15th World Congress on Computational Mechanics (WCCM-XV)
8th Asian Pacific Congress on Computational Mechanics (APCOM-VIII)
Virtual Congress: 31 July – 5 August 2022
S. Koshizuka (Ed.)

UNBONDED FIBER REINFORCED ELASTOMERIC ISOLATOR (UFREI) MADE OF HIGH DAMPING NATURAL RUBBER BLEND

GAETANO PIANESE[1], GABRIELE MILANI[1], AND ANTONIO FORMISANO[2]

[1] Department of Architecture, Built Environment & Construction Engineering (A., B., C.), Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
gaetano.pianese@polimi.it, gabriele.milani@polimi.it

[2] School of Polytechnic and Basic Sciences "Federico II" Piazzale Tecchio 80, 80125 Napoli, Italy
antonio.formisano@unina.it

Key words: Seismic isolation, Unbonded fiber reinforced elastomeric isolator (UFREI), High Damping Rubber, Finite Element analysis, Cyclic shear test.

Abstract. *Some commercial base isolators have been introduced in the last four decades to protect buildings from vibration and earthquakes. Typically, they are constituted by several alternating layers of rubber pads and steel (elastomeric isolator) interposed by two continuous pads, limiting vertical deformability. At the same time, they exhibit good deformation capacity in the horizontal direction when subjected to a seismic load. A very effective seismic isolator shall satisfy the following functions: good performance under all service loads, vertical and horizontal; provide enough horizontal flexibility to reach the target natural period for the isolated structure; recentering capability after the ground motion so that no residual horizontal displacement can downgrade the serviceability of the structure; provide an adequate level of energy dissipation (damping) to control the displacement that could damage other structural members. Steel-reinforced elastomeric isolators (SREIs) are the most used method of seismic isolation. Since these devices are generally too expensive due to the need to introduce thick steel plates for their supports and the high energy consumed for the manufacturing process, they are not suitable for ordinary residential buildings, especially in developing countries. Compared with SREIs, fiber-reinforced elastomeric isolators (FREIs) have considerably lower weight and can be installed between the structure in elevation and the foundation without any bonding or fastening in the so called unbonded application (UFREI), reducing costs hugely. Furthermore, without steel supports, the shear load is transferred through the friction generated between the isolator and the structure surfaces, improving the dissipation energy of the devices. The main feature of such a UFREIs is the large deformability thanks to the rollover deformation and the favorably lower lateral stiffness compared to the bonded isolator. In this paper, a series of experimental tests of the rubber compound and numerical analyses of UFREIs made of high damping rubbers (HDR) combined with glass fiber reinforcement have been performed. A HDR made of Natural Rubber and Ethylene Propylene Diene Monomer (NR-EPDM) blend has been considered. Finite Element shear test results have shown good dynamic performances of the proposed device.*

1 INTRODUCTION

To seismically isolate a structure, it is possible to interpose between the foundation and the super-structure a rubber device (elastomeric isolator) that increases the period of the building. This feature allows the structure to be "transparent" to the seismic excitation.

Low-damping rubber bearing (LDRB) is one of the first elastomeric isolators used to mitigate buildings from earthquake effects, with a damping ratio of 2% to 5%. The isolators are placed on thick steel plates at the top and bottom as supports, bonded by heating and pressure processes. The steel lamina between rubber layers has the role of improving the rubber pads vertical stiffness and preventing the bulging of the rubber without affecting the horizontal stiffness of the system.

In the 1970s, the most significant advance in damping came with the addition of a lead-plug down the center of the isolator. The system results in a nearly rectangular hysteresis loop, with consequent absorption of earthquake energy and control of oscillations [1].

High-damping rubber bearing (HDRB) presents a higher isolation performance due to the better ability of energy dissipation of the rubber compounds. The steel-reinforced elastomeric isolators (SREIs) have been employed to protect buildings, but such devices tend to be too expensive due to the need for thick steel plates for their supports and the high energy consumed for the manufacturing process.

Fiber-reinforced elastomeric isolator (FREI) is a new type of elastomeric isolator. Instead of steel lamina, thin fiber layers are utilized for vertical reinforcement. Compared with SREIs, FREIs have considerably lower weight and can be manufactured through cold vulcanization. In [2][3] fiberglass layers have been employed to produce FREIs. They can be applied to the structure in several methods: bonded [4], unbonded [5][6][7][8][9][10] and partially bonded [11][12].

