Horizontal Behaviour of Stable Unbonded Fiber Reinforced Elastomeric Isolators (SU-FREIs) with Holes

N.C. Van Engelen, M.J. Tait & D. Konstantinidis Department of Civil Engineering, McMaster University, Hamilton, Canada



SUMMARY:

Base isolation reduces the effect of horizontal ground motion by introducing structural elements with low horizontal stiffness at the foundation level. A *Stable Unbonded Fiber Reinforced Elastomeric Isolator* (SU-FREI) is designed to maintain positive tangential stiffness for all levels of imposed horizontal displacement. These larger strip isolators will potentially have an undesirably large horizontal stiffness, thus reducing the seismic mitigation efficiency. One approach for modifying the stiffness is the introduction of holes to the loaded surface of the isolator. This paper presents the findings of an experimental study on four SU-FREIs. Holes are introduced to three of the SU-FREIs in three different layouts. Cyclic horizontal tests are conducted parallel to the largest length. The horizontal load-displacement hysteresis loops are presented and discussed. It is shown that the horizontal properties of the isolator are heavily influenced by the introduction of holes into the loaded surface of the isolator.

Keywords: Stable Unbonded Fiber Reinforced Elastomeric Isolator (SU-FREI), Base Isolation, Holes

1. INTRODUCTION

By allowing large displacements to occur at flexible horizontal elements introduced at the foundation level of a structure, the seismic demand can be reduced significantly. This process, known as base isolation, lengthens the natural period and decouples the structure from the strong ground motions of an earthquake. The change in the natural period shifts the structure out of the critical high energy frequency range of an earthquake.

The design of a seismic isolator is generally dominated by the horizontal and vertical stiffnesses. Under normal service loadings, the structure should act as a conventional fixed base structure, however, the horizontal stiffness of the isolation layer must be sufficiently low to allow large displacements under strong ground motions. A vertical stiffness several times larger than the horizontal stiffness is necessary to adequately support the weight of the structure and to eliminate potential rocking motions introduced by the isolation system (Kelly and Konstantinidis 2011).

To date, variations of Steel Reinforced Elastomeric Isolators (SREIs) remain some of the most commonly used forms of base isolation (Naeim and Kelly 1999). The reinforcement is orientated in alternating horizontal layers with the elastomer and is necessary to obtain a higher vertical stiffness (Kelly and Konstantinidis 2011). The implementation of base isolation is typically limited to high importance structures primarily due to the substantial costs associated with the system (Naeim and Kelly 1999). The major cost components originate from two sources: the isolators; and the structural system necessary to transfer the weight of the structure to the isolators. As a means to reduce costs from the former source, the traditional steel reinforcement can be replaced with fiber reinforcement, is assumed to be extensible and to offer no appreciable flexural stiffness, which results in unique performance properties. The use of fiber reinforcement may also simplify the manufacturing process and allow for large pads to be created from which smaller isolators can be cut to the required size (Kelly 1999). This method of manufacturing permits the construction of large strip isolators which can

be used to further decrease costs. The use of strip isolators can reduce the requirements for a load transfer structural system by providing uniform support along walls. These cost savings will facilitate further application of base isolation to low-rise residential and high importance structures in developing countries (Kelly 2002).

If the Fiber Reinforced Elastomeric Isolator (FREI) is placed unbonded to the supports, it exhibits a rollover deformation under horizontal displacement (Kelly 1999) as shown in Fig. 1.1. The rollover is a result of the lack of flexural resistance of the fiber reinforcement and the unbonded application. As the horizontal displacement increases, these isolators will soften until the initially vertical faces of the isolator come into contact with the upper and lower supports. Under certain aspect ratios, defined as the ratio of the length to height in the direction of loading, the isolator will retain a positive tangential stiffness and will begin to stiffen at contact (Toopchi-Nezhad et al. 2008a). These isolators are denoted as *Stable Unbonded-Fiber Reinforced Elastomeric Isolators* (SU-FREIs) and have been investigated in detail by Toopchi-Nezhad et al. (2008a, 2008b, 2009). In order to optimize the base isolation system, it is necessary to be able to retain sufficient control over the horizontal and vertical stiffness without compromising the strip geometry of the isolators.



Figure 1.1. Horizontal profile of the deformed and un-deformed shape of a SU-FREI under lateral displacement

The following is a continuation of the study conducted by Van Engelen et al. (2012) to determine the influence of holes on the vertical properties of six SU-FREIs. In this study, the preliminary results of the influence of holes on the effective horizontal stiffness and damping are discussed for four SU-FREIs. These areas have not yet been investigated for strip isolators with holes in the loaded surface.

