EXPERIMENTAL BEHAVIOR OF FULL-SCALE UNBOUNDED POLYESTER-FIBER REINFORCED RUBBER ISOLATORS FOR RESIDENTIAL BUILDINGS

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Abstract

This paper presents the results of an investigation on full-scale innovative low-cost unbounded polyester-fiber reinforced high-damping elastomeric isolators (UPFREIs) to be used for seismic protection of residential buildings in Colombia, South America. In order to characterize the mechanical behavior of the UPFREIs, two full-scale prototypes were manufactured and tested at the Structures Laboratory of the Universidad del Valle. The experimental results were compared with results from the same test performed with two traditional connected steel reinforced isolators (SREIs). Both isolation systems were designed for a residential 5-story building with a target period of 2.5s located in a medium-high seismicity region. A dedicated set-up was designed and built specifically for the experimental tests. Results from shear tests up to 100% shear strain with sustained axial load exhibited very satisfactory behavior of the UPFREIs versus the SREIs with no residual deformation after unloading. An enhanced damping mechanism with damping ratio between 10 and 15% was provided by the frictional fiber interface. Lower horizontal stiffness of the UPFREIs was obtained at higher deformation levels due to the typical rollover deformation. Despite the higher axial flexibility with respect to SREIs, UPFREIs also provided an adequate vertical to horizontal stiffness ratio. The results show that the developed UPFREIs have great potential to be implemented as a low-cost seismic isolation system of residential buildings.

Keywords: UPFREIs, SREIs, High Damping Rubber, Unbounded Isolators, Polyester Fiber Reinforcement, Seismic Isolation.
1 INTRODUCTION

Base isolation is a technique through which the structure is uncoupled from the ground by installing flexible bearings at the foundation's level. This reduces the potentially damaging motion that earthquakes transmit to the structure and decreases the economic and human life losses after the event [1]. The isolation system has been widely studied [2]–[5] and implemented in developed countries with more than 12000 projects [6], and its effectiveness has been proved during different seismic events worldwide [7], [8]. An important number of developing countries are considered as high seismic activity regions, with the most devastating earthquake records in the last decades; however, the isolation system is rarely implemented in their infrastructure. Colombia is a distinct example of this, with seismic events like Armenia (January 1992, magnitude 6.6) earthquakes, which caused more than 2500 human losses, 6000 wounded, 43000 houses damaged and 50000 destroyed, in total. However, until 2016, only three buildings were isolated for a special use (education and health). The limited implementation is related to two main aspects. First, the most common type of isolation device is the steel-reinforced multilayer elastomeric isolator (SREI) [9], which is generally large, heavy and expensive due to the highly labor-intensive manufacturing process [10]. Second, the absence of manufacturing companies in Colombia requires the devices be imported which considerably increases the final cost of the isolator. For these reasons, their application has been only justified for large and expensive buildings, and they have not been accepted for typical residential buildings [11]. The production of low-cost seismic isolation systems, using a relatively simple manufacturing process, could encourage the applications of this type of earthquake-resistant strategy to ordinary housing and commercial low-rise buildings (three to five stories), which represent more than 80% of the constructions projects in the urban areas of the country.

Reducing an isolators’ cost and weight can be achieved by replacing the traditional steel plates with fabric reinforcement [12]. This type of device is known as fiber-reinforced elastomeric isolator (FREI), which can be manufactured using conventional fiber, such as carbon (bi-directional or quadri-directional fabrics), glass or nylon [13]–[17]; and non-conventional fibers, such as carbon-fiber-reinforced plastic meshes, polyamide and engineering plastic sheets [18]–[21]. The type of connection used between the FREIs and the structure is another aspect that can be modified [22] by selecting between fully anchored (bonded condition) or unanchored (unbonded condition). In the first case, the isolator is bonded to two steel end plates that are mechanically fastened to the supports; in the second case, these plates are eliminated and the isolator is placed between the upper and lower supports with no mechanical restraints [23]. This option results in less weight, lower cost and easier installation of the isolator. Regarding the behavior, during horizontal displacements the corners of unbonded FREIs roll off the supports due to the unbonded condition and the lack of flexural rigidity of the fiber reinforcement. This eliminates the high tensile stress regions developed in a bonded isolator when it is displaced horizontally [24], [25].

