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

SEISMIC ISOLATION OF A STEEL TRUSS SPAN UTILIZING FIBER REINFORCED ELASTOMERIC ISOLATION BEARINGS

Mark A. Torrie
Bridge Engineer, Associated Engineering, Canada
torriem@ae.ca

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

Peyman M. Osgooei
Graduate Researcher, McMaster University, Canada
moghimp@mcmaster.ca

ABSTRACT: Recent advances in isolation bearing technology have resulted in the development of stable unbonded fiber reinforced elastomeric isolators (SU-FREI). This type of bearing has desirable performance characteristics under seismic loading. This study examines the structural performance of a proposed seismically isolated steel truss bridge located in Vancouver, British Columbia. The seismic performance of this bridge, equipped with SU-FREI, was evaluated under earthquake loading. The lateral characteristics of the bearings were determined from experimental data and employed in a finite element model of the isolated bridge. The modelled bridge was then subjected to a comprehensive non-linear time history analysis to evaluate its response under seismic excitation.

1. Introduction

The advancement of seismic isolation technology over the years has led to the development of numerous new bearing and isolation components, including various modifications to traditional elastomeric bearings. These developments have included the implementation of fiber reinforcement to replace the integrally bonded steel plates typically found in laminated elastomeric bearings/ isolators (OPSS 922, 2009). In this paper bearings and isolators are used interchangeably.

Steel Reinforced Elastomeric Isolators (SREI) consist of layers of rubber bonded between steel reinforcing plates. The steel plates increase the vertical stiffness of the isolator by confining the rubber, which reduces the outward bulging of the rubber layers. Two thick steel end plates (also referred to as mounting plates) are usually located at the top and bottom surfaces of isolator. In a bonded application, the thick end plates are fastened to the superstructure above and substructure below. Low damped rubber bearings, high damped rubber bearings and lead plug rubber bearings are three different types of SREI (Naiem and Kelly 1999).

Low damped rubber bearings use unfilled rubber as the elastomeric material and possess equivalent viscous damping in the range of 2% to 5%, which is typically insufficient for seismic isolation applications (Naiem and Kelly 1999). One way to achieve the required level of damping is to use a high damping rubber compound as the elastomer, which can achieve inherent damping between 10% to 20% by adding fillers to the rubber compound (Naiem and Kelly1999). Alternatively, supplementary damping devices, such as a lead core, can be employed in combination with low damped rubber to achieve damping values of up to 30% (Taylor and Igussa 2004). This type of bearing, which is discussed in more detail in Section 4, was developed in New Zealand in 1975 and is currently the most commonly used type of isolator (Naiem and Kelly 1999).

Fiber reinforced elastomeric isolators (FREI) have the potential to be used as an alternative to conventional SREI (Kelly 1999b). FREI, which utilize fiber fabric reinforcement layers instead of steel reinforcement plates, have the potential to lead to significant cost savings, as they are substantially lighter than SREI (Kelly 2002). Furthermore, FREI can be manufactured without the steel end plates. This allows the isolators to be installed between the superstructure and substructure with no bonding or fastening, which is referred to as an unbonded application. In an unbonded application the shear force is transferred through the friction that develops between the isolator and the support surfaces.

The lateral behaviour of FREI has been investigated through several experimental test programs, including Kelly (1999b), Toopchi-Nezhad et al. (2007), Toopchi-Nezhad et al. (2008) and Russo et al. (2103). Test results have shown that the required horizontal flexibility for a seismic isolation system can be achieved with FREI. In addition, it has been observed that the energy dissipation obtained from FREI is greater than that of the elastomer itself. This increased energy dissipation is attributed to the internal friction mechanism developed between the individual fibers of the reinforcement as the isolator is displaced laterally (Kelly 1999b). A more detailed description of Stable Unbonded Fiber Reinforced Elastomeric Isolators (SU-FREI) is provided in Section 4.

In this paper the seismic behaviour of a truss bridge located in Vancouver British Columbia, outfitted with lead plug bearings, is compared to that of the same bridge equipped with SU-FREI. The SU-FREI was selected to have a lateral stiffness equal to the lead plug bearing at approximately 75% t_r (total thickness of rubber layers). The structure, originally isolated with lead plug bearings, was modelled using SAP 2000 (CSI, 2013) with the lead plug bearings represented by bi-linear link elements. The properties of the bi-linear link elements were set to represent the pre and post yield stiffness of the lead plug bearings under seismic excitation. The remodelled structure used both a multi-linear spring link element in series with a pivot link element to represent the behaviour of a theoretical SU-FREI bearing. Each model was then subjected to a non-linear time history analysis for the Design Basis Earthquake (DBE), 1.5 DBE and 2.0 DBE. The behaviour of each bearing was subsequently examined with respect to both peak force and displacement.