2. BACKGROUND

2.1 Modifications to the Loaded Area

The stiffness of a system containing unmodified strip isolators could be significantly higher than that of a system containing smaller concentrated isolators due to the increase in the loaded area. A higher horizontal stiffness will decrease the shift in the structure's natural period, increasing the seismic demand and reducing the efficiency of the system. The use of an elastomer with a lower shear modulus can aid to reduce the horizontal stiffness, however, additional modifications may be required. By removing portions of the loaded surface of the isolator, through the introduction of holes, the horizontal stiffness can be reduced without compromising the strip geometry. The removal of area accomplishes a reduction in stiffness in the following ways:

- The reduction in the loaded surface reduces the shear area, thus also reducing the horizontal stiffness.
- The reduction in loaded surface increases the applied compressive stress to the isolator. It has been shown that the horizontal stiffness is inversely proportional to the applied compressive stress (de Raaf et al. 2011).
- The stiffness of FREIs is known to be influenced by the shape factor of the isolator, defined as the ratio of the load area to the unloaded area of a single layer of elastomer. A decrease in the shape factor will also result in a decrease in the horizontal stiffness (Tsai and Kelly 2002, 2005a, 2005b).

Therefore, it is important to understand the influence of a reduction in loaded area and shape factor on the horizontal and vertical stiffness. Isolators of equal loaded area but of different shape factor can be obtained by placing the hole in the centre of the isolator, or with equal halves on the edges.

3. SPECIMENS AND TEST SETUP

3.1 SU-FREI Specimens

In this study, four quarter scale rectangular SU-FREI designs were considered. These SU-FREIs are identical to those whose vertical properties were investigated by Van Engelen et al. (2012). The isolator geometric properties are given in Table 3.1. The isolators had a total height, h, of 22 mm and consisted of seven elastomeric layers of total height, t_r , of 19 mm, with six fiber layers of 0.55 mm thickness each. The length, a, and width, b, of the isolator were 52 mm and 76 mm, respectively. It should be noted that the uppermost and bottommost layer of elastomer were half the thickness of the middle layers. This design is intended to reduce the amount of residual displacement in the layers during lateral displacements caused by the rollover of the ends. Subsequently, there are two unique shape factors for each isolator based on the different layer thickness.

Table 3.1. Isolator Properties									
Isolator	Area (mm ²)	Shape	Factor	Area Removed (%)					
B1	3952	4.9	9.7	-					
B2	3443	2.9	5.9	13%					
B3	3500	3.3	6.7	11%					
B4	3698	3.7	7.5	6%					

Isolator B1 was the reference case with no area removed. Isolator B2 had two identical holes placed centrally on each half of the isolator, B3 and B4 had holes placed in the geometric centre of the isolator. In total, three different layouts were considered with two different hole sizes. Fig. 3.1 shows each isolator's loaded surface geometry and the test specimens.



Figure 3.1. (a) Plan view of the four SU-FREIs investigated, and (b) the test specimens

3.2 Experimental Setup

The horizontal tests were conducted under lateral displacement control and vertical load control. Each isolator was monotonically loaded up to 8 kN, which corresponds to an approximate 2 MPa design pressure for isolator B1. All isolators were tested under the same compressive load to simulate their application on an identical structure. Twenty-one fully reversed sinusoidal cycles were conducted; three at each displacement amplitude of 25, 50, 75, 100, 150, 200, and 250% t_r. The test apparatus is shown in Fig. 3.2. The horizontal load and displacement were monitored with a load cell and displacement transducer, respectively, while the vertical displacement was monitored with four laser

displacement transducers, in addition to three identically placed load cells to measure the vertical load. Further information on the test setup is available in Foster (2011). Each isolator was tested parallel to the width b, followed by parallel to the length a, denoted as the 0 degree and 90 degree orientation, respectively. Vertical tests were conducted before and after each horizontal test as a means to monitor damage, such as delamination, within the isolator. This preliminary study only considers the results obtained from the 0 degree orientation.



Figure 3.2. Test apparatus

4. EXPERIMENTAL RESULTS

4.1 Deformed Shape

The typical deformed shape of an isolator under various horizontal displacement amplitudes is shown in Fig. 4.1. At very low displacements, about 50% t_r or less, the roll-off was small, and the isolator appeared to deform in a manner similar to a fully bonded isolator. As the displacement increased, the roll-off also increased and the curved profile became more distinguishable. At approximately 200% t_r , full rollover occurred and the initially vertical face came into full contact with the supports. As displacement continued, further rollover was resisted by the supports.



