The 11th Canadian Conference on Earthquake Engineering
Canadian Association for Earthquake Engineering

INVESTIGATION OF PARTIALLY BONDED FIBER-REINFORCED ELASTOMERIC ISOLATORS

Niel C. Van Engelen
PhD Candidate, McMaster University, Canada
vanengn@mcmaster.ca

Michael J. Tait
Associate Professor, McMaster University, Canada
taitm@mcmaster.ca

Dimitrios Konstantinidis
Assistant Professor, McMaster University, Canada
konstant@mcmaster.ca

ABSTRACT: Stable unbonded fiber-reinforced elastomeric isolators (SU-FREIs) have been presented as a potentially low-cost alternative to conventional steel-reinforced elastomeric isolators. The fiber reinforcement allows for a unique deformed shape to develop during horizontal displacement. This unique deformed shape, known as *rollover*, is the cause of a desirable softening response that increases with increasing horizontal displacement. For rollover to occur, it is necessary that the isolator be placed unbonded between the upper and lower supports. Although the unbonded application eliminates the requirement of large steel end-plates to mechanically fasten the isolator to the supports, it also develops concerns over the force transfer between the structure and the isolator. Notably, SU-FREIs rely solely on friction to transfer the horizontal force, which may allow slip and permanent displacements in certain loading conditions, and cannot transfer a vertical tensile load. It has been proposed that these concerns can be eliminated by *partially* bonding the isolator to the supports to form a hybrid between an unbonded isolator and a fully bonded isolator. Partially bonded fiber-reinforced elastomeric isolators (PB-FREIs) merge the beneficial characteristics of both types of isolators to retain the softening due to rollover deformation, prevent slip and provide some tensile resistance. This paper explores the concept of PB-FREIs through finite element analysis. The force-displacement relationship and vertical stress of a PB-FREI and SU-FREI displaced horizontally in both principal directions are investigated.

1. Introduction

Adaptive seismic isolation devices are characterized by a non-linear horizontal force-displacement relationship designed to achieve multiple performance objectives depending on the hazard level of the earthquake event. Most adaptive devices have a softening phase followed by a stiffening phase that begins at large displacements, typically near the maximum displacement capacity of the device. Isolation systems such as the triple friction pendulum (Fenz and Constantinou, 2008), sliding systems with variable curvature (Tsai et al., 2003, Lu et al., 2011), and several variations of elastomeric devices exhibit these basic non-linear characteristics (Toopchi-Nezhad et al., 2008, Yang et al., 2010).

The initial stiffness of an adaptive device prevents excessive displacements under smaller service loads. If a design-basis event occurs, the device significantly softens with horizontal displacement. The softening response increases the efficiency of the isolation system by shifting the fundamental frequency further out of the critical high-energy range of a typical earthquake event. During events that meet or exceed the maximum considered earthquake, large displacements occur and the system enters the stiffening phase.

The horizontal stiffening that occurs at large displacements is believed to perform as a self-restraint to prevent excessive horizontal displacements (Toopchi-Nezhad et al., 2008, Fenz and Constantinou, 2008, Yang et al., 2010, Lu et al., 2011).

The stable unbonded fiber-reinforced elastomeric isolator (SU-FREI) is an example of an elastomeric device that exhibits these adaptive characteristics. The softening and stiffening characteristics in SU-FREIs develop due to the combination of fiber reinforcement, used in lieu of conventional steel reinforcement, and the unbonded application. Steel-reinforced elastomeric isolators (SREIs) generally contain large steel end plates used to mechanically fasten the isolator to the upper and lower supports. The unbonded application removes these large steel end plates, resulting in a substantially lighter and potentially cost-effective isolator. Reducing costs is critical for seismic isolation to become widespread in developed and developing countries.

Although the unbonded application has been attributed to several beneficial performance features, such as the adaptive characteristics and reduced stress within the elastomer and reinforcement (Kelly and Konstantinidis, 2011, Toopchi-Nezhad et al., 2011), the transfer of horizontal forces to the isolator is entirely reliant on friction. Experimental testing has shown that friction often provides adequate force transfer (Toopchi-Nezhad et al., 2009). However, in certain extreme loading situations, such as events that exceed the maximum considered earthquake, slip may occur and result in an undesirable permanent displacement (Foster, 2011). Furthermore, the unbonded application also makes this type of isolator incapable of resisting any tensile forces which may occur in situations with large vertical accelerations or where overturning is of concern.

It was proposed that concerns over slip, resulting permanent displacements, and the transfer of tensile forces could be addressed by partially bonding the isolator (Van Engelen et al., 2015). The resulting isolator behaves as a hybrid between a conventional fully bonded isolator and an adaptive SU-FREI. This paper further investigates the concept of partially bonded fiber-reinforced elastomeric isolators (PB-FREIs) through a numerical investigation using the finite element method. The horizontal force-displacement relationship and vertical stress are presented and discussed for a PB-FREI and an identical SU-FREI displaced in both principal horizontal directions.

