Modelling and Characterization of Hybrid Rubber-Based Earthquake Isolation Systems

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Base isolation systems are nowadays largely used to protect the build environment and to avoid loss of life. While the behaviour of natural rubber bearings NRB and lead rubber bearings LRB is well-known, hybrid devices incorporating a NRB and a LRB, due to their complex behaviour, are difficult to be modeled. The authors have developed a theoretical model able to describe with high accuracy the performance during earthquakes of hybrid isolation systems, meantime permitting to determine the equivalent stiffness for all levels of horizontal loads. At the end of the paper numerical simulations give an overview about the possibilities to control the structure response by fitting some parameters of the device. Finally comparison with the behaviour of "classical" devices is performed.

Keywords: rubber, neoprene, composites, base isolation, earthquake

Earthquakes are natural hazards which can considerably affect the build environment and may cause injury and loss of life. As special constructions, bridges are extremely sensitive to earthquakes, but they have to provide an emergency link in a surface transportation network during and after natural disasters. To avoid, or at least mitigate damages on bridges due seismic actions, retrofitting is required. First attempts were focused on increasing member strength; merely this approach is not sustainable and cost-effective for short to medium span bridges with low pillars, while their fundamental period of vibration remains in the range of the predominant periods of earthquake-induced ground motions [1]. Figure 1 presents the case of an elastic pillar and the accelerations produces for its fundamental period (point 1), together with the consequence of reinforcing the pillar and increasing its rigidity (point 2). One can observe, in figure 2, the decrease of share force *V* and bending moment *M* at the pillar's foundation.

The solution found in the last decades is the so-called base isolation, consisting in the insertion of elastic elements between the pillars and the superstructure. It decuples the superstructure from the earth motion, permitting a relative displacement, and in the meantime change the system fundamental period; an isolated pillar (point 3) in figure 1 illustrats this concept. The accelerations decrease dramatically, thus mitigated loads act on the pillar, like it is presented in figure 2 for the isolated bridge [2].

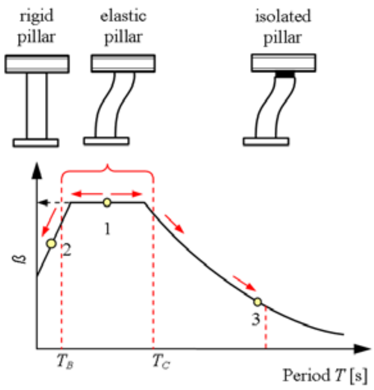

Fig.1. Acceleration values for the superstructure depending on the constructive solution

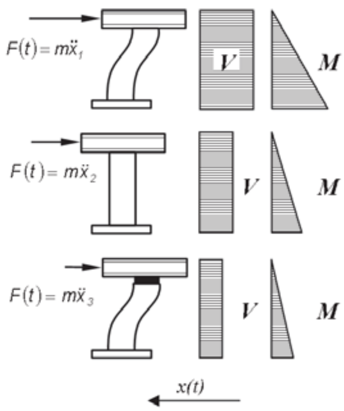

Fig.2. Loads due to earth move transmitted to the pillar function of the constructive solution

Rubber bearings, largely presented in literature [3 - 7], represent a common means for introducing flexibility into an isolated structure. They consist of thin layers of rubber, either natural or synthetic, that are vulcanized and bonded to steel plates or nets of fibers. Depending on the achieved damping level, one can differentiate between natural rubber bearings (NRB) exhibiting damping less than 2-3% and high damping rubber bearings (HDRB) exhibiting higher damping, up to 10-15%. Low-damping natural rubber bearings present a linearly elastic and linearly viscous behaviour at large shear strains. The increase in effective damping of high-damping rubber is achieved by the addition of chemical compounds that may also affect other mechanical properties of rubber, therefore it exhibit a hysteretic behaviour. Some high-damping rubber mechanical and physical properties, indicated by Alga Spa, are presented in table 1.