2. Existing Bridge Structure

The existing structure is a steel truss bridge built in the 1950's with a roadway width of 26.8 m. The 190 mm reinforced concrete deck is supported by a series of stringers that are in turn supported by transverse floor beams. The floor beams are supported by two steel trusses, 17.7 m apart, that rest on a series of concrete piers. The steel trusses are braced along the length by a series of portal braces. The deck is the primary contributor to the overall mass of the structure and inherently contributes significantly to the forces experienced by the structure during a seismic event. These forces are transferred through the concrete deck to the truss elements, substructure, and footings to the ground. The section of the structure under study in this paper is a 30.5 m simply supported truss supported by two concrete frame piers. The reinforced concrete piers are 2.2 m by 3.1 m in plan and approximately 18.3 m above grade. The piers are connected at the top by a 1.5 m by 1.5 m reinforced concrete beam to form a frame. The piers are founded on concrete footings supported by a series of timber piles.

3. Finite Element Model (FEM)

Finite element modeling of the structure was carried out to analyze the structure in its current configuration with lead plug bearings and then subsequently equipped with SU-FREI. The 3D finite element model of the structure was developed in SAP 2000 using the element types and boundary conditions listed in Table 1.

The properties of the bridge elements were modelled using their physical dimensions as found on the as constructed drawings for each member's respective moment of inertia. The elastic modulus (E) for the concrete members was taken as 24800 MPa, which is consistent with a concrete with a compressive strength of 28 MPa. The elastic modulus of the steel members was taken as 200,000 MPa. The foundation members are supported on flexible boundary restraints to represent the stiffness of the pile group. The lead plug bearings, located at the top of the piers between the substructure and the superstructure were modelled using non-linear link elements with bi-linear properties as shown in Figure 1. The mass of the structure considered both the specific masses and member self-weight. Mass and stiffness proportional (Rayleigh) damping of 5% was specified for the model.

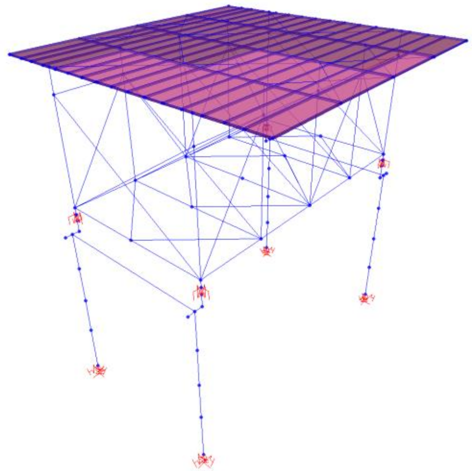


Fig. 1 – SAP 2000 FEM Model of Structure

Table - 1 SAP 2000 FEM Element Types

Bridge Component	Element Type
Deck	Thin Shell Element
Stringer	Frame Element
Floor Beam	Frame Element
Truss Members	Frame Element
Portal Bracing	Frame Element
Plan Bracing	Frame Element
Piers	Frame Element
Lead Core Isolators	Multilinear Elastic Element + Multilinear Plastic Element with Pivot Hysteresis (Pivot-Elastic Model)
SU-FRE Isolators	Pivot-Elastic Link Elements
Foundation	Linear Spring

4. Isolation of Bridge Structures

The practice of isolating bridge structures from seismic excitation is an effective way of reducing the seismic demands on both new and existing structures. This is typically accomplished by placing isolators between the superstructure and substructure. This concentrates the flexibility and resulting lateral deformations of the structure at the isolator level. Common types of seismic isolation devices used in bridge applications include friction pendulum, elastomeric isolators and hybrid systems. This study focuses on the seismic response of the structure described above (Section 2) when equipped with either lead plug bearings or SU-FREI.

4.1. Lead plug bearings

Lead plug bearings are a common type of seismic isolator found on high value structures such as hospitals, schools and bridges. These bearings are manufactured by incorporating a lead core into a traditional steel laminated bearing. The inclusion of the lead core, which is forced to deform in shear by the reinforcing steel plates, significantly increases the equivalent viscous damping of the bearing (Filiatrault, 2006). The bi-linear behaviour of lead at normal temperatures provides excellent energy dissipation to enhance the ability of lead plug bearings to accommodate seismic events. Under small displacements lead plug bearings provide a high initial stiffness as both the lead and the rubber behave in an elastic manner, however upon larger displacements and yielding of the lead plug, the stiffness of the bearing reduces and is controlled by the lateral stiffness of the rubber alone (Naiem and Kelly1999). A schematic of a typical lead plug bearing is shown in Figure 2.