2. SU-FREIs

The significant weight and cost of SREIs have acted as barriers to widespread base isolation application, notably within developing countries where the devastation due to earthquakes is often more severe. In order to address these limitations, it was proposed that the conventional steel reinforcement could be replaced by fiber reinforcement with similar mechanical properties in tension (Kelly, 1999). Furthermore, the large steel end plates used to mechanically fasten the isolator to the supports could be removed in favour of an unbonded application; further reducing the cost and weight. By removing the steel components of the isolator, it was suggested that FREIs could be manufactured in large pads and subsequently cut to the desired size (Kelly, 1999).

Experimental testing identified that the lack of flexural rigidity of the fiber reinforcement, combined with the unbonded application, developed a unique *rollover* deformation, shown in Fig. 1 (a) (Toopchi-Nezhad et al., 2008). Rollover occurs as the horizontal surfaces of the isolator lose contact with the upper and lower supports. Two curved rollover sections develop, often defined by a vertical line drawn from the opposing edge of the isolator that remains in contact with the supports.

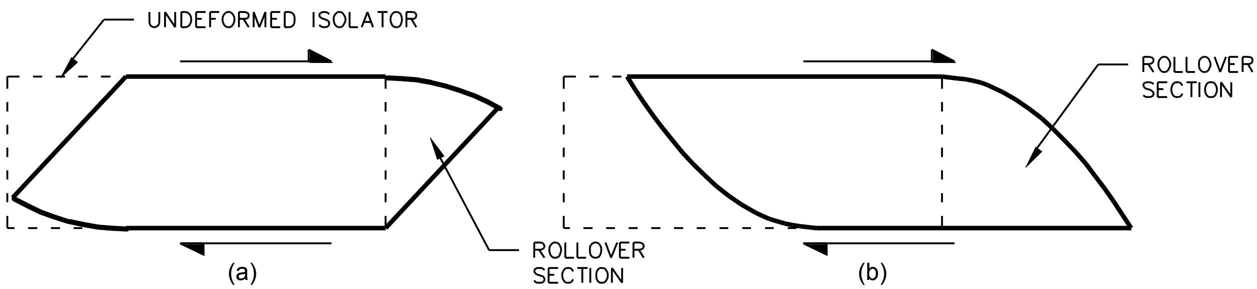


Fig. 1 – (a) Rollover and (b) Full Rollover of an Unbonded FREI

The resistance of the rollover sections to horizontal displacement is less than an equivalent section in simple shear (Van Engelen et al., 2014). Furthermore, the size of a rollover section is proportional to the horizontal displacement. Thus, as horizontal displacement occurs, the size of the rollover section increases and the isolator softens. The softening continues until the initially vertical faces of the isolator rotate and contact the upper and lower supports, completing *full rollover* (see Fig. 1 (b)). Full rollover prevents additional rollover, stiffening the isolator with additional horizontal displacement.

Rollover and full rollover determine the adaptive characteristics of SU-FREIs. The horizontal displacement that full rollover occurs at has been shown analytically to be a function of the layer design and stiffness of the fiber reinforcement in bending (Van Engelen et al., 2014). If the softening due to rollover continues, the isolator will become unstable as the horizontal tangential stiffness becomes negative. This is a concern in isolators with a low width-to-total height aspect ratio since the volume of elastomer that has undergone rollover is large compared to the total volume of the isolator. Analytical investigation (Van Engelen et al., 2014), reinforced with experimental findings (Toopchi-Nezhad et al., 2008), indicate that the transition between a horizontally unstable and stable isolator occurs at a width-to-total height aspect ratio of approximately 2.5, depending on the layer design. Conversely, large aspect ratios will reduce the magnitude of the softening since the volume of the rollover is small in comparison to the total volume of the isolator. In SU-FREIs with a width-to-total height aspect ratio of about 10 and greater the softening due to rollover becomes negligible (Van Engelen et al., 2014).

3. PB-FREIs

PB-FREIs were first proposed by Van Engelen et al. (2015) to address concerns over potential permanent displacement and uplift in certain loading situations. The study identified that a portion of an unbonded SU-FREI may permanently remain in contact with the supports regardless of rollover. This length, denoted as B_{max} and demonstrated in Fig. 2, represents the maximum internal bond length, B, that can be applied without entering the rollover sections. Based on the full rollover prediction by Kelly and Konstantinidis (2007), it was determined that a width-to-total height aspect ratio of 3.3 or greater is required for B_{max} to be greater than zero (i.e. a portion of the isolator will not experience rollover).

Russo et al. (2013) recognized that the vertical deflection of the isolator could delay the loss of contact of the rollover section from the upper and lower supports, thus reducing the size of the rollover sections. This was observed in the experimental testing conducted by Van Engelen et al. (2015) to expand the length of the bond that could be applied without entering the rollover section. Therefore, B_{max} was considered a theoretical lower bound bond length that could be applied without entering the rollover section. Numerical modelling was used to investigate the performance of a PB-FREI under horizontal displacement and a vertical tensile load. It was found that a similar horizontal force-displacement relationship as observed in compression could be obtained; although it was noted that the findings lacked experimental verification.

