k_2, c_2) are calculated through the relations given below Eq.(2).

$$\begin{aligned} K^{/}{}_1 &= K^{/} - K^{/}{}_2 \\ K^{//}{}_1 &= K^{//} - K^{//}{}_2 \end{aligned} \tag{4}$$

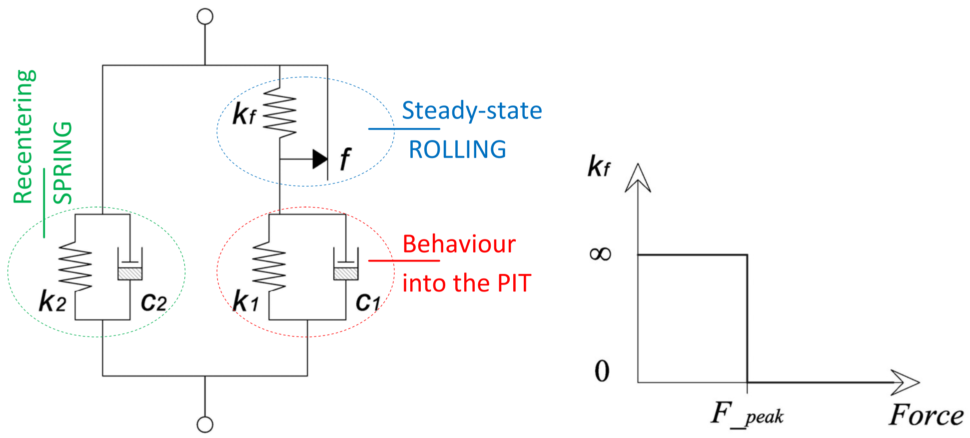


Figure 10. Authors' proposal for a new simple "no-updating" model

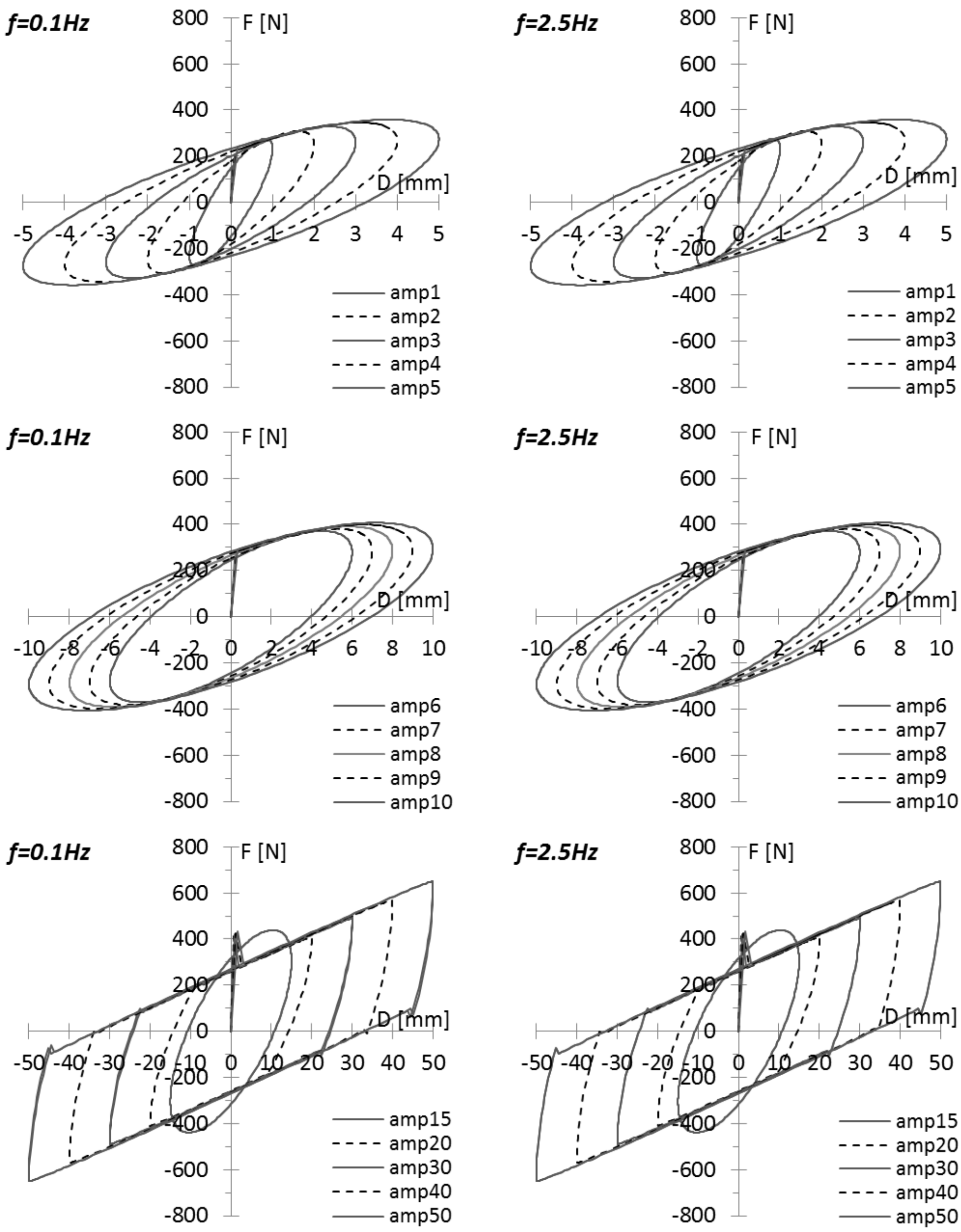


Figure 11. Force-displacement loops from the new model for selected amplitudes and frequencies

The "$F_{\_peak}$" value is the maximum force that can be absorbed by the Kelvin model representing the in-pit behaviour after which the fuse modelling the steady-state rolling is activated. The value of $F_{\_peak}$ = 400 N was opportunely assumed, from experimental results, to capture the change in the global model behaviour (from two Kelvin models in parallel to one Kelvin model in parallel with a fuse) during the transition phase of the RBRL device. To also simplify the model and ensure the model switches to the fuse behaviour for the relatively big amplitudes, the values of $K^{/}$ and $K^{//}$ calculated for an amplitude of 15 mm are assumed to also hold for amplitudes greater than 15 mm.

The same parametric sinusoidal analysis as performed for the Guerreiro model was performed for the new model, and is reported in Fig.11. The only assumption made is that the values of $K^{/}$ and $K^{//}$ are not significantly dependent on the frequency (or velocity), thus we used the equivalent viscoelastic parameters obtained by ECOEST results for 5 Hz (Fig.4a) for all the different frequencies analysed. This was confirmed by the new monoaxial-sinusoidal tests performed by the authors, presented and discussed in the next section.

The hysteresis loops, with this new model, seem more similar to the real ones for the small amplitudes (Fig.5).