The aim of this paper is to evaluate a novel unbounded polyester-fiber reinforced high-damping elastomeric isolators UP-FREIs, proposed for low-rise residential buildings, which are the most common type of projects in the principal cities of Colombia. The full-scale devices were manufactured with materials and technology commercially available in Colombia, in an unbonded condition, without lead core and with a high damping rubber (HDR) matrix. As a reinforcement material, a polyester fiber mesh was proposed and compared with the tra-
ditional SREIs. The specimens were tested under shear and compression loads applied simultaneously, to determine mechanical properties, such as stiffness and damping.

2 DESIGN AND MANUFACTURING OF THE PROTOTYPES

The prototypes were designed for a five-story structure whose dimensions are shown in Fig. 1, and represents a typical building in the city of Santiago de Cali, Colombia. The structure has a total self-weight of 21310 kN with a natural period of 0.5 s in the fixed base configuration and 2.5 s in the base isolated one. The assumed location of the structure was the seismic Zone 2 of the city, which has a design acceleration of SM1=0.50g corresponding to a 950-year return period event. The prototypes were design according to FEMA450 requirements [26], adopting the formulations developed by Naeim and Kelly [27], the characteristics of the ground motion at the site and the properties of the materials used for manufacturing. The maximum design displacement ($D_M = 320$ mm) was calculated according to the maximum acceleration at the site, assuming an equivalent damping ratio of 6%. The building is considered to be supported by 20 isolators, each one designed for an ultimate vertical load of 2000 kN and a target stiffness of 681 N/mm. Assuming a design shear strain of 114% and a vertical pressure of 6.8 MPa, an isolator with 277.4 mm total rubber height and 620 mm diameter is defined. According to these characteristics, the building was modelled in SAP2000 for an assessment of the expected behavior. In particular, the maximum base shear, story drift and accelerations reduce by 60 to 70% in the isolated configuration with respect to the fixed base one, thus confirming the capacity of the isolation system to reduce most relevant response parameters.

With the aim of selecting an efficient reinforcement and connection system for the isolators, from both economical and functional point of view, a different configuration was investigated using a high damping rubber compound developed by the authors [22]. Instead of the classical steel reinforcement, polyester fibers were considered. SREIs were only tested in bolted configuration in order to define a benchmark for FREIs. SREIs were not considered in unbolted configuration since this alternative is not deemed satisfactory in terms of both mechanical behaviour, due to flexural rigidity of internal steel shims, and higher cost and weight with respect to FREIs. Konstantinidis and Kelly [23] demonstrated that the usual thick and inflexible steel plates can be replaced by thin and flexible reinforcements to produce low-cost rubber isolators one order of magnitude cheaper. Considering the influence of the internal reinforcement cost (fiber layers versus steel plates) and different manufacturing process, the cost of UP-FREIs is estimated in the order of 30% less than the SREIs. Additionally, UP-FREIs have lower weight and provide additional benefits in terms of handling and installation process.

![Fig. 1. Dimensions of the design structure a) plan view and b) front view.](image-url)
Two different sets of isolators were manufactured with a different reinforcement and the same number of layers \( n_f = 37 \): i) (SREI) type 1 (T1), 1.9mm A-36 steel plates with yield stress of 254MPa and ultimate stress of 408MPa (Fig. 2a); and ii) (UP-FREI) type 2 (T2), 1.1mm bidirectional polyester fiber fabric with an elastic modulus of 1.176MPa (Fig. 2b).

For all prototypes, the same diameter (exterior \( \phi_e = 620\text{mm} \) and interior \( \phi_i = 610\text{mm} \)), rubber thickness \( t_r = 7.3\text{mm} \) and number of layers \( n_r = 38 \) were assumed, with a secondary shape factor (external diameter/total rubber height) of 2.2. Steel top and bottom plates \( (\bar{t}_T, \bar{t}_B = 25\text{mm}) \) with six fixed bolts of 22mm diameter were provided for the connection system of the SREIs. In total, four specimens were tested, two for each type (Table 1).

![Cross section of the prototypes: a) type T1, and b) type T2.](image)

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample</th>
<th>Reinforcement</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>Steel plates</td>
<td>Bolted</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>a</td>
<td>Polyester fiber</td>
<td>Unbolted</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Types of isolators for experimental campaign.