To ensure rigidity under service loads, Bill Robinson added to natural rubber bearings a lead core [8], resulting a new seismic isolation device, the lead rubber bearing (LRB). It is generally constructed of low-damping natural rubber with a preformed central hole into which the lead core is press-fitted. Under lateral deformation, the lead core deforms in almost pure shear, yields at low levels of stress (approximately 8 to 10 MPa in shear at normal temperature), and produces hysteretic behaviour. This behaviour is stable over many cycles, because lead

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Table 1
RUBBER PROPERTIES

Characteristic	Compound		
	SOFT	NORMAL	HARD
hardness (Shore A3)	40±3	60±3	75±3
tensile strain (%)	20	20	18
tensile strength (MPa)	750	600	500
share modulus *G* (MPa)	0.4	0.8	1.4
equivalent viscous damping (%)	10	10	16

recrystallizes at normal temperature, so that the repeated yielding does not cause fatigue failure.

Observations made on isolated structures reveal that, while for moderate earthquakes the performance of above presented isolation devices are satisfactory, these are not always sufficient in weak earthquakes [9]. Japanese researches developed a hybrid system, composed by a LRB and a NRB, known as hybrid lead rubber bearing (HLRB); it provides good behaviour in weak earthquakes and also seismic safety in strong earthquakes. Since this kind of devices perform a non-linear behaviour, development of proper models to characterize its dynamics under various levels of horizontal loads is necessary. Literature presented just simplified models, for which the share stiffness can not be deduced with high accuracy.

This paper presents a mathematical model of such a device developed by the authors, for which is given the analytic expression of the equivalent share stiffness for every level of horizontal displacement.

Functional analysis and modelling of hybrid lead rubber bearing

The HLRB is vertically composed by a LRB (placed on the upper side) and a NRB (placed on the bottom of the device) with a stopper which limits its mobility. The two bearings have a common plate, placed on the center of the device in the vertical field; additionally, the LRB has an upper plate and the NRB a bottom plate respectively. Both LRB as well as NRB are multi-layered, consisting of neoprene layers vulcanized on steel sheets. The neoprene has usually a low-damping characteristic, but high-damping materials can also be used.

An inner stopper, composed by a steel pin placed on the centre of the bottom plate and a ring made of glass fiber reinforced plastic mounted in the median plate, limit the horizontal displacement of NRB. The clearance between the pin and the ring controls the range in that the NRB mainly works. The glass fiber reinforced plastic ring has also the role to absorb the impact energy resulted by collision of pin and ring due significant earthquakes. Therefore the elastic behavior of a NRB with stopper can be modeled with sufficient accuracy as a non-linear hardening spring, having the stiffness k_N^{LRB} as long as the stopper dose not act, and infinite after the horizontal displacement is blocked.

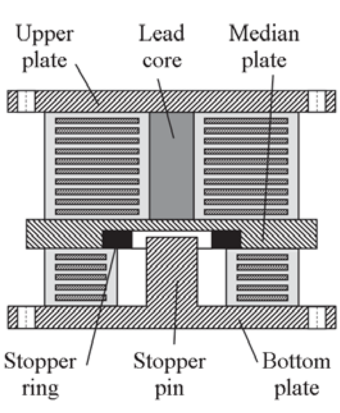

Fig.3. Constitutive components of a hybrid lead rubber bearing

Regarding the LRB, it is manufactured as a normal NRB with a central hole into which a lead core with stiffness around 10 times bigger than the neoprene-steel sandwich is press-filled.

Under lateral deformation, the lead core deforms in almost pure shear, yields at low levels of stress (approximately 8 to 10 MPa in shear at normal temperature), and produces hysteretic behaviour that is stable over many cycles. Because lead recrystallizes at normal temperature, repeated yielding does not cause fatigue failure. Usually the elastic behavior of a LRB is described as bilinear [6], with stiffness $k_N^{LRB} + k_{PB}$ for the interval before the lead core yields, respectively k_N^{LRB} after that moment. The physical model can be realized by using a linear spring for the neoprene element and a non-linear softening spring for the lead core.