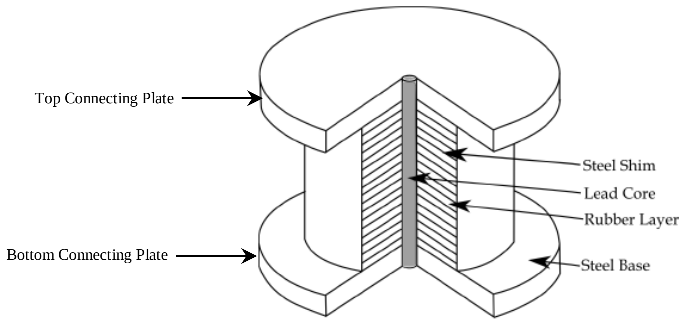


Fig. 2 – Lead Plug Bearing Schematic (from T.K. Datta, 2010)

The hysteretic behaviour of the lead plug bearings used in the bridge under lateral deformation is shown in Figure 3. This behaviour can be characterized in the form a bi-linear approximation with K1 (pre-yield stiffness), K2 (post-yield stiffness) and Qd (characteristic strength).

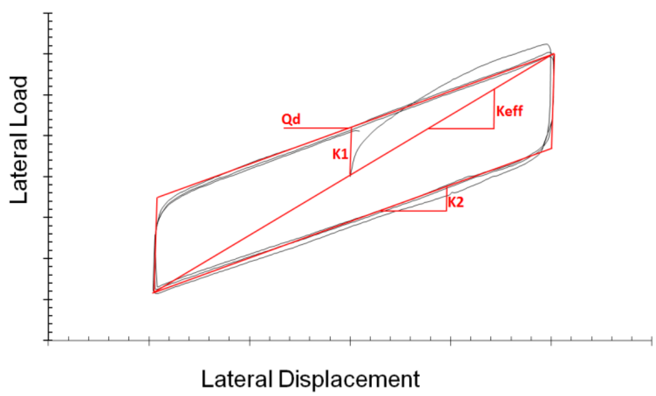


Fig. 3 – Lead Plug Bearing Hysteresis Loops

The lead plug bearings employed on the structure investigated in this study had the manufacturer supplied properties shown in Table 2. The properties were then entered into the 3D Finite Element Model as bi-linear link elements at each of the isolator locations to represent and simulate the behaviour of the bearing under seismic excitation.

Table - 2 Lead Plug Bearing Properties

Pre-Yeild Stiffness	17500 N/mm
Post Yield Stiffness	1750 N/mm
Characteristic Strength	93 KN
Bearing Height	138mm
Rubber Shear Modulus	1500 MPa

4.2. Stable Un-Bonded Fiber Reinforced Elastomeris Isolators (SU-FREI)

An emerging alternative to traditional seismic isolation units are SU-FREI. These isolators replace the traditional steel shims found in laminated steel bearings with sheets of fiber reinforcement and do not have thick end plates. These modifications provide several benefits, including the potential for reduced manufacturing costs and enhanced performance. Traditional fabrication methods for steel reinforced bearings involve chemical treatment of the steel plate prior to placement of the plates within a pre-determined layered arrangement of both rubber and steel plates. These plates and layers then undergo a hot vulcanization process to form a single continuous bearing assembly. This manufacturing process is expensive and requires precise fabrication tolerances in order to maintain the rubber cover over the steel plates for corrosion resistance (OPSS 1202, 2008). This can lead to relatively expensive and heavy bearings, depending on the size of the bearing required for the application. Conversely, the fabrication of the SU-FREI bearing involves layering of the rubber and fiber sheets and combining these layers using a cold vulcanization process (Toopchi-Nezhad et al., 2009). It is postulated that this fabrication method can be completed economically as large sheets could first be constructed and individual bearings subsequently cut from a large sheet to the required size. This ability has potential for accelerated bridge construction applications where fine adjustment to the bearings dimensions on site may be required.