Without steel supports, the isolators can simply be installed between the upper structure and foundation without bonding or fastening. So, the shear load is transferred through the friction generated between the isolator and the structure surfaces. The possibility of unbonded application is a promising feature of the FREIs since the effect of rolling-over and friction may improve the dissipation energy of the isolators.

The unbonded applications result in a stable rollover lateral deformation, which reduces the horizontal stiffness and increases the efficiency of the devices. Compared to the identical specimen but in bonded conditions, the unbonded FREIs result in superior performance concerning the damping ability [13].

For elastomeric isolators, rubber pads have a main role. Natural Rubber (NR) is the most used, but artificial rubber seems promising for fabricating isolators since NR is vulnerable to rapid aging and its industrial production capacity is limited. Damping performance is a prerequisite for isolation-bearing materials [14]. Besides, the materials must have an excellent overall performance, such as high strength to resist damage [15][16]. NR exhibits desirable physical and mechanical properties, good processing properties, and excellent flexibility, and it is an indispensable material for industrial applications. However, NR has a quite poor damping performance, which significantly limits its application in anti-seismic materials [17][18]. As an alternative, a natural rubber compound with enough inherent damping ratio, called high-damping rubber (HDR) has been proposed. It may increase the damping ratio up to 10-15% by adding carbon black, oils or resins, and other proprietary fillers [19]. Furthermore, the blending of two or more types of rubbers is an important way to prepare and develop rubber blends with properties superior to those of individual constituents. O. Ranaei et al. in [20] have investigated the mechanical and dynamic properties of viscoelastic compounds based on NR and butyl (IIR) for viscoelastic dampers. The numerical results have shown that the IIR can provide high energy dissipation capacity. In [21], J-C. Li et al. have developed high damping NR/IIR composites compatibilized by isobutylene-isoprene block copolymer (IIBC) for isolation bearing. The NR/IIR/IIBC blends are expected to be potential materials for high-damping isolation rubber bearings.

This study proposes a new low-cost base seismic isolator made of high damping rubber. First, a rubber compound made of NR and Ethylene Propylene Diene Monomer (EPDM) blend has been developed and characterized through several experimental tests. Subsequentially, a circular UFREI has been designed and modeled into Finite Element (FE) software code Abaqus. FE cyclic shear tests have been performed to investigate the seismic behavior. The results obtained have shown good dynamic performances of the proposed device.

2 HIGH DAMPING RUBBER COMPOUND (NR-EPDM)

The first part of the study has been focused on the characterization of the rubber compound. A high-performance rubber composition (good durability and exceptional cyclic dissipation) made of an NR-EPDM blend has been proposed. The rubber compound behavior has been characterized through various experimental tests: tensile test, tear-resistance test, compression set, ozone resistance, relaxation test, accelerated air oven aging, hardness measurement, and shear tests. Mechanical and physical properties have met the minimum requirements of table 9 of UNI EN 15129 [22], reported in Table 1. Results are summarized in Table 2 and Table 3.

Table 1 - Mechanical and physical properties of high damping elastomers [22]

Property	Minimum Requirement	Test method
Tensile strength at break (MPa)	12	IS037 Type 2
Elongation at break (%)	400	IS037 Type 2
Tear resistence (MPa)	7	ISO 34 Method A
Compression set 70 °C, 24 h, max.	60	ISO 815 Type A 25% compression
Ozone resistance Elongation 30% - 96 h 40 °C ± 2 °C	No cracks	ISO 1431-1
Accelerated air oven aging. Maximum change from unaged value		
Hardness (IRHD)	-5, +8	ISO 188, Method A
Tensile strength (%)	± 15	ISO 48
Elongation at break (%)	± 25	ISO 37 Type 2

