

Two Low-Cost Seismic Isolation Systems

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SUMMARY

This paper examines two types of multi-layer elastomeric isolation bearings where the reinforcing elements, normally thick and inflexible steel plates, are replaced by thin flexible reinforcement. In the first type the reinforcement is provided by carbon fiber, while in the second type it is provided by *thin* flexible steel shims. The use of this alternative reinforcement together with the elimination of the thick end plates that are used in conventional isolators dramatically reduces the cost associated with the manufacture and installation of these bearings.

A theoretical analysis of the ultimate displacement capacity of these bearings suggests, and test results confirm, that it is possible to produce in these ways a strip isolator that matches the behaviour of a conventional steel-reinforced isolator. Tested bearings survived very large shear strains, comparable to those expected of conventional seismic isolators under seismic loading. However their cost is in the hundreds of dollars as compared to the cost of conventional isolators in the thousands of dollars.

The aim of this research is to provide low-cost lightweight isolation systems for the retrofit of housing and public buildings in highly seismic areas of the world where conventional isolation bearings are cost-prohibitive.

Keywords: seismic isolation, low-cost, fiber bearings, developing countries

1. INTRODUCTION

Many large urban centres are extremely vulnerable to the damaging effects of large earthquakes. For example, large cities such as Istanbul and Tehran have many thousands of buildings that were built prior to the enforcement of stringent building codes. Buildings in the range of two to six stories have been constructed using only vertical load designs and no provision for horizontal resistance. These are in many cases valuable buildings and are used as residences, offices and shops. There are so many of them that they cannot realistically be demolished and replaced; and retrofitting them by conventional methods would be highly disruptive to the occupants.

Modern methods of structural control would be much too expensive for these buildings, but it is possible that a system of inexpensive seismic isolation could be adapted to improve the seismic resistance of poor housing and other buildings such as schools and hospitals. In at least one retrofit project in Armenia, a large multi-family housing block was retrofitted using elastomeric isolators with no need for the families to leave while the work was done.

Development of low-cost seismic isolators that can be mass produced by a relatively simplified manufacturing process would stimulate world-wide application of the seismic isolation technology to the retrofit of existing structures with deficiencies and to new construction in lesser developed countries.

2. REALIZATION OF TWO TYPES OF POSSIBLE SYSTEMS FOR IMPLEMENTATION

This goal can be achieved in two ways, both of which lead to low-cost isolation systems that can be mass produced and are lighter than conventional steel-reinforced bearings. The first is achieved by replacing the steel shim plates in elastomeric bearings with fiber reinforcement. The seismic effectiveness of the *Fiber-Reinforced Elastomeric Isolators* (FREIs) has been demonstrated by an analytical model that estimates the vertical stiffness of the fiber-reinforced bearing and shows that the vertical stiffness of the bearing can be close to that of a conventional steel-reinforced bearing (Kelly 1999, Kelly and Takhirov 2001). In addition the results of an experimental research program conducted at the University of California, Berkeley (Kelly and Takhirov 2004), have confirmed that the main properties of the seismic isolators are preserved. Namely, the vertical stiffness is significantly greater than the horizontal one, providing the capacity to carry large vertical loads and provide isolation of the building from ground shaking in the horizontal direction. Further experiments conducted at McMaster University by Toopchi-Nezhad et al. (2008a,b, 2009a,b) confirmed these findings in component tests as well as in shake table tests of a model structure supported on FREIs. More recently, Van Engelen et al. (2012a,b) have investigated the vertical and horizontal behaviours of FREI bearings that have been modified through the introduction of holes on the loaded surface in an effort to alter the horizontal stiffness and damping properties of the bearings.

The weight reduction is possible as fiber materials are available with an elastic stiffness that is of the same order as steel. Thus the reinforcement needed to provide the vertical stiffness may be obtained by using a similar volume of much lighter material. The cost savings are also possible since the use of fiber allows a simpler, less labour-intensive manufacturing process. Another benefit of using fiber reinforcement is that it would then be possible to build isolators in long rectangular strips, whereby individual isolators could be cut to the required size. All isolators are currently manufactured as either circular or square. Rectangular isolators in the form of long strips would have distinct advantages over square or circular isolators when applied to buildings where the lateral resisting system is walls. When isolation is applied to buildings with structural walls, additional wall beams are needed to carry the wall from isolator to isolator. A strip isolator would have a distinct advantage for retrofitting masonry structures and for isolating residential housing constructed from concrete or masonry blocks (as shown in Fig. 1).

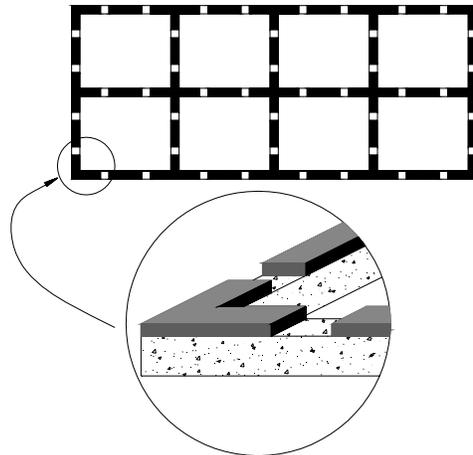


Figure 1. One of the proposed installations of the strip bearings

The other system of low-cost isolators is the use of standard thermal expansion bridge bearings as isolators. The effectiveness of these isolators has been demonstrated by a theoretical analysis covering the mechanical characteristics of these bearings where the reinforcing elements, normally thick and inflexible steel plates, are replaced by thin flexible reinforcement (Konstantinidis et al. 2008). The

reinforcement in these bearings, in contrast to the steel in the conventional isolator (which is assumed to be rigid both in extension and flexure), is assumed to be completely without flexural stiffness. This is of course not completely accurate, but it allows the determination of a lower bound to the ultimate lateral displacement of the isolator. In addition, there are fewer reinforcing layers than in conventional isolators, which makes them lighter. The most important aspects of these bearings are that (a) they do not have thick end plates, which again reduces the weight, and (b) they are not bonded to the upper and lower support surfaces. This at first sight might seem to be a deficiency of this design, but it has the advantage that it eliminates the presence of tensile stresses in the bearings. It is these tensile stresses and the bonding requirements that arise from them that lead to the high costs of conventional bearings.