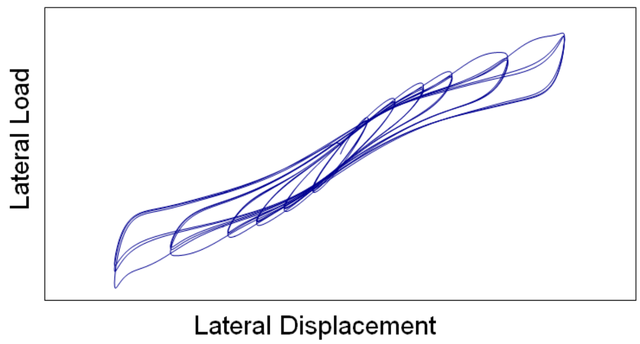


Fig. 4 – SU-FREI Hysteresis Loops (from Toopchi-Nezhad et al. 2009)

Due to the absence of the thick end plates and the flexural flexibility of fiber reinforcement layers, SU-FREI undergo a unique rollover deformation when subjected to lateral loading. As a result, the effective (secant) stiffness of the bearing decreases as the lateral displacement increases (see Figure 4). At larger lateral displacements the originally vertical faces of the bearing come into contact with the upper (superstructure) and lower (substructure) surfaces, providing an increase in the effective stiffness. This increase in effective stiffness is deemed beneficial (Toopchi-Nezhad et al., 2007), as it limits the isolation displacement under larger seismic events. In addition to this change in stiffness based on displacement, results from experimental tests indicate that the lateral tangential stiffness of SU-FREI with suitable aspect ratios (the ratio of the bearing width to height) remains positive for lateral deformations exceeding 300% t_r (de Raaf et al., 2011). This behaviour provides SU-FREI with an inherent ability to recenter itself after a seismic event, a common code requirement for seismic isolation devices for both bridge (CSA S6-06, 2006) and building structures. The properties of the bearings were derived from previous ¼ scale experimental tests conducted by Toopchi-Nezhad et al. (2008). The geometric properties were scaled to match the height of the exisiting lead plug bearings. The dimensions of the scale model bearing and prototype bearing are shown in Table 3.

Table - 3 SU-FREI Properties

Parameter	Model	Prototype
t_r (mm)	19	105
Height (mm)	25	138
Length (mm)	70	385
Pad Thickness (mm)	1.59	8.77
Aspect Ratio	2.8	2.8
Width (mm)	70	510
Area (mm^2)	4900	196000

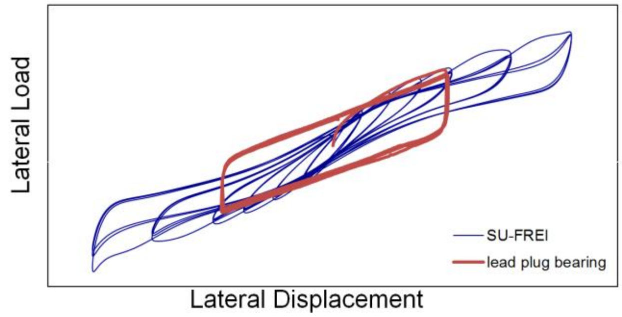


Fig. 5 – Comparison of Hysteresis Loops

The properties of the SU-FREI were scaled to match the stiffness of the lead plug bearing at 75% t_r. The hystertic loops of the lead plug bearing and SU-FREI are compared in Figure 5. It can be observed in Figure 5 that the lead plug bearing possesses greater effective damping relative to the SU-FREI. Additional damping could be achieved in the SU-FREI by increasing the volume of fiber relative to rubber or increasing the damping of the rubber itself. However, in this study the damping achieved by the SU-FREI test by Toopchi-Nezhad et al. (2009) was maintained (approximately 10%). To represent the behaviour of the the lead plug bearings a bi-linear link element was used in the finite element model. To accurately capture the changing stiffness of the SU-FREI with lateral displacement a different modelling scheme was implemented. The lateral behaviour of SU-FREI was simulated using a Pivot-Elastic model (Osgooei et al. 2015). This model is composed of a bilinear pivot element connected in-parallel to a nonlinear elastic spring (see Fig. 6). The Pivot-Elastic model is capable of simulating the variation of the effective stiffness and effective damping of SU-FREI, and was implemented in the SAP 2000 model. This was accomplished using two different elements; one element was used to assign the bi-linear pivot properties and the second was assigned non-linear elastic properties. The pair were connected in parallel between the substructure and superstructure to represent the SU-FREI bearing.