Figure 4.1. Deformed shape under lateral displacement

4.2 Effective Horizontal Stiffness

The effective horizontal stiffness, K_{eff} , can be determined from the experimentally obtained hysteresis loops and is defined as:

$$K_{eff} = \frac{(F_{max} - F_{min})}{(\Delta_{max} - \Delta_{min})}$$
(4.1)

where Δ_{max} , Δ_{min} and F_{max} , F_{min} correspond to the maximum and minimum displacement and lateral force at these displacements for each cycle, respectively. The following results and discussion correspond to the unscragged (first) cycle of each displacement amplitude.

Te e let e e	Displacement Amplitude							
Isolator	25% t _r	50% t _r	75% t _r	100% t _r	150% t _r	200% t _r	250% t _r	
B1	91.7	74.6	62.9	55.0	46.2	49.6	52.1	
B2	73.2	55.9	47.6	42.4	38.9	45.2	48.9	
B3	72.7	53.9	43.0	35.6	31.5	43.0	47.2	
B4	86.3	62.7	51.0	43.0	36.7	45.5	51.1	

Table 4.1. Effective Horizontal Stiffness (N/mm)

Table 4.1 shows the effective horizontal stiffness obtained from the experimental study. In all cases, the reference isolator B1 displayed the highest effective horizontal stiffness. Shown graphically in Fig. 4.2, it can be seen that isolators of similar design, B3 and B4, followed a similar trend with decreasing effective horizontal stiffness as the loaded area of the isolator removed increased. B2, which contained two holes, performed between B3 and B4. All isolators showed an increase in effective horizontal stiffness beginning at 200% t_r, which corresponds to the approximate displacement at which full contact was observed to occur. The increase in effective horizontal stiffness at higher displacement amplitudes is considered a desirable feature to restrict displacements beyond design-basis events (Toopchi-Nezhad et al. 2008b).



Figure 4.2. Effective horizontal stiffness as a function of lateral displacement

Overall, the relative horizontal stiffness, or the horizontal stiffness of the isolator normalized by B1, was relatively consistent in the midrange displacement amplitudes between 50 to 150% t_r for isolators B3 and B4. It is interesting to note that the relative performance at displacement amplitudes

corresponding to full contact, 200 and 250% t_r, the relative stiffness approaches unity as shown in Table 4.2 and graphically in Fig. 4.3. This high degree of consistency at large displacement amplitudes between the various designs, at a minimum of 0.91 for B3 at 250% t_r, suggests that the effective horizontal stiffness is relatively independent of the hole size and location past full contact. This is especially remarkable for isolator B3, which had a minimum relative stiffness of 0.65 at 100% t_r and a maximum relative stiffness of 0.91 at 250% tr.

Table 4.2. Relative Effective Horizontal Stiffless								
Isolator	Displacement Amplitude							
	25% t _r	50% t _r	75% t _r	100% t _r	150% t _r	200% t _r	250% t _r	
B2	0.80	0.75	0.76	0.77	0.84	0.91	0.94	
B3	0.79	0.72	0.68	0.65	0.68	0.87	0.91	
B4	0.94	0.84	0.81	0.78	0.79	0.92	0.98	

Table 1 2 Relative Effective Horizontal Stiffness



Figure 4.3. Relative effective horizontal stiffness as a function of lateral displacement

The hysteresis loops of all four isolators considered are shown in Fig. 4.4. It can be seen that the introduction of the holes to the loaded surface can significantly alter the hysteresis loops in both the loading and unloading paths. In intermediate displacements, scragged cycles of isolator B3 and B4 had a low tangential stiffness and subsequently had little change in lateral load with increasing displacement. The effective horizontal stiffness will continually decrease in this range. It can be observed that a substantial increase in lateral load occured at higher displacement amplitudes. This increase began shortly after 150% tr for all isolators, corresponding to contact of the initially vertical face of the isolator. The lateral load continued to increase up to 250% t_r, which was the maximum considered displacement amplitude.



