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Innovative low-cost recycled rubber–fiber reinforced isolator: Experimental tests and Finite Element Analyses

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ABSTRACT

An experimental study on unbounded square carbon Recycled Rubber–Fiber Reinforced Bearings (RR-FRBs) was conducted to investigate their lateral and vertical behavior, under seismic loading. These low-cost rubber bearings are innovative elastomeric bearings that employ recycled rubber and fiber as reinforcement material. They have significant advantages compared to those bearings made up of natural rubber reinforced by steel layers or fiber sheets: higher dissipation capacity, lower manufacturing cost, light weight. RR-FRBs are intended for seismic isolation of ordinary low-rise buildings located in high seismic risk regions, and are designed to be mounted with no need of bonding to the upper and lower structures. This feature allows them to deform freely, reducing, and possibly eliminating, the tensile stresses generated by shear deformations. In this work, the seismic performance of the proposed bearings is investigated by means of both experimental tests and Finite Element Analyses (FEAs). The study provides useful information on both horizontal and vertical stiffness, and on the damping properties of the isolators. Moreover, a description of the instability of the bearings is discussed. The sensitivity of RR-FRBs to lateral displacement history and vertical pressure applied on the bearings is pointed out. Moreover, the validity of easy to apply design criteria is discussed.

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1. Introduction

Seismic isolation is a mature technology that is mainly applied to strategic constructions. The isolators generally adopted are large, heavy and expensive: most of their weight derives from two steel end-plates and a consistent number of reinforcing layers used to achieve the desired vertical stiffness. Their high cost is due to a highly labor-intensive manufacturing process that ends with the vulcanization of the compounded rubber layers and the bonding of the steel reinforcements. Their application is surely justified for large and expensive buildings, but it is questionable in case of ordinary constructions. The production of low-cost seismic isolation systems through a relatively simple manufacturing process could stimulate applications of this earthquake resistant strategy to ordinary housing and commercial low to medium-rise buildings, either new or existing ones. It could also represent a valid solution for the developing countries where the design and construction of small and poorly constructed buildings in many urban areas do not provide an adequate level of structural safety against even moderate seismic events. The experience of past earthquakes just suggests that the introduction of simple but reliable low-cost isolation devices would have resulted in fewer buildings failure and decreased loss of lives.

The most important aspects of Fiber Reinforced Bearings (FRBs) are that they do not have thick end-plates which remains relatively rigid in both extension and flexure, they have no need to be bonded to top and bottom support surfaces, and their thin layers of fiber reinforcements are flexible in extension and have little flexural rigidity. The experimental behavior of FRBs has been discussed in different works (*e.g.* [1–5]). Toopchi-Nezhad et al. [1] tested unbounded square carbon fiber-reinforced elastomeric bearings to investigate their lateral and vertical response. The same authors presented in [2] the results of a time-history analysis performed on both a fixed-base and a base-isolated model of a prototype masonry shear wall structure, that is representative of a typical small low-rise building. De Raaf et al. [3] performed a comprehensive investigation into the stability of stable unbonded fiber-reinforced elastomeric isolators, by means of two test methods: the first one employed a dynamic buckling test to investigate the stability under sinusoidal lateral excitation and increasing axial load; the second one (the rollout test) investigated the stability under design axial load and increasing lateral displacement. The main objective of both tests was to determine the conditions leading to instability of the bearings. Karimzadeh Naghshineh et al. [4] proposed to use fiber mesh instead of fiber sheets, as reinforcement of elastomeric

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isolators, and compared their experimental behavior with that one of conventional steel-reinforced bearings. Russo et al. proposed in [5] a simplified geometric model to describe the deformed configuration of fiber-reinforced elastomeric isolators under compression and shear, based on the observation of its experimental behavior. The general result of the studies mentioned above was the necessity of further investigations, in order to verify the possibility of using Fiber Reinforced Bearings as seismic isolators for all types of residential buildings.

The research herein presented aims to assess the belief that, due to the absence of tensile stress in FRBs, materials with lower performance, but also lower costs, can be used for their production. In other words, the authors' work aims to answer the following question: is it possible to fully exploit the potentiality of the recycled rubber for the production of low-cost FRBs?

In the present paper, it is demonstrated that the use of recycled rubber [6], derived from used tires and rubber factory leftovers, represents the ideal possibility of a further significant costs reduction, by ensuring superior energy dissipation capability. It is proposed a low-cost innovative type of isolator, with the aim to be a step toward a proposal of a design methodology for RR-FRBs. Prototype square isolators were simply obtained, so that identical mechanical properties in the two perpendicular horizontal directions could be achieved. No end plates were used, so that they could be easily installed between the superstructure and the foundation with no bonding at the contact surfaces. The prototyping manufacturing of the proposed isolator was made by the Italian Company Isolgomma S.r.l. (Vicenza, Italy), specialized in the use of recycled rubber for the production of antivibrating mats for railway applications. The Company has computed for the prototype bearing a total cost of about ten Euros, while the market price of an equivalent traditional steel reinforced rubber isolator is ten times larger. A further comparative economic evaluation of some isolators having larger dimensions has confirmed approximately the same ratio between the cost of a traditional isolator and the cost of a RR-FRB. Most of this difference is due to the costs of the natural rubber and the vulcanization process. The manufacturing of a Fiber Reinforced Bearing anyhow includes the latter two costs, while it reduces the installation cost due to the absence of the end plates. For this reason, the ratio between the cost of a FRB and the cost of an equivalent RR-FRB remains significant in the perspective to considerably increase the number of isolation system applications.