In literature it is presented that for small horizontal loads, i.e. reduced displacements, due to different rigidities of LRB and NRB, just this last bearing deforms until the stopper blocks the horizontal displacement. It is a raw approach, numerical and experimental studies performed by the authors argue against this theory. Furthermore, the total stiffness of the device is even lower than that of the NRB, no matter how low it is.

To improve knowledge in this field and to get accurate mathematical relations for the mechanical behaviour of HLRB, we performed a structural and functional analysis of this device. Based on the remarks presented above and considering the neoprene element (as linear spring) and lead core of LRB (as non-linear softening spring) in parallel connection and LRB with NRB (as non-linear hardening spring) in serial connection, we developed a physical model, presented in figure 4. It has to be mentioned that the hardening spring is replaced with a linear spring with limited displacement, while the softening spring is modeled using two linear springs, from which the second spring acts by higher displacement against the first one to counterbalance its effect.

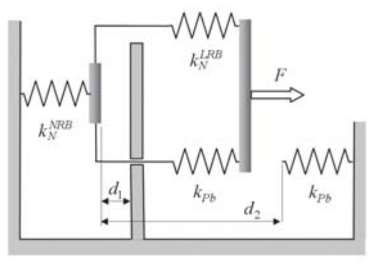

Fig.4. Physical model of the HLRB

We can now decompose the phenomenon in three domains:

- weak earthquakes, actuating with horizontal forces F that produce displacements in the NRB in the range of the stopper clearance, i.e. displacements lower than d_1;
- moderate earthquakes, actuating with forces F that do not induce yielding in the lead core, i.e. displacements in the LRB lower than d_2;
- strong earthquakes, producing plastic deformations in the lead core.

Figure 5 present the three domains, together with the stiffness for the HLRB components.

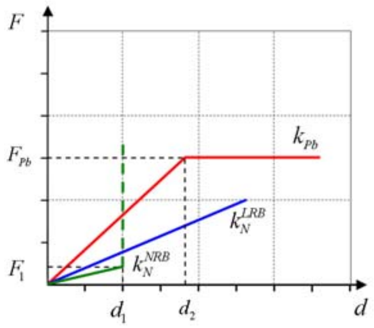

Fig.5. Stiffness representation for the HLRB components

Next chapter presents the dynamic behaviour of HLRBs in terms of stiffness, analytical expressions for this structural property being defined for the characteristic domains.

Equivalent stiffness prediction

Due to its non-linear behaviour, the HLRB presents variable stiffness, depending on the excitation range or imposed displacements. Considering the model presented in figure 4, one remark that for the first domain ($F < F_1$) the NRB exhibit displacements without restrictions; for the force F_1 the critical displacement d_1 is reached, thus the stopper blocks the NRB. In this last case the LRB deforms with d^{LRB}. Between force F_1 and displacement d_1 and respectively (figs. 5 and 6), the relation is:

$$F_1 = k_N^{NRB} \cdot d_1 \tag{1}$$

$$F_1 = (k_N^{LRB} + k_{Pb}) \cdot d^{LRB} \tag{2}$$

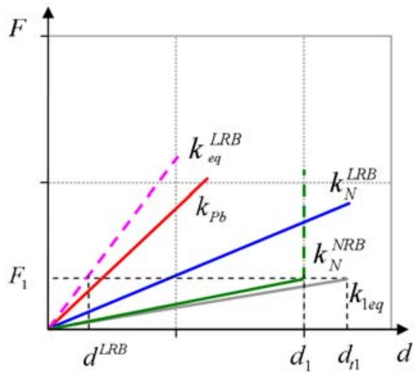

Fig.6. Displacements d_1 and under critical force F_1

From relations (1) and (2) one obtains:

$$(k_N^{LRB} + k_{Pb}) \cdot d^{LRB} = k_N^{NRB} \cdot d_1 \tag{3}$$

which permits obtaining the displacement of the LBR in relation to the maximum permitted displacement of the NRB and the stiffness of the three HLRB components, as follows:

$$d^{LRB} = \frac{k_N^{NRB}}{k_N^{LRB} + k_{Pb}} \cdot d_1 \tag{4}$$

Relation (4) reveals that, for low horizontal loads, displacement of LRB is significantly smaller than d_1 associated to NRB. The total displacement d_{t1} reached by the HDRB under critical force F_1 (fig. 6) can be expressed:

$$d_{t1} = \frac{k_N^{NRB} + k_N^{LRB} + k_{Pb}}{k_N^{LRB} + k_{Pb}} \cdot d_1 \tag{5}$$