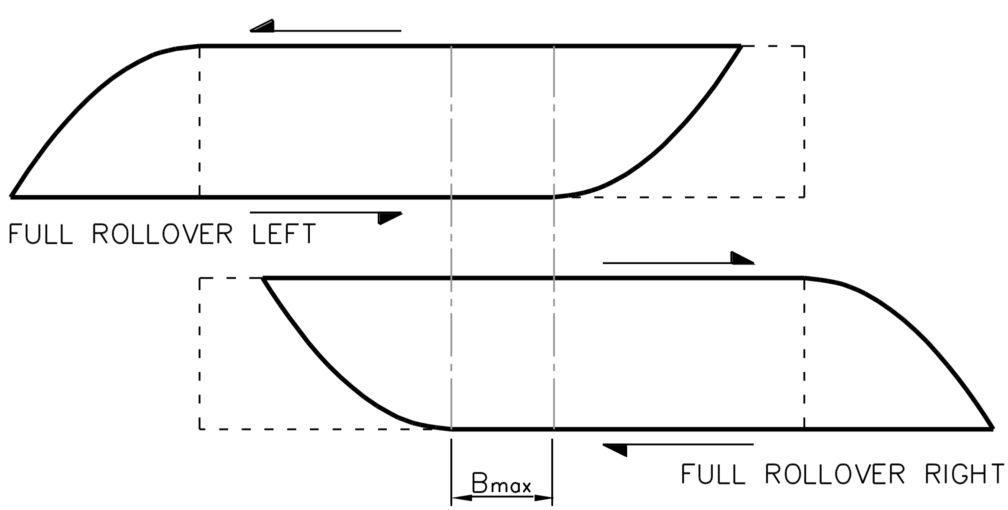


Fig. 2 – Schematic of B_{max}, the Portion of the Isolator that does not Rollover

The concept of PB-FREIs is most appropriate for isolators with relatively large width-to-total height aspect ratios. Relatively large aspect ratios are required in order to have a sizable bonded portion that does not enter the rollover section. Thus, it is anticipated that large square or circular isolators may become a common form of PB-FREIs. However, the experimental program and finite element analysis in Van Engelen et al. (2015) considered only rectangular specimens and the horizontal displacements parallel to the width of the isolator. If the concept of a PB-FREI is applied to rectangular isolators with a low length-to-total height aspect ratio (i.e. perpendicular-to-width), illustrated in Fig. 3, the partial bond can only be positioned such that it will not be influential over rollover for displacements in the parallel-to-width direction. The response of a rectangular PB-FREI in the perpendicular-to-width direction has not been investigated in the literature.

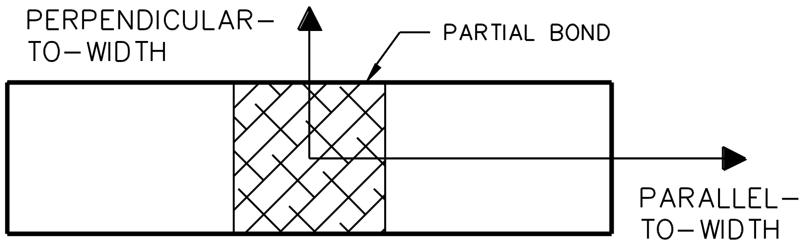


Fig. 3 – Plan View of a PB-FREI

4. Finite Element Analysis

4.1. Isolator Design

The layer design and material properties of the isolator considered in this study were identical to specimen E1 from Van Engelen et al. (2015). The quarter scale model isolator contained seven layers of neoprene with a total height of 22.35 mm and a total thickness of the elastomeric layers, t_r, of 19.05 mm. The five interior layers of elastomer had a thickness of 3.175 mm, and the two exterior layers had a thickness of 1.5875 mm. The reinforcement matrix had a thickness of 0.55 mm, representing the combined thickness of the fiber reinforcement and bonding agent. A shear modulus of G = 0.4 MPa and bulk modulus of 2000 MPa were selected to model the neoprene. The isolator had a width-to-total height aspect ratio, R_1, of 3.0 and a length-to-total height aspect ratio, R_2, of 1.5. A bond length of B = 43 % was applied in the parallel-to-width direction and a bond length of B = 100 % was applied in the perpendicular-to-width direction (i.e. the special case where the isolator is fully bonded to the edge).

4.2. Finite Element Model

The finite element analysis was conducted with MSC Marc (2011), a commercially available finite element software package. The isolator was modelled in three dimensions, shown in Fig. 4, with an updated Lagrangian framework, similar to the method used in Van Engelen et al. (2015). The elastomeric layers were modelled with eight-node hexahedron isoparametric elements. The fiber reinforcement was modelled with four-node quadrilateral membrane elements with no flexural rigidity. The non-linear material properties of the elastomer were modelled with a compressible neo-Hookean material model.