### 3 SHEAR TEST SETUP AND PROTOCOL

The prototypes were tested under simultaneous shear and compression loads. In the vertical direction, a 2000kN load was used and the corresponding vertical displacement was measured. A displacement protocol, considering the testing program in FEMA450 [26], was applied horizontally, which should be carried out on the isolators prior to installation by using the design displacement as the maximum deformation (114%). The protocol was composed by three parts: part 1, consisted of three fully reversed cycles of loading at each increment of displacement \( (0.25D_M, 0.50D_M, 0.67D_M, 1.00D_M) \); in part 2 three fully reversed cycles of loading at the maximum displacement \( (1.00D_M) \) were applied; in part 3 ten continuous fully reversed cycles of loading at 0.75 times the total maximum displacement \( (0.75D_M) \) were used (Fig. 3a) [26]. Due to the characteristics of the setup and the rollover process of the T2 prototypes, the third part of the protocol was applied up to \( 0.90D_M \) (102% strain) (Fig. 3b); and for both cases, according to the control system of the setup a period of \( T = 100\text{s} \) was possible used. The correspondence between the percentage of \( D_M \) and \( \gamma_s \) is presented in Table 2.

![Displacement protocols for the shear tests for: a) T1, and b) T2.](image)
Table 2. Equivalence between percentage of $D_M$ and $\gamma_s$.

<table>
<thead>
<tr>
<th>%$D_M$</th>
<th>$\gamma_s$ [%]</th>
<th>Displacement [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>29</td>
<td>80</td>
</tr>
<tr>
<td>0.50</td>
<td>57</td>
<td>160</td>
</tr>
<tr>
<td>0.67</td>
<td>77</td>
<td>214</td>
</tr>
<tr>
<td>0.75</td>
<td>86</td>
<td>240</td>
</tr>
<tr>
<td>0.90</td>
<td>105</td>
<td>290</td>
</tr>
<tr>
<td>1.00</td>
<td>114</td>
<td>320</td>
</tr>
</tbody>
</table>

For the shear test program an experimental platform was designed and built at the Laboratorio de Pruebas para Homologaciones (MaP-H) of the Universidad del Valle. The setup was made by steel frames with a dedicated reaction framework. The setup allows to apply a total cyclic horizontal load up to 1000kN to two isolators in double shear configuration under a constant vertical load of 2000kN. The vertical load was applied through two hydraulic actuators with a capacity of 1000kN each and 100 mm stroke. For the horizontal load a hydraulic actuator with a stroke of ±500mm and a force capacity of 1000kN was used. Finally, instruments to measure the sliding guides position, the vertical load and the lateral load time-histories were employed (Fig. 4).

![Shear test setup](Fig. 4. Shear test setup.)

4 SHEAR TESTS RESULTS

Through the shear tests, the hysteresis loops shown in Fig. 5 were obtained. In all cases, a stiffness reduction with respect to the first cycles was observed for each deformation levels, due to the rupture of the bonds among the polymer chains and the reinforcement particles (Mullins effect) [28]. Secant stiffness and equivalent damping ratios parameters [29] were calculated for each step of the applied protocol (Fig. 6 and Fig. 7). The T2 prototypes showed lower stiffness than T1 (50% less for the design level) due to the reduction of the contact area, when top and bottom faces roll off the contact supports, as a result of their unbonded conditions (rollover deformation) [14]. However, these prototypes showed a stable rollover and returned to their initial position after each test without residual deformation. Regarding the target horizontal stiffness (680N/mm), with T1 a lower period in the building will be obtained (2.3s); however, due to the minimum difference (8%), an acceptable behavior in the isolated building could be expected. Meanwhile, with T2 a period higher than the design one will be achieved (3.2s) because, for compari-
son purpose, the same dimensions of T1 was used without taking account the detachment of the area during the roll over process.