Being a simple model, although it is able to represent the real behaviour for the small amplitudes and for the steady rolling with a sufficient approximation, it is not able to capture the return of the balls into the original indentations (as in Guerreiro model), or the complicated behaviour in the transition between the small strain behaviour and free rolling, but these features are of secondary importance and will be addressed in a future publication.

NEW CHARACTERISATION TESTS

The ECOEST characterisations of the system were limited to a separate test for the recentering springs done at TARRC, and sinusoidal accelerations of the mass-down configuration on AA tracks (together with the recentering springs) carried out on the ISMES shaking table at 5 Hz. It was decided to carry out more comprehensive monoaxial sinusoidal tests at TARRC on AA tracks for the current project. These tests (see Fig.12) were performed in single shear configuration for one RBRL device with no recentering springs, using both constant velocity and sinusoidal displacement excitations (Table.2). The parameters were:

- vertical load 150 kg
- number of steel balls 6 balls → 25 kg/ball (in ECOEST project: 23,8 kg/ball)
- time of dwelling before tests 24 hours
- type of rubber layers AA - BB

The rubber tracks used in this experimentation were moulded for ECOEST project (15 years ago).

From the force-displacement loops obtained by our tests, again through the Harmonic Method, we calculated the equivalent viscoelastic parameters, for the different velocity-inputs considered. These values are presented for both rubber types AA and BB in Fig.13: the assumption made before about the negligible velocity (frequency) dependency of $K^{/}$ and $K^{//}$ is confirmed.