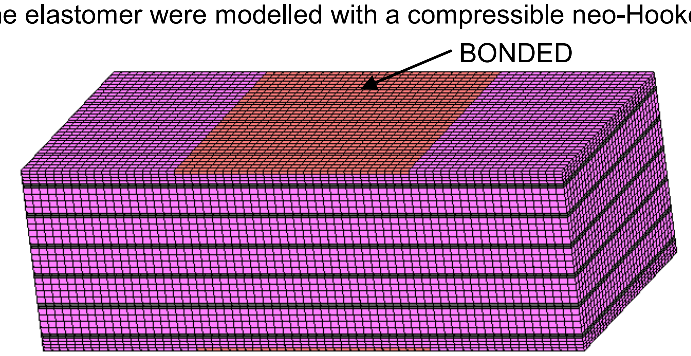


Fig. 4 – Finite Element Model of the PB-FREI

The contact between the elastomer and the upper and lower supports was characterized by Coulomb friction. The coefficient of friction between the elastomer and the upper and lower surfaces was selected to prevent slip between these surfaces when contact occurred. The partial bond was modelled by defining a glued contact between the partially bonded region (identified in Fig. 4) and the upper and lower supports.

Two bond variations, unbonded and partially bonded, as described above, were considered. Four tests were conducted; both bond configurations were displaced horizontally in the two principal directions. In each test, the isolator was monotonically loaded to an average vertical stress of 2.0 MPa and displaced horizontally up to a maximum displacement of u/t_r = 1.75.

4.3. Parallel-to-Width Direction

4.3.1. Force-Displacement Relationship

The force-displacement relationship in the parallel-to-width direction is compared in Fig. 5, where the force has been normalized by G and the total plan area, A, and u has been normalized by t_r. The figure shows the partially bonded (PB), unbonded (UB) and idealized fully bonded (FB) cases. Note that the idealized fully bonded case was provided for comparative purposes based on the expected constant horizontal stiffness of a fully bonded isolator. A fully bonded isolator was not modelled in this investigation.

The softening due to rollover is evident in Fig. 5 as the PB and UB cases diverge from the FB case with increasing u/t_r. At very low horizontal displacements, less than u/t_r = 0.5, the force-displacement relationship between the three cases were similar. As the horizontal displacement increased, the PB and UB cases diverged from the FB case due to rollover. At u/t_r = 1.75, F/GA = 1.05 and F/GA = 0.92 in the PB and UB cases, respectively. These values correspond to a 40 % and 47 % decrease over the FB case of F/GA = 1.75 at the same horizontal displacement.

Despite the presence of the partial bond, the PB and UB case are indistinguishable up to u/t_r = 1.40. Note that a partial bond of B = 43 % determines that the bond enters the rollover section at a displacement of u/t_r = 1.00 for the isolator considered. This was consistent with the observations made in Van Engelen et al. (2015) where it was found that the bond could extend past the theoretical limit without being pronounced in the horizontal force-displacement relationship. Despite the divergence of the PB and UB case at displacements exceeding u/t_r = 1.40, it should be noted that the magnitude of the deviation was small. Consequently, the effect on the performance of a base isolated structure with the PB-FREI considered in comparison to the UB case is also anticipated to be small; although this was not investigated in this study.

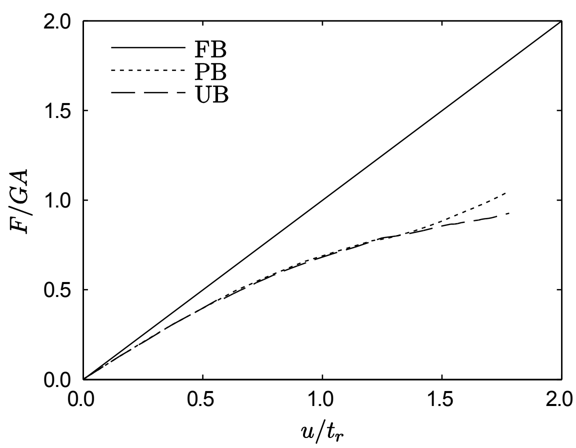


Fig. 5 – Horizontal Force-Displacement Relationship in the Parallel-to-Width Direction, Obtained from Finite Element Analysis

4.3.2. Vertical Stress

In a finite element investigation, tensile stress within the elastomeric layers have been found to be significantly lower in unbonded FREIs than identical bonded FREIs under horizontal displacement (Toopchi-Nezhad et al., 2011). In a bonded isolator, tensile stress develops to equilibrate the unbalanced moment generated by horizontal displacement. In an unbonded isolator, this tensile stress cannot develop and the unbalanced moment is equilibrated by a shift in the compression centroid (Konstantinidis et al., 2008). Partially bonding the isolator may re-introduce the possibility of tensile stress developing in a bonded rollover section. A bonded rollover section develops as the partial bond enters what would otherwise constitute the rollover section of the isolator, illustrated in Fig. 6. The bonded rollover section prevents additional rollover, simultaneously delaying full rollover and stiffening the isolator.