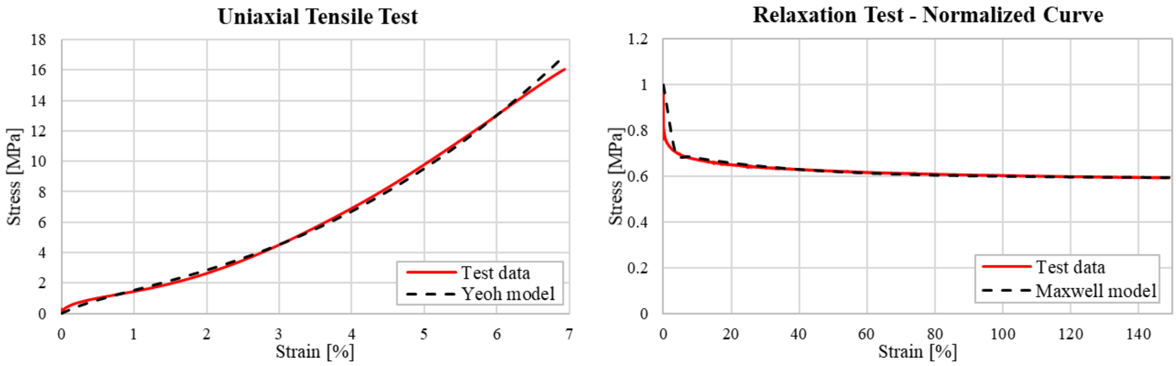
Table 2 - Mechanical and physical properties of rubber compounds

Density	Hardness	Tensile Strenght at break	Elongation at break	Young Modulus	Tear Resistance
[g/cm^3]	[IRHD]	[MPa]	[%]	[MPa]	[kN/m]
1.129	59.98	16.06	693.0	1.63	22.84

Table 3 - Results of the rubber compounds after accelerated aging and compression set

Accelerated air oven aging			Compression Set
Δ H	Δ TS_{break}	Δ E_{break}	
[IRHD]	[%]	[%]	[%]
1.00	-4.51	-9.51	35

Before fabricating the specimens for the experimental shear tests, a numerical simulation has been developed. Uniaxial tensile and relaxation tests have been performed to obtain the hyperelastic and viscoelastic properties of the rubber pads. Such experimentation was crucial to correctly define a FE model that has been used to simulate the cyclic shear behavior for the rubber first and later for the complete device. The experimental values have been inserted on FE software code Abaqus to be fitted with the Yeoh model (hyperelasticity) and the Maxwell model (viscoelasticity) (Figure 1).



a) b)

Figure 1: Comparison between experimental data and numerical model: Yeoh (a) and Maxwell (b)

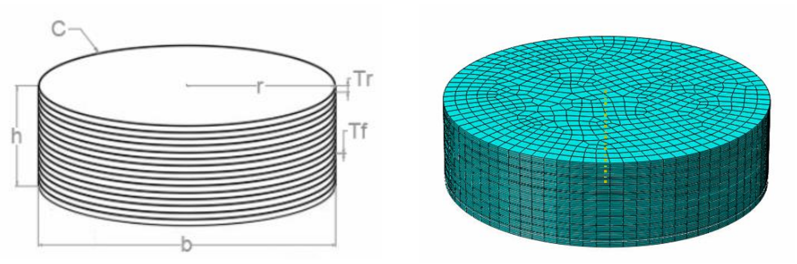
The FE preliminary results have shown good performance in terms of damping ratio. So, the quadruple shear specimens have been produced, and the experimental shear tests have been performed. The experimental results have confirmed the numerical ones. Following the code, shear tests have also been performed after aging, varying the frequencies and the temperatures (Table 4). Also in this case, the NR-EPDM rubber compound has met the minimum requirements of the code [22].

Table 4 - Numerical and experimental shear test results

Numerical		Experimental															
		Fresh		Aged		Frequency				Temperature							
ξ	G Modulus	ξ	G Modulus	Δξ	ΔG	0.1Hz		2.0 Hz		40°C		0°C		(-10°C)		(-15°C)	
						Δξ	ΔG	Δξ	ΔG	Δξ	ΔG	Δξ	ΔG	Δξ	ΔG	Δξ	ΔG
[%]	[MPa]	[%]	[MPa]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
8.49	0.70	8.38	0.77	-12	+19	+2	+1	+4	-6	+10	-15	+12	+30	+29	+47	+45	+68

3 UFREI200 – FE MODEL

After the rubber compound characterization, the UFREI has been designed. It is a circular device constituted by alternating layers of rubber pads (4 mm thick) and GFRP laminas (0.5 mm thick). It presents a base of 200 mm and a height of 67 mm (Figure 2a). The main geometrical characteristics are summarized in Table 5.



a) b)