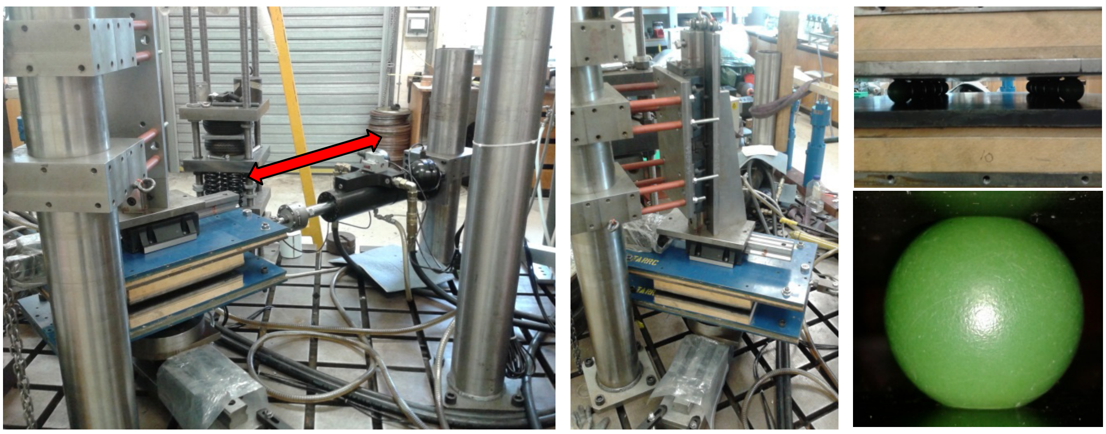
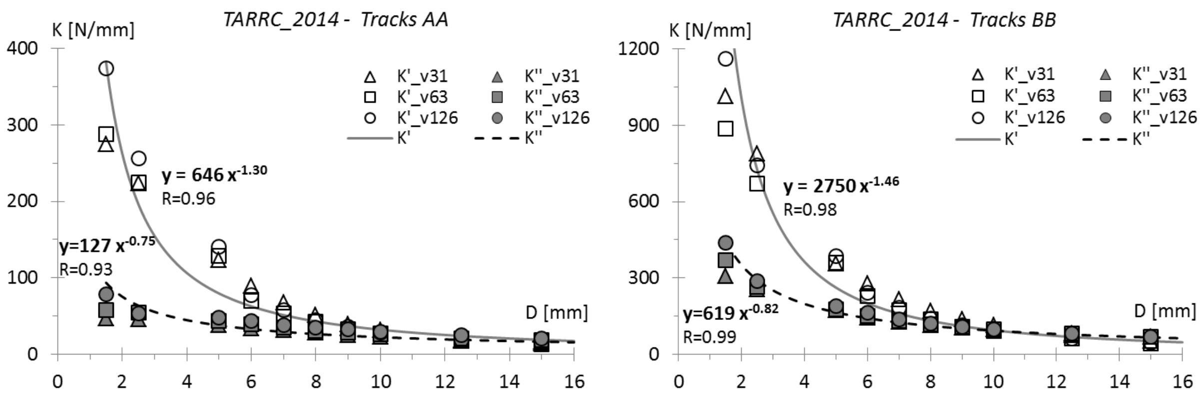


Figure 12. Images of the "set-up" for the new tests at TARRC

Table 2. Sinusoidal constant-velocity input used for the new characterisation tests

Amplitudes [mm]	INPUT 1 Velocity = **31** mm/s	INPUT 2 Velocity = **63** mm/s	INPUT 3 Velocity = **126** mm/s
	Frequency [Hz]	Frequency [Hz]	Frequency [Hz]
1.5	3.33	6.67	13.33
2.5	2.00	4.00	8.00
5	1.00	2.00	4.00
6	0.83	1.67	3.33
7	0.71	1.43	2.86
8	0.63	1.25	2.50
9	0.56	1.11	2.22
10	0.50	1.00	2.00
12.5	0.40	0.80	1.60
15	0.33	0.67	1.33



a) b)

Figure 13. Equivalent viscoelastic parameters calculated from the new tests: a) AA tracks, b) BB tracks