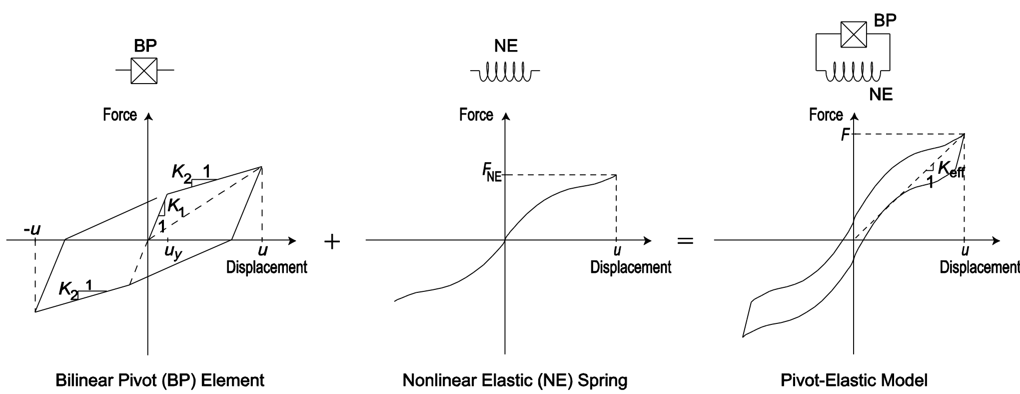


Fig. 6. The Pivot-Elastic Model

Assuming a fifth order polynomial for the nonlinear elastic (NE) spring, the force of the element (F_{NE}) is related to the isolation displacement with

$$F_{NE} = a_1 u + a_2 u^3 + a_3 u^5 \tag{1}$$

where u is the isolation displacement and a_i are the polynomial parameters. The effective stiffness and effective damping of the Pivot-Elastic can be calculated by (Osgooei et al. 2015)

$$K_{eff} = \begin{cases} K_1 + a_1 + a_2 u^2 + a_3 u^4 & u < u_y \\ (K_1 - K_2)\frac{u_y}{u} + K_2 + a_1 + a_2 u^2 + a_3 u^4 & u \geq u_y \end{cases} \tag{2}$$

$$\beta_{eff} = \frac{(K_1 u_y + K_2 u - K_2 u_y)(K_1 - K_2)(u - u_y)}{2\pi K_{eff} K_1 u^2} \tag{3}$$

The model parameters can be determined by minimizing the error between experimentally obtained values for K_{eff} and β_{eff} with those calculated using Eqs. (2) and (3). The model parameters used to represent the SU-FREI used in this study are listed in Table 4.

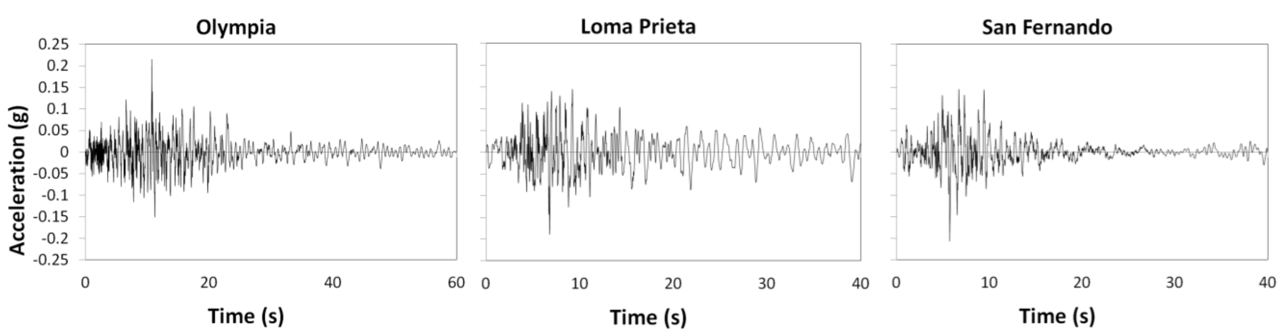
Table - 4 Pivot-Elastic Model Properties

Pivot Model Parameters		**Nonlinear Spring Parameters**	
K_1	6175 N/mm	a_1	2,155 N/mm
u_y	7.2 mm	a_2	-0.066 N/mm^3
K_2	560 N/mm	a_3	1.0x10^{-6} N/mm^5

4.3. Ground Motion Records

Upon development of the FEM with the lead plug bearings and a parallel model with SU-FREI, each model was subjected to the 1965 Olympia, 1971 San Fernando and 1989 Loma Prieta earthquake ground motions. The ground motion records were applied to the nodes at the base of the pier elements representing the foundations of the bridge structure. A non-linear direct integration time history analysis was carried out for three intensity levels: the Design Basis Earthquake (DBE), 1.5 DBE and 2.0 DBE level ground motions.