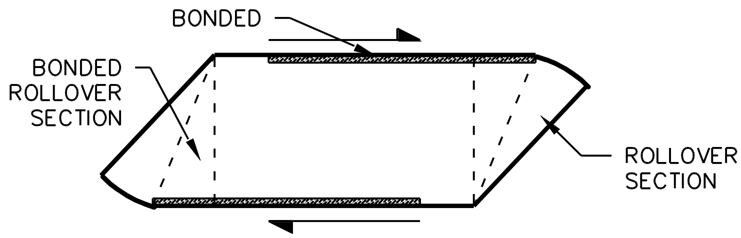


Fig. 6 – Idealized Division of a PB-FREI into Sections

The concept of PB-FREIs was proposed in part to provide some level of tensile resistance. Cavitation in multilayer elastomeric isolators is a concern when the isolator experiences tensile stress. Although cavitation can occur at relatively low tensile strains under pure tension, under the combined action of tension and shear, this damaging effect can be avoided (Kelly and Konstantinidis, 2011). The vertical stress was considered herein since it is of most interest with respect to the PB-FREI concept.

A cross section of the vertical stress, normalized by the average vertical compressive stress, is shown in Fig. 7 for the UB and PB case at u/t_r = 1.75. The vertical cross section was taken along the center of the length. The UB and PB isolator were both dominated by compressive stress in the central section, where the contact between the upper and lower supports and the isolator overlaps. Localized deformations were observed in what would constitute the bonded rollover sections in the PB case. These localized deformations were associated with the minor increase in the force-displacement relationship identified in Fig. 5. The bonded rollover section caused an increase in tensile stress in these regions. Consequently, the compressive stress in the central section was larger in the PB case to equilibrate the tensile stress in the bonded rollover sections. The vertical stress in the rollover sections outside of the localized area influenced by the partial bond were otherwise small in both cases.

4.4. Perpendicular-to-Width Direction

4.4.1. Force-Displacement Relationship

The force-displacement relationship in the perpendicular-to-width direction is compared in Fig. 8, where the force has been normalized by *GA*, and *u* has been normalized by t_r. The softening in the perpendicular direction is more pronounced than the parallel direction (see Fig. 5). This occurs due to the lower aspect ratio in the perpendicular direction (i.e. R_2 = 1.5, compared to R_1 = 3.0 in the parallel direction). As rollover occurs with horizontal displacement, the volume of elastomer that experiences rollover is large in comparison to the total volume of the isolator. Since the horizontal resistance of a rollover section is less than an equivalent volume in simple shear, the isolator becomes horizontally unstable. For the isolator considered, horizontal instability occurred at u/t_r = 0.73 and u/t_r = 1.13 in the UB and PB cases, respectively. The force at the respective points of instability was *F/GA* = 0.27 and *F/GA* = 0.42. These forces correspond to a 63 % decrease over the FB case at the same horizontal displacement in both cases.