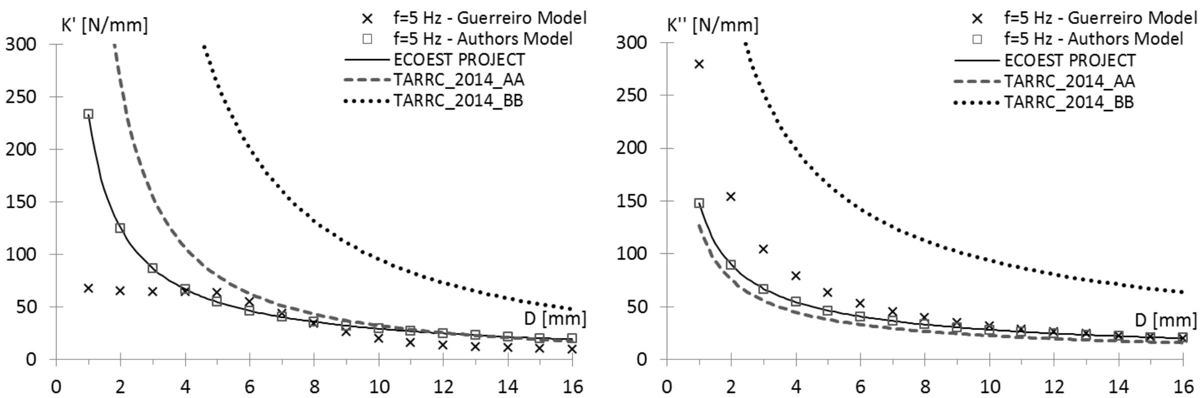


Figure 14. Equivalent viscoelastic parameters calculated from both the ECOEST and the new tests, and from both the Guerreiro and new models

Fig.14 gives a comparison of K' and K'' values either from measurements at 5 Hz during the ECOEST project (for type rubber AA), in the fresh tests reported here (for both AA and BB rubber tracks), and as obtained from the parametric sinusoidal analysis using the Guerreiro model and the new model presented above. It is evident that the new model agrees very well with the ECOEST test results (from which it is calibrated), much better than does the Guerreiro model. The B-B type tracks give substantially greater stiffness and damping. There is some difficulty in reproducibility of the test results, perhaps arising from a sensitivity to the dwell time for the static configuration.

CONCLUSIONS

1. The ECOEST results confirm that the RBRL isolation system provides very effective reduction of excitation of the first mode of the isolated structure for small seismic events, for a wide range of frequency content, despite its being very much stiffer when the deflections across the isolators are small (< 5mm). The primary factor responsible is probably the very high damping, together with the changed mode shape resulting from the compliance of the isolators, although the non-linear behaviour may also be significant.

2. For larger seismic excitations the system was shown earlier to perform very well (Guerreiro et al., 2007), as expected from an isolation system that offers good scope in choice of period and damping.

3. Equivalent viscoelastic frequency domain parameters and force-displacement loops have been used to compare the properties of the actual RBRL system with two different time-domain models. An error in Fig.9 of Guerreiro et al.(2007) has been identified; the experimental data actually gives 10 times the stiffness reported there.

4. A new time-domain model is presented which gives a better representation of the behaviour of the RBRL system than the Guerreiro model is given.

5. Depending on the choice of parameters, the RBRL system provides a rich variety of possibilities, including primary seismic mitigation strategies of isolation, damping or fuse functions.

REFERENCES

Ahmadi HR and Muhr AH (1997) "Modelling dynamic properties of filled rubber", *Journal of Plastics, Rubber and Composites Processing and Applications*, 26(10):451-461

Ahmadi HR and Muhr AH (2008) "Dynamic properties of filled rubber. Part I - experimental data and FE simulated results", *Rubber Chem & Tech*, 81, 1-18

Ahmadi HR and Muhr AH (2011) "Dynamic properties of filled rubber. Part II - Physical basis of contributions to the model", *Rubber Chem & Tech*, 84, 24-40

Bettinali F, Bellorini S, Bergamo G, Muhr AH, Diehl A (2001) "Seismic Risk Mitigation of Light Structures by means of novel Rolling-Ball Rubber-Layer Systems", *Proceeding of 5th World Congress on Joints, Bearings and Seismic Systems for Concrete Structures,* Rome, Italy, 7–11 October

Cook J, Muhr AH, Sulong M, Thomas A (1997) "Rolling-ball Isolation System for Light Structures", *Proceeding of International Post-SMiRT Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Seismic Vibrations of Structures*, Taormina, Italy, 25-27 August, 795-811

Foti D and Kelly JM (1996) <u>Experimental study of a reduced scale model seismically base-isolated with Rubber-Layer roller bearings</u>, Monograph IS-18, (Monograph Series in Earthquake Engineering, ed. A.H. Barbat), International Center for Numerical Methods in Engineering, Barcelona, Spain

Guerreiro L, Azevedo J, Muhr AH (2007) "Seismic Tests and Numerical Modeling of a Rolling-ball Isolation System", *Journal of Earthquake Engineering*, 11(1):49-66

Muhr AH and Bergamo G (2010) "Shaking Table Tests On Rolling-Ball Rubber-Layer Isolation System", *Proceeding of 14th ECEE 2010,* Ohrid, Macedonian, 30 August – 03 September, paper 745

Muhr AH, Sulong M, Thomas AG (1997) "Rolling-ball Rubber-layer Isolators", *Journal of Natural Rubber Research*, 12(4):199-214