Consequently, for the first domain, in which the horizontal force takes values between 0 and the critical force F_1, stiffness k_{1eq} associated to the HLRB assembly will be:

$$k_{1eq} = \frac{F_1}{d_{t1}} = \frac{F_1 \cdot (k_N^{LRB} + k_{Pb})}{(k_N^{NRB} + k_N^{LRB} + k_{Pb}) \cdot d_1} = = k_N^{NRB} \frac{(k_N^{LRB} + k_{Pb})}{k_N^{NRB} + k_N^{LRB} + k_{Pb}} \tag{6}$$

One observes that, for the first domain, the stiffness k_{1eq} of the HLRB assembly is always smaller than the stiffness of the NRB.

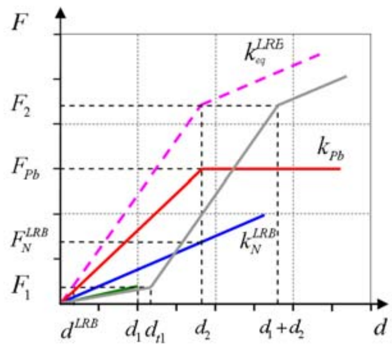

Fig.7. Equivalent stiffness of the HDRB for the three characteristic domains

For the second domain, where moderate forces act on the HLRB, supplementary displacements occur just in the LRB due to restrictions imposed to the NRB by the stopper. Therefore, the displacement of the NRB is limited to:

$$d_1 = \frac{F_1}{k_N^{NRB}} \tag{7}$$

while the LRB exhibits a displacement:

$$d_{2X} = \frac{F(d_X)}{k_N^{LRB} + k_{Pb}} \tag{8}$$

The total displacement d_X of the HLRB due to horizontal force F(d_x), is:

$$d_X = d_1 + d_{2X} = \frac{F_1}{k_N^{NRB}} + \frac{F(d_X)}{k_N^{LRB} + k_{Pb}} = = \frac{F_1 \cdot (k_N^{LRB} + k_{Pb}) + F(d_X) \cdot k_N^{NRB}}{k_N^{NRB} \cdot (k_N^{LRB} + k_{Pb})} \tag{9}$$

or, denoting $F(d_x) - F_1 = \Delta F(d_x)$ results:

$$d_X = \frac{F_1 \cdot (k_N^{LRB} + k_{Pb}) + F_1 \cdot k_N^{NRB} + \Delta F(d_X) \cdot k_N^{NRB}}{k_N^{NRB} \cdot (k_N^{LRB} + k_{Pb})} = = d_{t1} + \frac{\Delta F(d_X)}{k_N^{LRB} + k_{Pb}} \tag{10}$$

One remarks that for the limit cases $F(d_x) = F_1$ the total displacement of the HLRB takes the value $d_x=d_{t1}$, whereas for $F(d_x)=F_2$ the total displacement of the HLRB takes the value $d_x=d_{t2}=d_1+d_2$, confirmed by figure 7.