As expected, in all cases the damping ratio was higher than the one obtained for the pure rubber (Fig. 7) [15], due to interaction with the reinforcement, being this effect more significant in prototypes T2. However, for both cases the damping ratio was higher than the required value for the design process (6%). It can be noticed that, for all deformation levels, the damping ratios of the unbonded isolators tends to be larger than those of the corresponding bolted one. Specifically, for T2 damping ratios higher than 10% were always attained, which are expected values for FREIs with high damping rubber [14]–[16], [30], [31]. Even though the secant stiffness of UP-FREIs was lower than steel reinforced one (T1) (Fig. 6), higher values of damping ratios can ensure a superior hysterical behavior of UP-FREIs with respect to SREIs (Fig. 7). With respect to the design target stiffness, UP-FREIs exhibited a 37% lower value despite to SREIs having 22% higher stiffness.
In T2, the flexibility of the reinforcement allowed the unbonded surfaces to roll off the loading surfaces and relieving the tensile stresses [12], achieving the design deformation without damage (Fig. 8b). In one of prototypes T1, the failure occurred due to the delamination of some layers. This detachment may be produced by a deficient impregnation process when the adherence material was applied to the steel plates and by the high tensile stress regions developed in this bonded device (Fig. 8a). In Table 3, the results for the tested deformation levels are summarized.

![Fig. 8. Deformation of the isolators during the shear test: a) T1, and b) T2.](image)

<table>
<thead>
<tr>
<th>Type</th>
<th>( K_{v_s} ) [kN/mm]</th>
<th>( \beta ) [%]</th>
<th>( K_{H} ) [kN/mm]</th>
<th>( \beta ) [%]</th>
<th>( \gamma_s=29% )</th>
<th>( \gamma_s=57% )</th>
<th>( \gamma_s=77% )</th>
<th>( \gamma_s=105% )</th>
<th>( \gamma_s=114% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1023</td>
<td>8</td>
<td>891</td>
<td>7</td>
<td>867</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T2</td>
<td>893</td>
<td>12</td>
<td>671</td>
<td>11</td>
<td>552</td>
<td>12</td>
<td>429</td>
<td>13</td>
<td>835</td>
</tr>
</tbody>
</table>

Table 3. Isolator’s properties for \( \gamma_s \) = 29%, 57%, 77%, 105% and 114%.

Regarding the vertical behavior, displacements during initial axial loading were measured in order to estimate a secant vertical stiffness \( K_{v_s} \) of the devices (Table 4) to be compared with the horizontal one at the design displacement level. The lower vertical stiffness of FREIs compared with classical SREIs has been commonly acknowledged [23]. This aspect can be seen in Table 4, where, as expected, UP-FREIs are more flexible than SREIs in the vertical direction due to lower stiffness of fiber layers [13]. Since the horizontal to vertical stiffness ratio is one order of magnitude lower in the case of UP-FREIs, at the current state of development these isolators could be mainly devoted to low rise buildings that would produce lower settlements under self-weight. (Table 4). Results on UP-FREIs confirmed that analytical models for stiffness evaluation have to take into account both contact area and shear modulus reduction [32]. A deeper investigation is ongoing on stability issues and vertical stiffness of FREIs, as well as different fiber reinforcing layers.

<table>
<thead>
<tr>
<th>Type</th>
<th>( K_{v_s} ) [kN/mm]</th>
<th>( K_{H} ) [kN/mm]</th>
<th>( K_{v_s}/K_{H} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>2500</td>
<td>0.84</td>
<td>2976</td>
</tr>
<tr>
<td>T2</td>
<td>100</td>
<td>0.43</td>
<td>233</td>
</tr>
</tbody>
</table>

Table 4. Isolator’s vertical stiffness and vertical and horizontal stiffness ratio.
5 CONCLUSIONS

- This paper presents a preliminary investigation of novel FREIs reinforced with polyester fiber, whose mechanical properties were obtained through a full-scale experimental program, according to the requirements of FEMA450.

- Compared to SREIs, the UP-FREIs showed a satisfactory behavior with a lower horizontal stiffness due to the rollover deformation and higher damping ratio. In order to obtain a target horizontal stiffness in unbounded applications, the variation of the contact area and the shear modulus should be considered simultaneously.

- A satisfactory behavior of UP-FREIs was obtained in the horizontal direction, thanks to lower stress at the interface between different layers, achieving the design strain without failure. They showed a positive tangent stiffness and stable rollover. Also, the UP-FREIs provided an adequate vertical to horizontal stiffness ratio, which could ensure a stable behavior of the isolators under vertical and horizontal loads.

- The results highlight an interesting comparison between UP-FREIs and SFREIs, with both satisfying required design values. Nevertheless, taking into account the fact that the price of polyester fiber is less than steel plates and that manufacturing process of the UP-FREIs is cheaper, this seems to be a very promising option, with greater potential to be implemented as a lighter and lower-cost seismic isolation system for developing countries.

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