The Olympia ground motion record, shown in Figure 6a, consisted of 3000 points at intervals of 0.02 seconds for a total record length of 60 seconds with a peak ground acceleration (PGA) of 0.214g. The Loma Prieta ground motion record, shown in Figure 6b, consisted of 4000 points at intervals of 0.01 seconds for a total record length of 40 seconds with a PGA of 0.176g. The San Fernando ground motion record, shown in Figure 6c, consisted of 4000 points at intervals of 0.01 seconds for a total record length of 40 seconds with a PGA of 0.210g.



a) **b)** **c)**

Fig. 6 – DBE Ground Motion Records a) Olympia, b) Loma Prieta and c) San Fernando

5. Analysis, Results and Discussion

5.1. Hysteretic response of bearings

Figure 7 compares the hysteretic response of the lead plug bearings and SU-FREI for the DBE, 1.5 DBE and 2.0 DBE intensity levels. As seen in Figure 7, the area within the lead plug bearing hysteresis loops is significantly larger than the area found within the SU-FREI hysteresis loops. This is due to the higher effective damping of the lead plug bearings. It has been shown that although damping is effective in controlling isolator displacement it can lead to an increase in structural accelerations due to higher modes. Naeim and Kelly (1999) discussed the negative impact that excessive isolator damping can have on the performance of an isolation system. It should be noted that the effect of higher modes on the response of the structure is beyond the scope of this current study.

As the isolator displacement increases with increased seismic intensity the progression of the softening behaviour of the SU-FREI can be seen to develop. This softening behaviour is most pronounced at the 2.0 DBE intensity level. This softening of the SU-FREI bearing relative to the lead plug bearing results in lower shear forces for the San Fernando earthquake at the 2.0 DBE intensity level. However, this reduction at the 2.0 DBE intensity level is not as pronounced for the Olympia and Loma Prieta earthquakes.

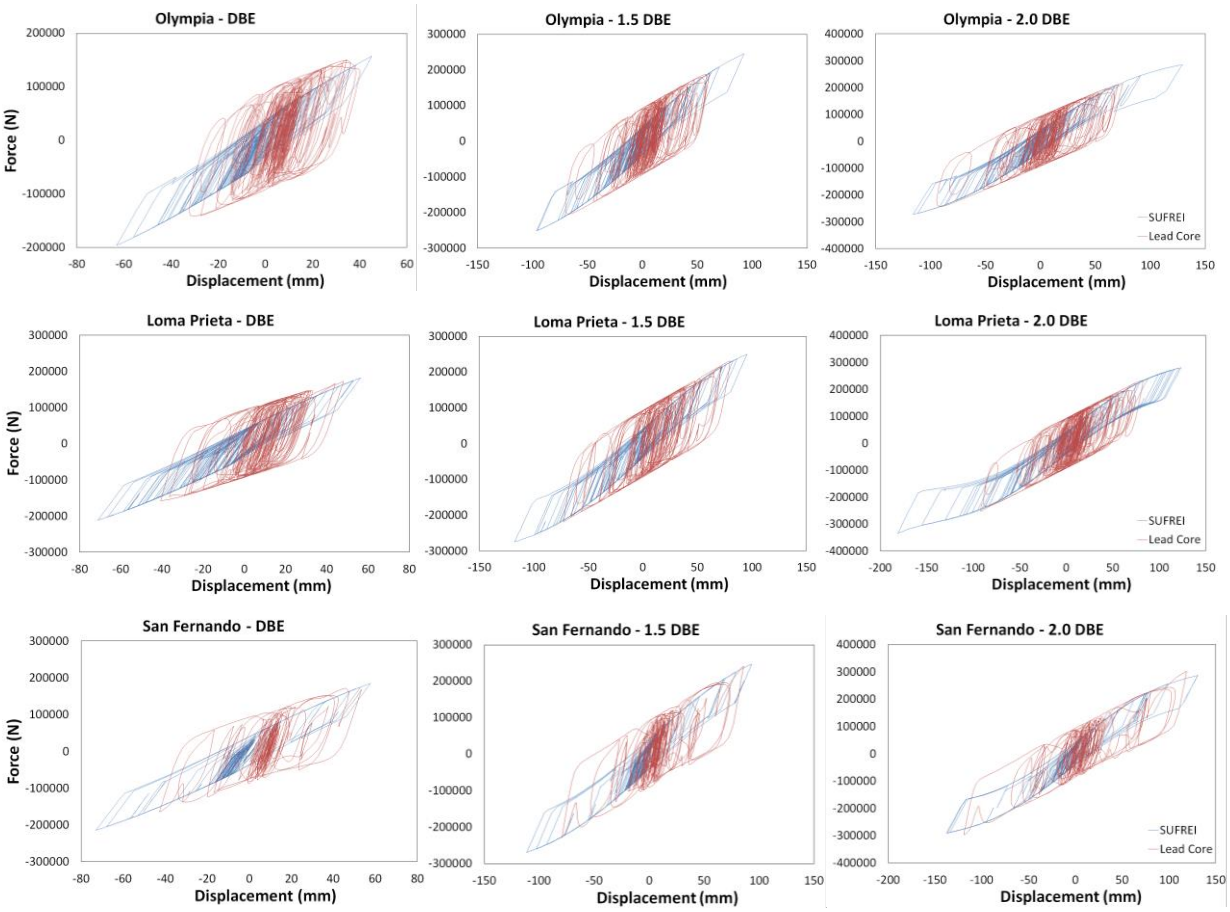


Fig. 7 – DBE, 1.5 DBE and 2.0 DBE Hysteresis Loops

5.2. Peak shear force and peak isolator displacement

Fig. 8 compares the peak shear force and peak isolator displacement of the lead plug bearings to the SU-FREI for the DBE, 1.5 DBE and 2.0 DBE intensity levels.