Figure 4.4. Horizontal load-displacement hysteresis loops showing the effective horizontal stiffness at 25% t_r and 250% t_r for tests conducted with an 8 kN compressive load

4.3 Equivalent Viscous Damping

Toopchi-Nezhad et al. (2008b) showed that SU-FREIs are able to obtain significantly higher damping than the inherent damping of the elastomer. This additional damping is believed to originate from the fiber reinforcement layers as the individual fibers move along one another during lateral displacement (Kelly 1999). When the test forcing frequency is equal to the target natural frequency of the structure, the equivalent viscous damping ratio, henceforth referred to simply as damping, for each cycle is:

$$\xi_{\rm eq} = \frac{W_{\rm d}}{4\pi W_{\rm s}} \tag{4.2}$$

where W_d is the dissipated energy, or the area contained within the hysteresis loop, and W_s is the restored elastic energy defined as:

$$W_{s} = \frac{1}{2} K_{eff} \Delta_{max,ave}^{2}$$
(4.3)

and

$$\Delta_{\max,\text{ave}} = \frac{(\Delta_{\max} + |\Delta_{\min}|)}{2} \tag{4.4}$$

The damping from the experimental study is shown in Table 4.3. At all displacement amplitudes, isolator B1 was found to contain the lowest damping with values ranging between 7.8% and 10.5% of critical. The damping reached a maximum of 19.7% for B3 at a displacement amplitude of 100% t_r .

Isolator	Displacement Amplitude							
	25% t _r	50% t _r	75% t _r	100% t _r	150% t _r	200% t _r	250% t _r	
B1	10.5	10.5	9.6	9.2	9.6	8.1	7.8	
B2	15.6	17.1	15.9	15.0	14.0	10.9	9.7	
B3	16.3	18.8	18.9	19.7	19.5	12.9	11.6	
B4	18.9	14.8	14.2	14.2	14.5	10.6	9.5	

Table 4.3. Equivalent Viscous Damping (% of Critical)

The damping as a function of displacement amplitude is shown graphically in Fig. 4.5. Similar observations can be made as with the effective horizontal stiffness results. Isolators with central holes, B3 and B4, followed a similar trend in damping with the exception of 25% t_r . As the amount of area removed within the similar design increased, the damping increased. As the isolators approached full rollover, a drop in damping was observed. This drop is similar to the convergence of the effective horizontal stiffness discussed previously. In comparison to the other isolators, B1 was relatively independent of displacement amplitude. B1 displayed a minor decreasing trend as displacement amplitude increased. The high damping in B4 at 25% t_r was not observed on subsequent scragged cycles and is unique to the first cycle.



Figure 4.5. Equivalent viscous damping as a function of lateral displacement

The relative damping values, or the damping normalized by B1, are shown in Table 4.4 and graphically in Fig. 4.6. Here the convergence of the damping at higher displacement amplitudes was a maximum of 1.49 corresponding to the 250% t_r displacement amplitude of isolator B3. Although substantially more variation is noted than seen with the effective horizontal stiffness, the relative drop in damping at full rollover is significant. It is postulated that the variation in damping originates from two sources: the first being the changes in effective horizontal stiffness; the second being from a decreased length in fibers. The damping ratio is inversely proportional to the effective stiffness, thus changes in stiffness will also influence the damping. The overall reduced length in fibers, due to the introduction of holes, causes increased inter-fiber movement, and thus increased damping. When full contact occurs, the rollover deformation of the isolator is at a maximum. Thus the highly distorted curved displacement profile ceases, which is believed to result in less damping as the amount of movement undertaken by the fibers is also decreased in addition to the reduction due to increased stiffness.

Table 4.4. Relative Equivalent Viscous Damping

Isolator	Displacement Amplitude							
	25% t _r	50% t _r	75% t _r	100% t _r	150% t _r	200% t _r	250% t _r	
B2	1.49	1.63	1.66	1.63	1.46	1.35	1.24	
B3	1.55	1.79	1.97	2.14	2.03	1.59	1.49	
B4	1.80	1.41	1.48	1.54	1.51	1.31	1.22	



Figure 4.6. Relative damping as a function of lateral displacement

4.4 Damage

After each horizontal and vertical test, the isolators were inspected for damage such as delamination or bulging. Overall the isolators performed well with only a minor delamination of approximately 10 mm in length being observed on B4 as shown in Fig. 4.7. Due to the setup of the experiment, it is unclear if the free surface of the holes came into contact with each other at higher displacement amplitudes. No delaminations were observed within the holes, suggesting that this did not occur.