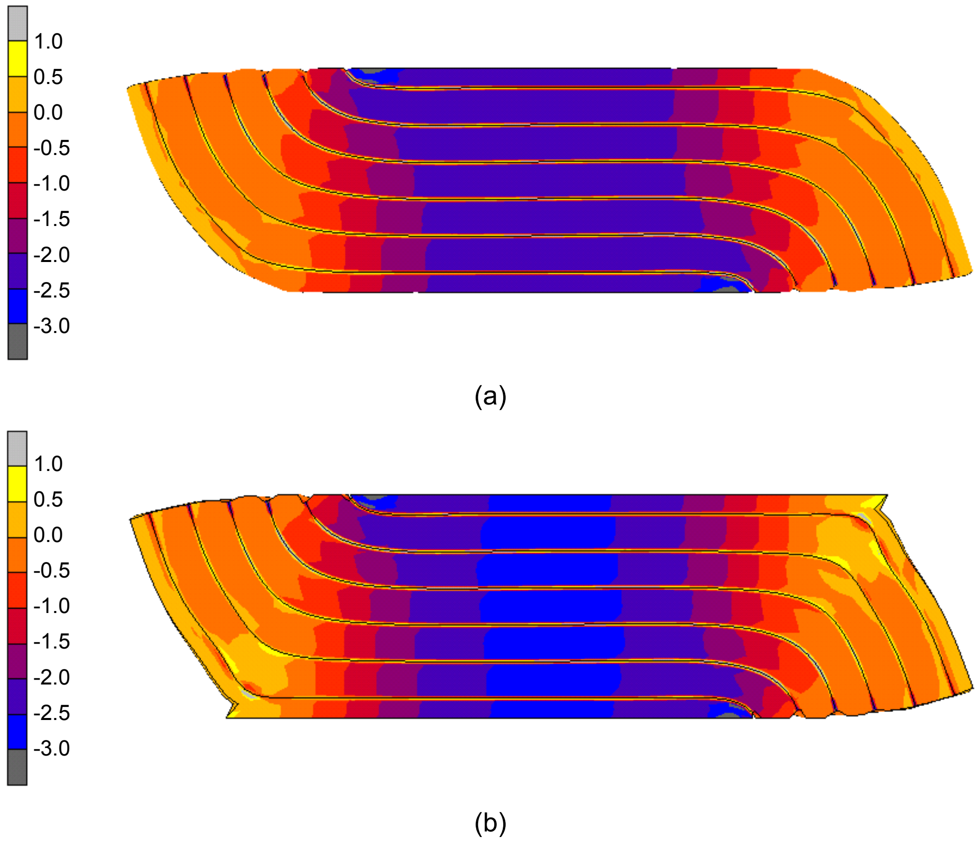


Fig. 7 – Normalized Vertical Stress at u/t_r = 1.75 along the Center of the Length for the (a) UB and (b) PB cases

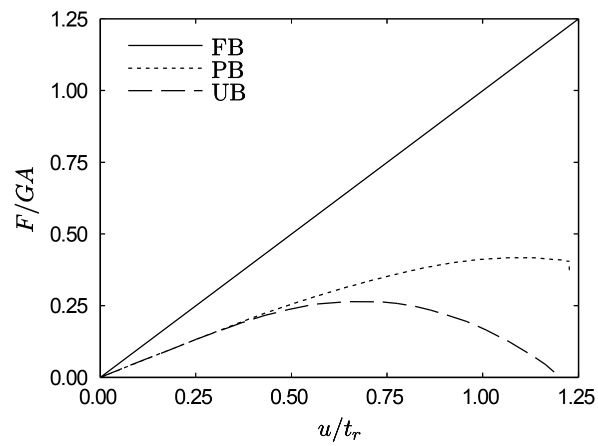
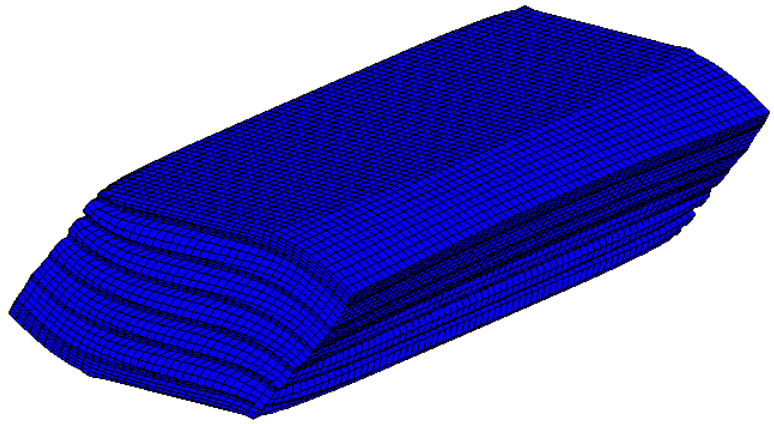
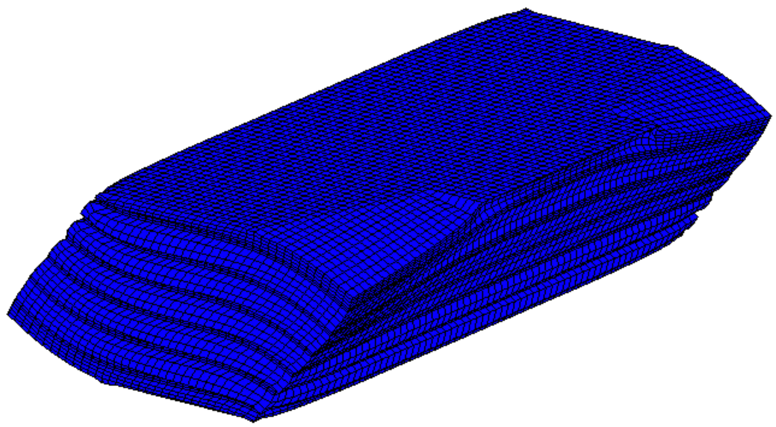


Fig. 8 – Horizontal Force-Displacement Relationship in the Perpendicular-to-Width Direction, Obtained from Finite Element Analysis

Although the PB-FREI became horizontally unstable at u/t_r = 1.13, the introduction of the partial bond delayed the instability to a larger horizontal displacement. The delayed instability increased the displacement capacity of the isolator by 55 % over the UB case. Figure 9 shows the deformed shape of the PB and UB isolators at the respective points of horizontal instability. In the UB case, it can be seen that a large portion, approximately 40 %, of the isolator has rolled over. In the PB case, a unique deformed shape occurred where the ends of the isolator experienced rollover. The amount of rollover decreases towards the bonded portion.