5.2.1. Peak Shear Force

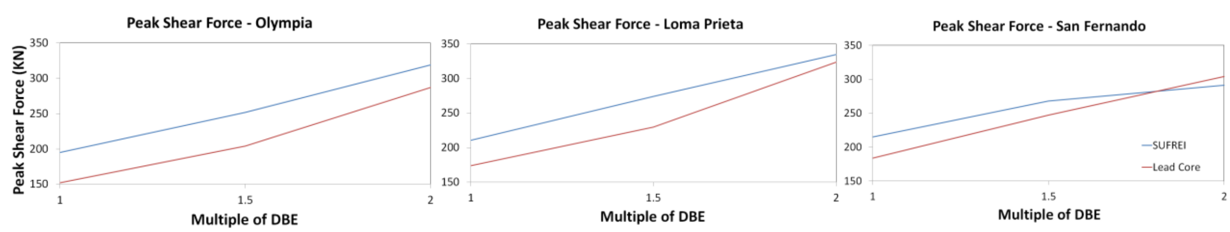


Fig. 8 – Peak Shear Force – Olympia, Loma Prieta and San Fernando

The peak shear force transmitted by the isolator to the foundation is one of the key characteristics used to evaluate seismic performance. As shown in Figure 8 the peak shear force for all three earthquakes for the SU-FREI is higher at the DBE intensity level, however, as the intensity is increased to the 1.5 DBE and 2.0 DBE levels the peak shear force of the SU-FREI begins to decrease relative to the lead plug bearings. It can be seen that at the 2.0 DBE intensity level for the San Fernando earthquake the SU-FREI results in a lower peak shear force. This reduction in peak shear force can be attributed to the softening of the SU-FREI at larger displacements, as seen in Figure 7.

5.2.2. Peak Isolator Displacement

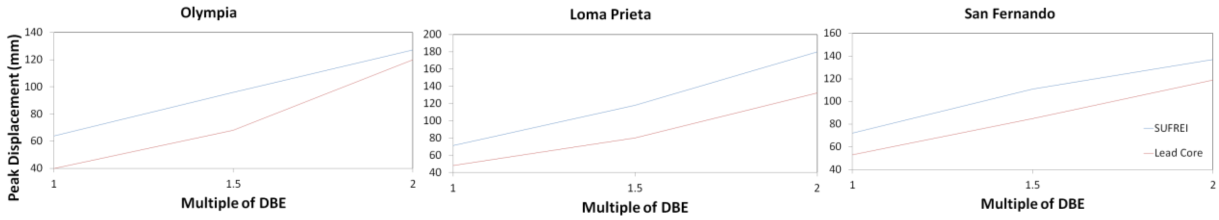


Fig. 9 – Peak Isolator Displacement – Olympia, Loma Prieta and San Fernando

The peak isolator displacement for each earthquake at the three intensity levels is shown in Figure 9. For the lead plug bearing the peak isolator displacement increases at a greater rate as the intensity level is increased for all three earthquake ground motions considered in this study. For the Loma Prieta earthquake the SU-FREI exhibits the same trend as the lead plug bearing as the intensity levels are increased. However, it can be observed that for the San Fernando earthquake the SU-FREI peak isolator displacement is found to increase at a lower rate as the intensity level is increased due to its softening behaviour. It should be noted that the peak isolator displacements were consistently higher for the SU-FREI at all three intensity levels compared to the lead plug bearing.

6. Summary

The focus of this study was to undertake a cursory review of SU-FREI behaviour in a bridge application, and compare the results to the behaviour of existing lead plug bearings when subjected to a series of earthquakes using nonlinear time history analysis. This was accomplished using a finite element model developed in SAP2000 of the existing bridge with lead plug bearings modelled using a bi-linear model and the SU-FREI modelled using a Pivot-Elastic model. The behaviour of SU-FREI was incorporated utilizing results from a previously tested bearing (Toopchi-Nezhad, 2008) with the evaluated properties augmented to provide similar response to that of the lead plug bearing at a displacement of 75% t_r. The models were then subjected to three earthquakes (Olympia 1965, Loma Prieta 1989 and San Fernando 1971) at three intensities consisting of the Design Basis Earthquake (DBE), 1.5 DBE and 2.0 DBE. It was found that compared to the lead plug bearings the peak displacements from each event were consistently higher for the SU-FREI. However, the peak shear force values for the SU-FREI showed a reduction relative to the lead plug bearings. It should be noted that the SU-FREI design was not optimized for this investigation (for example, additional damping could be added to the SU-FREI) and was simply matched at 75% t_r to provide an initial basis for the analysis.