After a brief review of practical analytical tools describing the mechanics of FRBs, the proposed work shows the results of static and dynamic experimental tests performed on some prototypes, and verifies their mechanical behavior by means of FEAs. RR-FRB prototypes were designed, manufactured and tested in the framework of the JETBIS (Joint Experimental Testing on Base Isolated Structures) Program sponsored by the 2010–2013 ReLUIS Executive Project, supported by the Italian Department of Civil Protection. The experimental activity was carried out in the Laboratories of the Department of Structures for Engineering & Architecture and the Department of Industrial Engineering, University of Napoli Federico II (Italy).

The main objective was to evaluate the design properties of square RR-FRBs through vertical compression tests (to measure the compressive stiffness) and horizontal cyclic tests (to measure the horizontal stiffness and effective damping). The viability of RR-FRBs as seismic isolation devices was just verified through the results of experimental tests.

2. Mechanics of square RR-FRBs

In the following, a review of the results derived by Kelly et al. [7] is shown: details are given on the mechanical behavior of Fiber Reinforced Bearings under compression and shear deformations.

2.1. Behavior under compression

The compression stiffness of a rectangular isolator is given by $K_c = E_c \cdot A/t_r$ where $A = 4a \cdot b$ is the area of the isolator ($2a$ and $2b$ represent the length of its sides), t_r is the total thickness of the elastomer, E_c is the effective compressive modulus for a single bonded layer of elastomer, defined as:

$$E_c = \frac{24G \cdot S^2}{\pi^2 (\alpha \cdot a)^2} \left(1 + \frac{a}{b}\right)^2 \sum_{n=1}^{\infty} \frac{1}{(n-1/2)^2} \cdot \left(\frac{\tanh \gamma_n b}{\gamma_n b} - \frac{\tanh \beta_n b}{\beta_n b} + \frac{\tanh \bar{\gamma}_n a}{\bar{\gamma}_n a} - \frac{\tanh \bar{\beta}_n a}{\bar{\beta}_n a} \right) \quad (1)$$

In the formula, G is the shear modulus of the elastomer, $S = a \cdot b/[(a+b) \cdot t]$ is the shape factor for a rectangular layer of elastomer (of thickness t), $\gamma_n = (n - 0.5) \cdot \pi/a$ and $\bar{\gamma}_n = (n - 0.5) \cdot \pi/b$ are parameters defined by two apparently unrelated effects of stretching of the reinforcement ($\alpha t = \sqrt{12G \cdot t/k_f}$, where t is the thickness of a elastomer layer, $k_f = E_f \cdot t_f/(1 - \nu^2)$ is the in-plane stiffness of the reinforcement, E_f is the elastic modulus of the reinforcement, t_f is the thickness of a reinforcement layer, and ν is the Poisson coefficient) and compressibility of the elastomer ($\beta_n = \sqrt{\gamma_n^2 + \alpha^2}$ and $\bar{\beta}_n = \sqrt{\bar{\gamma}_n^2 + \alpha^2}$). From Eq. (1), it is known that the ratio $E_c/(G \cdot S^2)$ is a function of the aspect ratio a/b. After some passages, the normalized effective compression modulus E_c/G can be expressed as a function of the ratios a/b, a/t and $k_f/(G \cdot t)$. When a/t tends to infinity, Eq. (1) becomes:

$$E_c|_{a/t=\infty} = \frac{2}{\pi^2} \frac{k_f}{t} \sum_{n=1}^{\infty} \frac{1}{(n-1/2)^4} \cdot \left(\frac{\tanh \gamma_n b}{\gamma_n b} + \frac{\tanh \bar{\gamma}_n a}{\bar{\gamma}_n a} \right) \quad (2)$$

The curves of E_c/G versus $k_f/(G \cdot t)$ are plotted in Fig. 1 for $a/b = 0.5$ and several a/t values.

2.2. Shear behavior

In conventional bonded bearings deformed in shear (see Fig. 2a), the compression is carried through the overlap region between top and bottom surfaces, and the unbalanced moment is carried by tension stresses in the regions outside the overlap. Conversely, in unbonded FRBs, the moment created by the offset of the resultant compressive loads, P, balances the moment created by the applied shear, V, as shown in Fig. 2b.

This phenomenon has been described also in analytical formulations. Kelly et al. [7] introduced two limiting displacement criteria able to completely describe the stable load–displacement range and the ultimate behavior of the bearings. A first criterion is needed to identify the peak of the load–displacement path (eq. stable range). Assuming that only the core of the bearing $B - \Delta$ is resisting to the applied displacement Δ it can be written that the resisting force is $F = G(B - \Delta) \cdot \Delta/t_r$ and consequently the force–displacement curve presents zero slope when $\Delta = B/2$. In other words, the RR-FRBs remain stable for displacements smaller than half of its base dimension. A second criterion [8,9] aims to describe the displacement at which the vertical surfaces, while rotating, touch the horizontal subgrades. The basic assumptions adopted for the demonstration are: (i) the material is incompressible; (ii) the reinforcing plates are completely flexible; (iii) the free surfaces of the roll-off portions are stress free.

In these hypotheses, it is demonstrated that the ultimate horizontal displacement is equal to the total thickness of the rubber. In broad terms these bearings can experience a displacement equal to their height before they run the risk of damage by sliding. These simple to derive design tools are validated by the results of numerical shear tests, performed with MARC 2005 MSC Software [10] and shown in the last paragraph (Section 5).

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