(a)



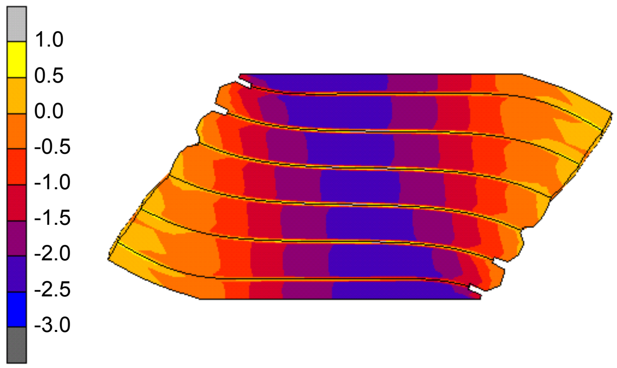
(b)

Fig. 9 – Deformed Shape of the (a) UB and (b) PB Isolators at the Respective Points of Instability

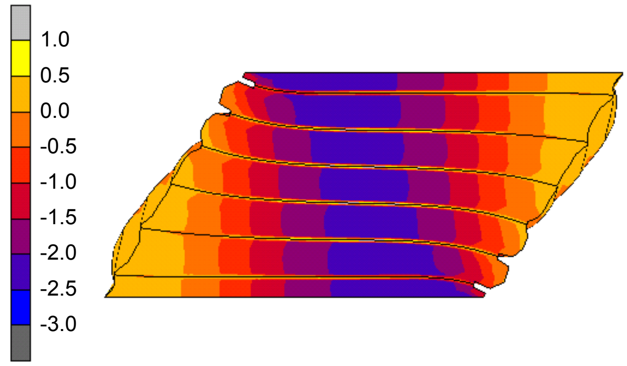
4.4.2. Vertical Stress

A cross section of the vertical stress, normalized by the average vertical compressive stress, is shown in Fig. 10 for the PB and UB case at the displacement at which horizontal instability occurs in the UB case (i.e. u/t_r = 0.73). The vertical cross section was taken along the center of the width. Similar to the parallel direction, the central section of both isolators was dominated by compressive stress. The magnitude of the stress within the rollover section of the UB isolator was small. The vertical stress in the rollover and bonded rollover sections is further investigated in Fig. 11; note that the fiber reinforcement has been omitted from the figure. In the PB case, a clear transition between compressive and tensile stress occurred. Inward lateral bulging can be observed as a result of the tensile stress within the bonded rollover sections.

For rectangular PB-FREIs to be feasible, the bond between the elastomer and steel must resist potential stress concentrations. The investigation presented herein only considered stress along the center of the width. However, larger stress concentrations are anticipated to occur at the transition between the bonded and unbonded portions (see Fig. 9). These areas are of particular interest and warrant further experimental and numerical investigation using finite element analysis.

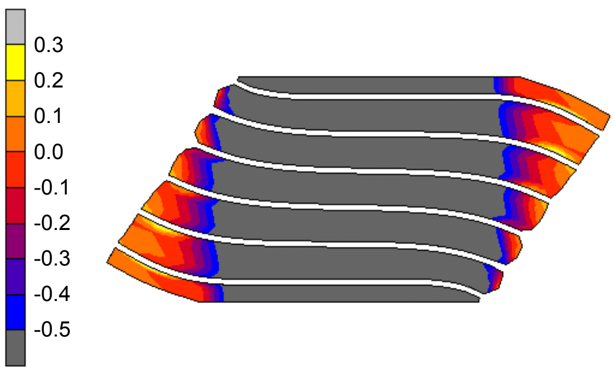


(a)

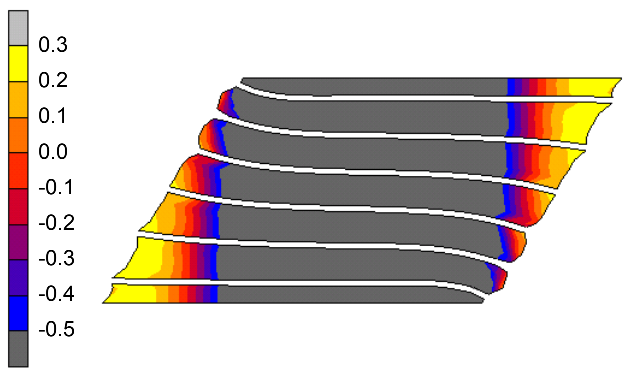


(b)

Fig. 10 – Normalized Vertical Stress along the Center of the Width for the (a) UB and (b) PB Cases at u/t_r = 0.73



(a)



(b)

Fig. 11 – Normalized Vertical Stress of the Rollover and Bonded Rollover along the Center of the Width for the (a) UB and (b) PB Cases at u/t_r = 0.73

5. Conclusions

The concept of a hybrid between unbonded and fully bonded isolators, denoted as PB-FREIs, was investigated through finite element analysis. By partially bonding an interior region of an unbonded FREI the advantageous softening due to rollover can be retained while simultaneously preventing slip under certain load conditions and introducing some level of tensile resistance. In this paper, a rectangular PB-FREI was subjected to horizontal displacement in each of the perpendicular principal horizontal directions and compared to an identical SU-FREI. The isolator was designed such that displacement parallel to the width was horizontally stable, and horizontally unstable in the perpendicular direction.