For the second domain, the stiffness k_{2eq} of the HLRB can be expressed:

$$k_{2eq}=\frac{F(d_X)}{d_X}=\frac{F(d_X)}{\dfrac{F_1\cdot(k_N^{LRB}+k_{Pb})+F(d_X)\cdot k_N^{NRB}}{k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}}=\frac{F(d_X)\cdot k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}{F_1\cdot(k_N^{LRB}+k_{Pb})+F(d_X)\cdot k_N^{NRB}} \quad (11)$$

and takes the extreme values:

$$k_{2eq}=\begin{cases} k_{1ech}=k_N^{NRB}\dfrac{(k_N^{LRB}+k_{Pb})}{k_N^{NRB}+k_N^{LRB}+k_{Pb}}, & for\ F(d_X)=F_1\\ \dfrac{F_2\cdot k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}{F_1\cdot(k_N^{LRB}+k_{Pb})+F_2\cdot k_N^{NRB}}, & for\ F(d_X)=F_2 \end{cases} \quad (12)$$

For the third domain, i.e. $F(d_x) > F_2$, the total displacement of the HLRB can be written as the sum of displacements produced by the critical force F_2 and that imposed to the LRB by a load $\Delta F(d_x) = F(d_x) - F_2$. It has to be mentioned that just the elastomeric element of the LRB provide stiffness, as the lead core yielded. Therefore, the total displacement will be:

$$d_X=d_{2t}+d_{3X}=\frac{F_1\cdot(k_N^{LRB}+k_{Pb})+F_2\cdot k_N^{NRB}}{k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}+\frac{\Delta F(d_X)}{k_N^{LRB}} \quad (13)$$

hence

$$d_X=\frac{\left[F_1\cdot(k_N^{LRB}+k_{Pb})+F_2\cdot k_N^{NRB}\right]\cdot k_N^{LRB}+\Delta F(d_X)\cdot k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}{k_N^{NRB}\cdot k_N^{LRB}\cdot(k_N^{LRB}+k_{Pb})} \quad (14)$$

$$d_X=\frac{F_1\cdot(k_N^{LRB}+k_{Pb})\cdot k_N^{LRB}-F_2\cdot k_N^{NRB}\cdot k_{Pb}+F(d_X)\cdot k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}{k_N^{NRB}\cdot k_N^{LRB}\cdot(k_N^{LRB}+k_{Pb})} \quad (15)$$

The HLRB's stiffness k_{3eq} for this domain will be:

$$k_{3eq}=\frac{F(d_X)\cdot k_N^{NRB}\cdot k_N^{LRB}\cdot(k_N^{LRB}+k_{Pb})}{F_1\cdot(k_N^{LRB}+k_{Pb})\cdot k_N^{LRB}-F_2\cdot k_N^{NRB}\cdot k_{Pb}+F(d_X)\cdot k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})} \quad (16)$$

For the critical force $F(d_x)=F_2$ the equivalent stiffness of the HLRB assembly is:

$$k_{3eq}=k_{2eq}=\frac{F_2\cdot k_N^{NRB}\cdot(k_N^{LRB}+k_{Pb})}{F_1\cdot(k_N^{LRB}+k_{Pb})+F_2\cdot k_N^{NRB}} \quad (17)$$

which is similar with the one obtained for the upper limit of the second domain, provided by relation (12). Relation (16) and figure 7 show that the increase of the horizontal force over the critical value F_2 produces a decrease of the equivalent stiffness k_{3eq}.

Results and discussions

To find out the evolution of the equivalent stiffness in respect to the imposed displacement, numerical experiments have been performed. For simulations three cases are considered, the stiffness values of the HLRB components for all cases are presented in table 2.

To find out the equivalent stiffness for the three isolator types, horizontal forces increasing until they produces a displacement d = 15 mm where applied to the upper plate of the isolators. Using relations (6), (11) and (16) the equivalent stiffness k_{1eq}, k_{2eq} and k_{3eq} for the three characteristic domains were calculated; figure 8 illustrates these results.

Table 2
STIFFNESS VALUES FOR THE THREE NUMERICAL ANALYZED CASES

Variable / Case	k_N^{NRB} [N/m]	k_N^{LRB} [N/m]	k_{Pb} [N/m]
1	0,50	0,75	2,50
2	0,50	0,50	2,50
3	0,50	0.75	3,00

It is obvious that for small displacements, the HLRB assembly performs a linear behaviour, depending essentially on stiffness of the NRB and insignificant on the stiffness of LRB. However, k_{1eq} is always lower than k_N^{NRB}. By higher forces, determining the action of the stopper, the rigidity increases significantly, until the lead core yields; afterwards, the rigidity decreases solely.