Figure 2 - Proposed design (a) and 3D FE model (b) of FREI200

Table 5 - Geometrical characteristics of FREI200

r	H	b	C	A	T_r	T_f	n°rubber layers	n°fiber laminas	T_{rtot}	T_{ftot}	R=b/h	S_1=A/(C*Tr)
[mm]	[mm]	[mm]	[mm]	[mm^2]	[mm]	[mm]	[-]	[-]	[mm]	[mm]	[-]	[-]
100	67	200	628.32	31415.92	4	0.5	15	14	60	7	2.98	12.50

The isolator has been modeled using eight-node brick elements (C3D8H). The final mesh is shown in Figure 2b. Unbonded and bonded conditions have been simulated and compared. For the first one, there is no bonding between the supports and the rubber pad. So, a penalty surface-interaction model has been introduced between the two surfaces, and a friction coefficient of μ=1 has been applied. Instead, for the second one, a perfect tie constrain has been considered. In both conditions, tie constrains between rubber and GFRP have been modeled. Yeoh and Prony models have been used to represent the rubber behavior as described in the previous section. Table 6 and Table 7 summarize the coefficients adopted for the Yeoh and Maxwell models. The fiber has been assumed isotropic-elastic with a Young modulus of E=80000 MPa and a Poisson ratio υ=0.2, in accordance with many references [23][24][25].

Table 6 - Yeoh model coefficients

C10	C20	C30	D
0.411327320	6.170050466E-03	-7.890913554E-06	0

Table 7 - Maxwell model (Prony Series) coefficients

g1	τ_1	g2	τ_2
0.29131	0.17077	0.11519	35.303

The device has been subjected to a 0.5 Hz cyclic horizontal displacement up to 60 mm (Figure 3 and Figure 4), equal to the total height of the rubber pads, applied at the top support, under constant vertical pressure of 3.5 MPa, i.e. the expected working pressure.

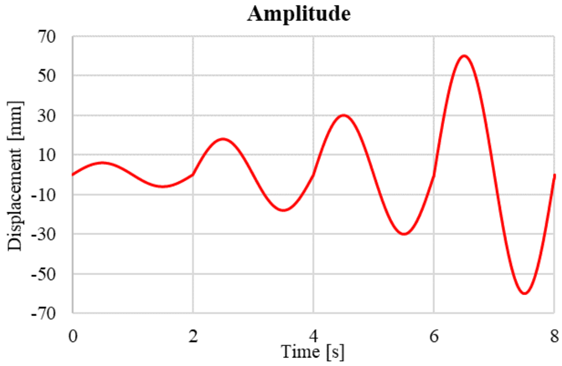
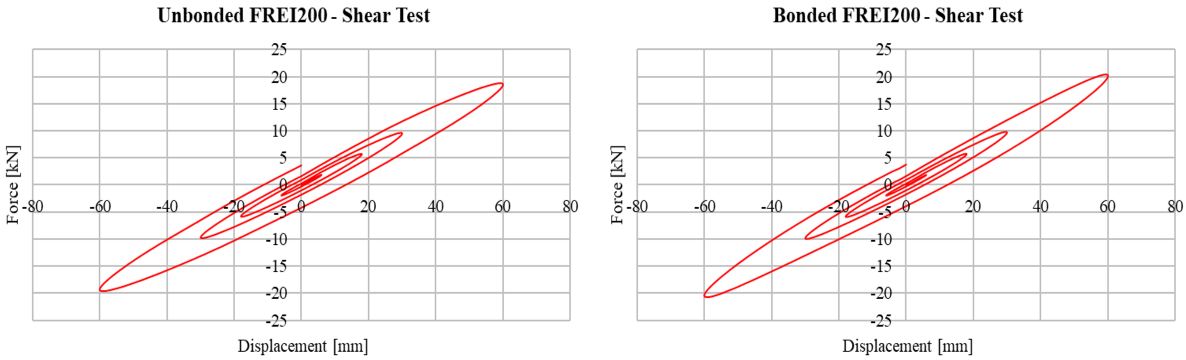


Figure 3 - Cyclic horizontal displacement amplitude



a) b)
Figure 4 – FREI200 Force-Displacement curves: unbonded (a) and bonded (b

Effective horizontal stiffness K_{Heff} and damping ratio ξ have been evaluated. The computations are based on Equations (1)-(4). In Table 8, the damping ratio and effective horizontal stiffness for each cycle (10%, 30%, 50% and 100%, respectively) are summarized.