In the parallel-to-width, or horizontally stable direction, the findings of this investigation demonstrate that a considerable portion of the isolator can be bonded without significantly altering the horizontal force-displacement relationship. In the perpendicular-to-width direction, or horizontally unstable direction, it was found that the partial bond could delay horizontal instability and significantly extend the displacement capacity of the device. Potential stress concentrations at the interface of the bonded and unbonded areas were identified as an area requiring further investigation.

This paper considered only one isolator design and bond length. Further numerical and experimental investigations are required to expand upon the findings of this investigation. It is postulated that additional investigations can yield criteria for determining an allowable length and geometry of partial bonds dependent on the geometry of the isolator.

6. Acknowledgements

Financial support for this study was provided by the McMaster University Centre for Effective Design of Structures (CEDS) funded through the Ontario Research and Development Challenge Fund (ORDCF) as well as an Early Researcher Award (ERA) grant, both of which are programs of the Ministry of Research and Innovation (MRI). Support was also provided through the Natural Sciences and Engineering Research Council (NSERC) of Canada. The support of a Vanier Canada Graduate Scholarship is also gratefully acknowledged.

7. References

Fenz, D., Constantinou, M.C., "Spherical Sliding Isolation Bearings with Adaptive Behaviour: Theory", *Earthquake Engineering and Structural Dynamics*, Vol. 37, 2008, pp. 163-183.

Foster, B.A.D., *Base Isolation using Stable Unbonded Fibre Reinforced Elastomeric Isolators (SU-FREIs)*, M.A.Sc. thesis, McMaster University, Hamilton, 2011.

Kelly, J.M., Konstantinidis, D., "Low-cost Seismic Isolators for Housing in Highly-seismic Developing Countries", *ASSISi 10th World Conference on Seismic Isolation, Energy Dissipation and Active Vibrations Control of Structures*, 2007.

Kelly, J.M., "Analysis of Fiber-reinforced Elastomeric Isolators", *Journal of Seismology and Earthquake Engineering*, Vol. 2, No. 1, 1999, pp. 19-34.

Kelly, J.M., Konstantinidis, D., *Mechanics of Rubber Bearings for Seismic and Vibration Isolation,* Wiley, Chichester, 2011.

Konstantinidis, D., Kelly, J.M., Makris, N. *Experimental Investigations on the Seismic Response of Bridge Bearings,* EERC Report No. 2008-02, Earthquake Engineering Research Center, University of California, Berkeley, 2008.

Lu, L.Y., Lee, T.Y., Yeh, S.W., "Theory and Experimental Study for Sliding Isolators with Variable Curvature", *Earthquake Engineering and Structural Dynamics*, Vol. 40, 2011, pp. 1609-1627.

MSC Marc, Theory and user information, Vol. A. MSC Software Corporation: Santa Ana, 2011.

Russo, G., Pauletta, M., Cortesia, A. "A Study on Experimental Shear Behavior of Fiber-Reinforced Elastomeric Isolators with Various Fiber Layouts, Elastomers and Aging Conditions", *Engineering Structures*, Vol. 52, 2013, pp. 422–433.

Toopchi-Nezhad, H., Tait, M.J., Drysdale, R.G., "Lateral Response Evaluation of Fiber-Reinforced Neoprene Seismic Isolators Utilized in an Unbonded Application", *Journal of Structural Engineering*, Vol. 134, No. 10, 2008, pp. 1627-1637.

Toopchi-Nezhad, H., Tait, M.J., Drysdale, R.G., "Shake Table Study on an Ordinary Low-Rise Building Seismically Isolated With SU-FREIs (Stable Unbonded-Fiber Reinforced Elastomeric Isolators)", *Earthquake Engineering and Structural Dynamics*, Vol. 38, 2009, 1335-1357.

Tsai, C.S., Chiang, T.C., Chen, B.J., "Finite Element Formulations and Theoretical Study for Variable Curvature Friction Pendulum System", *Engineering Structures*, Vol. 25, No. 14, 2003, pp. 1719-1730.

Van Engelen, N.C., Tait, M.J., Konstantinidis, D., "Model of the Shear Behavior of Unbonded Fiber-Reinforced Elastomeric Isolators", *Journal of Structural Engineering,* 2014.

Van Engelen, N.C., Osgooei, P.M., Tait, M.J., Konstantinidis, D., "Partially Bonded Fiber-Reinforced Elastomeric Isolators (PB-FREIs)", *Structural Control and Health Monitoring*, Vol. 22, No. 3, 2015, pp. 417-432.

Yang, T.Y., Konstantinidis, D., Kelly, J.M., "The Influence of Isolator Hysteresis on Equipment Performance in Seismic Isolated Buildings", *Earthquake Spectra*, Vol. 26, No. 1, 2010, pp. 275-293.