Based on the finite element analysis and modelling exercise comparing the two isolation schemes the following inference and trends can be drawn for the application of SU-FREI in a bridge bearing application:

- SU-FREI have excellent potential for enhanced seismic isolation performance under larger seismic events or if optimized for a target displacement in the order of 100% to 200% t_r as this allows the bearing to soften.
- SU-FREI achieves this performance gain at larger displacements due to their unbonded nature and inherent lower internal stresses.
- SU-FREI bearing behaviour can be effectively modelled in a commercial finite element package using commonly available Pivot and Multi-linear elastic link elements.

There appears to be encouraging potential for SU-FREI in bridge applications as an isolator for the reasons outlined previously but as well due to the typically higher axial forces and no uplift conditions commonly found in bridge structural configurations. While encouraging, further study of SU-FREI in a bridge application is required as optimization of the bearing performance under seismic loading may yield significantly greater force reductions.

7. Acknowledgements

This study was carried out with the support of McMaster University Centre for Effective Design of Structures (CEDS) funded through the Ontario Research and Development Challenge Fund (ORDCF). Support provided by Associated Engineering is also gratefully acknowledged.

8. References

CAN/CSA S6-06 with Supplements 1,2,3. Canadian Highway Bridge Design Code. Canadian Standards Association, 2006

Datta, T.K., Seismic Analysis of Structures. John Wiley & Sons (Asia) Pte Ltd., 2010, p. 472.

de Raaf M. G. P., Tait M. J., and Toopchi-Nezhad H. (2011). "Stability of Fiber Reinforced Elastomeric Bearings in an Unbonded Application", Composite Materials, 45(18): 1873-1884.

Filiatrault A, Christopoulos C., "Principles of Passive Supplemental Damping and Seismic Isolation", IUSS Press, Italy, 2006

Kelly J. M. "Analysis of Fiber Reinforced Elastomeric Isolators", Journal of Seismology and Earthquake Engineering (JSEE), Vol. 2, No. 1, 1999b, Pages 19-34.

Kelly J. M. "Seismic Isolation Systems for Developing Countries", Earthquake Spectra, Vol. 18, No. 3, 2002, Pages 385–406.

Moon BY, Kang GJ, Kang BS, Kim GS, Kelly JM. "Mechanical Properties of Seismic Isolation System with Fiber-Reinforced Bearing of Strip Type", International Applied Mechanics 2003; 39(10):1231–9.

Naiem F., and Kelly J. M. Design of Seismic Isolated Structures, Wiley, New York, 1999

OPSS 922, Ministry of Transportation Ontario, Construction Specification for Installation of Isolators. Toronto, Ontario, 2009.

OPSS 1202, Ministry of Transportation Ontario, Material Specification for Isolators – Elastomeric Plain and Steel Laminated. Toronto, Ontario, 2008.

Osgooei, PM, "Advanced Numerical Modeling of Fiber-Reinforced Elastomeric Isolators (FREIs)", McMaster University, Hamilton, Ontario, 2015

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

Toopchi-Nezhad H., Tait M, Drysdale R. "Experimental Study on Carbon-Fiber-Reinforced Square Seismic Isolators", Proceedings, 9th Canadian Conference on Earthquake Engineering, Ottawa, Ontario, 2007, Paper 1426.

Toopchi-Nezhad H, Tait M, Drysdale R, "Parametric Study on the Response of Stable Unbonded-Fiber Reinforced Elastomeric Isolators (SU-FREIs)", Journal of Composite Materials, 2009, Issue 43, 2009

Toopchi-Nezhad H, Tait M, Drysdale R., "Lateral Response Evaluation of Fiber-Reinforced Neoprene Seismic Isolators Utilized in an Unbonded Application", Journal of Structural Engineering, 2008, Vol. 134, No.10, pp.1627–37.

Toopchi-Nezhad H, Tait MJ, Drysdale R. "Testing and Modeling of Square Carbon Fiber-Reinforced Elastomeric Seismic Isolators", Structural Control and Health Monitoring 2007;15(6):876–900.

Taylor A. W., and Igussa T. Primer on Seismic Isolation, American Society of Civil Engineers, ASCE, Reston, Virginia, 2004