$$K_{H,eff}= (F_{max}- F_{min})/(\Delta_{max}- \Delta_{min}) \quad (1)$$

$$\xi=W_d/(4\Pi W_s) \quad (2)$$

$$Ws=(1/2)*K_{H,eff}*\Delta^2_{max,ave} \quad (3)$$

$$\Delta_{max,ave}=(\Delta_{max} + \Delta_{min})/2 \quad (4)$$

For the UFREI, the effective horizontal stiffness decreases passing from the first three cycles to the last one. This is a typical feature of unbonded applications. In particular, the device at 100% t_r of displacement starts to experience a rollover (Figure 5), which causes a nonlinear behavior, decreasing the effective stiffness. Another remarkable feature is the variation of damping ratio with the increase of lateral displacement. Compared to the bonded one, the unbonded device generally presents a lower stiffness and a higher damping ratio.

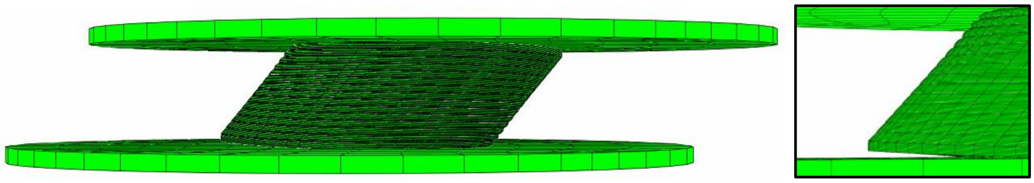


Figure 5 – UFREI200 starting rollover at 100%t_r of displacement

Table 8 - Horizontal stiffness and damping ratio evaluated for each cycle in unbonded and bonded condition

	Unbonded		**Bonded**	
	K_{Heff}	**ξ**	**K_{Heff}**	**ξ**
	[kN/mm]	**[%]**	**[kN/mm]**	**[%]**
1° Cycle (10% t_r)	0.32	5.75	0.33	4.66
2°Cycle (30% t_r)	0.32	7.44	0.33	7.33
3° Cycle (50% t_r)	0.32	8.30	0.33	7.89
4° Cycle (100% t_r)	0.30	9.29	0.34	8.74

4 CONCLUSIONS

In this study, a high damping circular UFREI has been proposed. First, the rubber compounds have been characterized through several experimental tests: tensile test, tear-resistance test, compression set, ozone resistance, relaxation test, accelerated air oven aging, hardness measurement, and shear tests. Mechanical and physical properties have met the minimum requirements of UNI EN 15129 [22] for high damping rubber compounds for elastomeric isolators. Subsequentially, uniaxial tensile and relaxation tests have been performed to obtain the hyperelastic and viscoelastic properties of the rubber pads for the 3D FE model. The experimental values have been inserted on FE software code Abaqus to be fitted with the Yeoh model (hyperelasticity) and the Maxwell model (viscoelasticity). A comparison of shear test experimental and numerical results has confirmed the reliability of the parameters considered.
The second part of the study has been focused on the design and FE modeling of the device. A circular UFREI has been proposed. It is constituted by alternating layers of rubber pads (4 mm thick) and GFRP laminas (0.5 mm thick) and presents a base of 200 mm and a height of 67 mm.

The isolator has been modeled using eight-node brick elements (C3D8H). Unbonded and bonded conditions have been simulated. Once again, Yeoh and Maxwell models have been used to represent the rubber behavior. Instead, the GFRP has been assumed isotropic-elastic. The device has been subjected to a 0.5 Hz cyclic horizontal displacement up to 60 mm (total height of the rubber pads) applied at the top support, under constant vertical pressure of 3.5 MPa, i.e. the expected working pressure.

Effective horizontal stiffness K_{Heff} and damping ratio ξ have been evaluated for each cycle (10%, 30%, 50%, and 100%, respectively). The device starts to experience a rollover, which causes a nonlinear behavior, decreasing the effective stiffness from the first three cycles to the last cycle one at 100% t_r of displacement. This is a typical feature of unbonded applications. Another remarkable feature is the increase in damping ratio with the increase of lateral displacement. Compared to the same device in bonded condition, the unbonded one presents a lower horizontal stiffness and a higher damping ratio.

The good dynamic performances of the proposed device have highlighted the possibility of their use for the seismic mitigation of low-rise masonry buildings in developing countries. Further studies with experimental shear tests and FE structural application of the device are under investigation by the authors for a complete characterization.

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