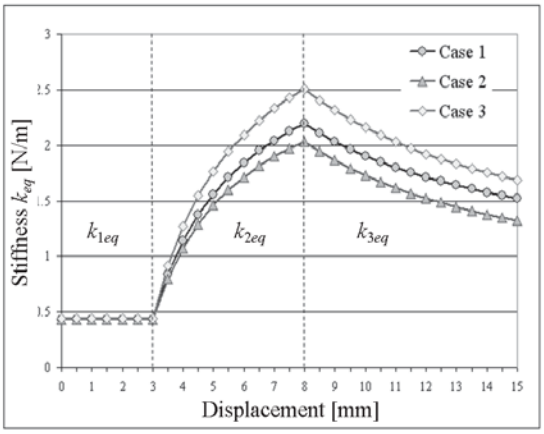

Fig.8. Equivalent stiffness vs. displacement for the three characteristic domains of the HLRB

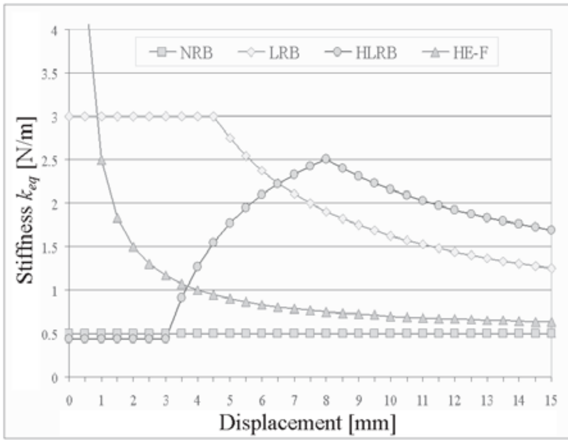

Fig.9. Comparative chart of equivalent stiffness for various base isolation systems

Comparing the stiffness evolution under horizontal loads for the HLRB with that of the natural rubber bearing NRB, lead rubber bearing LRB and hybrid elastic-friction bearing HE-F one observe that, even if they act totally different, on specific domains the performance is equivalent. However, each system proves its utility for specific applications, defined by the type and nature of the isolated structure, the non-structural elements to be protected placed on the structure, typical excitations due seismic activity etc.

The advantage of the HLRB, comparing to other devices [10], is that at low excitations there are permited displacements and change the frequency of the isolated construction (an acceleration decrease to one-half is reported by Tanaka et al. [8]), protecting pillars of bridges or sensitive equipment placed in buildings, while for high horizontal loads it becomes stiff and dissipates a big amount of energy. This qualify the isolator for bridges and buildings containing sensitive equipment, like hospitals with surgery rooms, laboratories, a.s.o.

Conclusions

The paper presents researches performed by the authors in order to define with high accuracy the mathematical relation between horizontal displacement in hybrid lead rubber bearings HLRB due seismic forces and the global stiffness of this isolation device.

Numerical simulations revealed an important advantage of the HLRB, consisting in the possibility to control the stiffness and consequently the frequency and the hysteretic behavior of this device. It can be made by fitting:

- the clearance for the lower NRB with stopper, which define the extent of the first domain;
- the individual stiffness of the lower NRB with stopper, which strongly influence the global stiffness of the HLRB in the first domain;
- the stiffness of the elastomeric element and that of the lead core of the LRB, defining the maximum global stiffness of the HLRB;
- the yield force of the lead core, which control the extend of the second domain and the point from which the global stiffness start to decrease.

Consequently, HLRB, as an adaptive isolation device, can be successfully used in protection of bridge-like structures or buildings containing sensitive non-structural equipment. For this last case, it protects the equipment to weak earthquakes, reducing dramatically the transmitted accelerations, while at strong earthquakes it changes the behavior becoming stiff and protecting mainly the structure.

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