Figure 4.7. Damage located on the shorter (52 mm) length of isolator B4

5. CONCLUSIONS

This paper presented the initial experimental results of SU-FREIs with holes in the loaded surface. Four SU-FREIs were investigated with three different hole configurations. Two isolators contained central holes, one contained two holes placed centrally on each half of the isolator, and one had no area removed. It was determined that the effective horizontal stiffness at higher displacement amplitudes, 200 to 250% t_r , performed consistently regardless of the hole geometry. A minimum relative stiffness of 0.91 was observed at a displacement amplitude of 250% t_r . However, intermediate effective horizontal stiffness was found to vary between isolators. These results suggest that the stiffness of the isolator can be optimized at intermediate amplitudes without compromising the increase in stiffness at large displacement amplitudes. This is a desirable result as the seismic mitigation efficiency in mid-displacement ranges can be increased, while still retaining a high effective horizontal stiffness beyond design-basis events.

The introduction of holes was found to provide improved damping properties. This is attributed to two sources: a decrease in K_{eff} ; and a reduction in the length of the fibers. It was postulated that the introduction of holes to the loaded surface allowed increased inter-fiber movement, resulting in an increase in the observed damping. Peak damping was observed in the intermediate displacement amplitudes, with a significant decrease in damping occurring at larger displacement amplitudes corresponding to full rollover.

Additional parametric studies and theoretical analysis are required in order to determine the combined influence on the horizontal and vertical properties of SU-FREIs with holes in the loaded surface. Preliminary findings on the horizontal properties indicate that the potential for considerable control over the effective horizontal stiffness and damping of strip isolators exists. These results indicate that strip isolators are a promising approach to seismic isolation with additional advantages over conventional approaches.

ACKNOWLEDGEMENT

This research was carried out as part of the mandate of the McMaster University Centre for Effective Design of Structures and funded through the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Ministry of Economic Development and Innovation.

REFERENCES

- de Raaf, M.G.P., Tait, M. J. and Toopchi-Nezhad, H. (2011). Stability of Fiber-reinforced Elastomeric Bearings in an Unbonded Application. *Journal of Composite Materials*. **45:18**, 1873-1884.
- Foster, B.A.D. (2011). Base Isolation Using Stable Unbonded Fibre Reinforced Elastomeric Isolators (SU-FREI). M.A.Sc. thesis, McMaster University.
- Kelly, J.M. (1999). Analysis of Fiber-reinforced Elastomeric Isolators. *Journal of Seismology and Earthquake Engineering*. **2:1**, 19-34.
- Kelly, J.M. (2002). Seismic Isolation Systems for Developing Countries. Earthquake Spectra. 18:3, 385-406.
- Kelly, J.M. and Konstantinidis, D. (2011). *Mechanics of Rubber Bearings for Seismic Isolation and Vibration Isolation*, John Wiley & Sons, Chichester, U.K.
- Naeim, F. and Kelly, J.M. (1999). *Design of Seismic Isolated Structures: From Theory to Practice*, John Wiley & Sons, United States of America.
- Toopchi-Nezhad, H., Tait, M.J. and Drysdale, R.G. (2008a). Testing and Modeling of Square Carbon Fiberreinforced Elastomeric Seismic Isolators. *Structural Control and Health Monitoring*. **15**, 876-900.
- Toopchi-Nezhad, H., Tait, M.J. and Drysdale, R.G. (2008b). Lateral Response Evaluation of Fiber-Reinforced Neoprene Seismic Isolators Utilized in an Unbonded Application. *Journal of Structural Engineering*. 134:10, 1627-1637.
- Toopchi-Nezhad, H., Drysdale, R.G. and Tait, M.J. (2009). Parametric Study on the Response of Stable Unbonded-Fiber Reinforced Elastomeric Isolators (SU-FREIs). *Journal of Composite Materials*. **43:15**, 1569-1587.
- Tsai, H.C. and Kelly, J.M. (2002). Stiffness Analysis of Fiber-Reinforced Rectangular Seismic Isolators. *Journal* of Engineering Mechanics. **128:4**, 462-470.
- Tsai, H.C. and Kelly, J.M. (2005a). Buckling of Short Beams with Warping Effect Included. *International Journal of Solids and Structures*. **42**, 239-253.
- Tsai, H.C. and Kelly, J.M. (2005b). Buckling Load of Seismic Isolators Affected by Flexibility of Reinforcement. *International Journal of Solids and Structures*. **42**, 255-269.
- Van Engelen, N.C., Tait M. J. and Konstantinidis, D. (2012). Vertical Response Behaviour of Stable Unbonded Fiber Reinforced Elastomeric Isolators (SU-FREIs) with Holes in the Loaded Surface. *Canadian Society for Civil Engineering Annual General Conference*. Edmonton, Alberta, Canada. June 6-9, 2012.