Thermal expansion bridge bearings, in contrast to seismic isolation bearings, are much less expensive. The in-service demands on these bearings are, of course, much lower, but tests have shown that even if displacements of seismic-demand magnitude are applied to them, they can deform without damage. The primary reason for this is the fact that the top and bottom surfaces can roll off the support surfaces (Fig. 2, left), as is the case for FREI bearings (Fig. 2, right), and no tension stresses are produced. The unbalanced moments are resisted by the vertical load through offset of the force resultants on the top and bottom surfaces, as shown in Fig. 3. Thermal expansion bridge bearings were tested at the University of California, San Diego (Konstantinidis et al. 2008) and were shown to be able to survive very large shear strains comparable to those expected of conventional seismic isolators under seismic loading. However, their cost was in the hundreds of dollars as compared to the cost of conventional isolators, which is in the thousands of dollars.

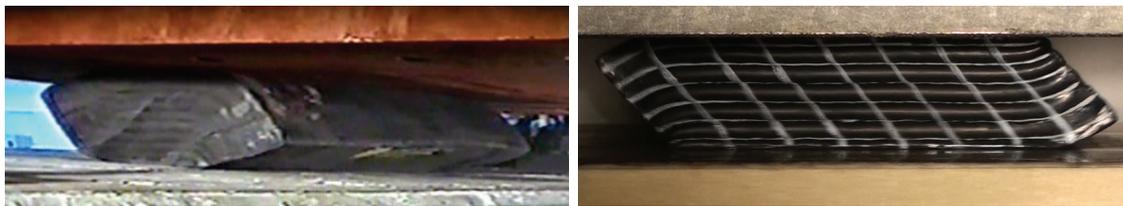


Figure 2. Bearings rolling off their supports under horizontal displacement. Left: thermal expansion bridge bearing (from Kelly and Konstantinidis 2007). Right: FREI (from Van Engelen 2012b).

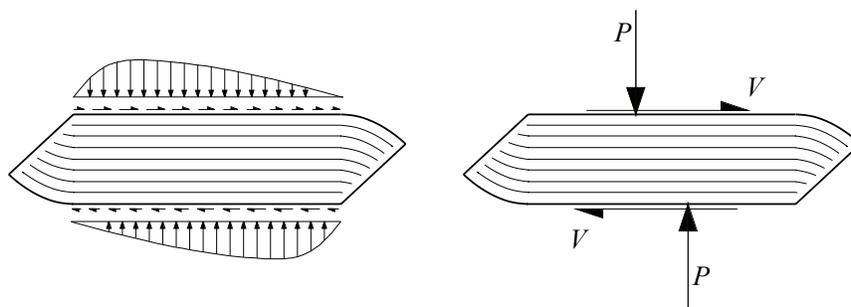


Figure 3. *Left:* Normal and shear stress distributions on the top and bottom faces of the unbonded bearing in its deformed shape. *Right:* The moment created by the offset of the resultant compressive loads, P , balances the moment created by the shear, V .

3. THEORETICAL ESTIMATION OF EFFECTIVE COMPRESSION MODULUS

To calculate the effective vertical stiffness of a steel-reinforced bearing, an approximate analysis is used that assumes that each individual pad in the bearing deforms in such a way that horizontal planes

remain horizontal and points on a vertical line lie on a parabola after loading. The plates are assumed to constrain the displacement at the top and bottom of the pad. Linear elastic behaviour with incompressibility is assumed, with the additional assumption that the normal stress components are approximated by the pressure. This leads to the well-known *pressure solution* (Kelly and Konstantinidis 2011), which is generally accepted as an adequate approximate approach for calculating the vertical stiffness. It is shown that the extensional flexibility of the fiber reinforcement can be incorporated into this approach, and that predictions of the resulting effective compression modulus be made (Kelly and Takhirov 2001). The vertical stiffness of the bearing, K_V , can be defined as

$$K_V = \frac{E_c A}{t_r} \quad (3.1)$$

where E_c is the compression modulus of the bearing (steel- or fiber-reinforced), A is the area of the bearing, and t_r is the total thickness of elastomer in the bearing.

For a steel-reinforced strip isolator the effective compression modulus, E_c^s , can be estimated from the following expression (Kelly and Konstantinidis 2011):

$$E_c^s = 4GS^2 \quad (3.2)$$

where G is a shear modulus of the elastomer, and S is the shape factor of a single layer defined as the ratio of loaded area to area that is free to budge. For a strip bearing with half width b and elastomer layer thickness t ,

$$S = b/t \quad (3.3)$$

The experimental study by Kelly and Takhirov (2004) showed that the thickness variation of the shims in steel-reinforced bearings does not cause significant variation of the bearing's vertical stiffness. This fact supports the idea of possibly replacing the steel reinforcement with a fiber reinforcement that can stretch during vertical loading of the bearing. In the FREI, the effective compression modulus, E_c^f , can be estimated from the following expression (Kelly and Takhirov 2001)

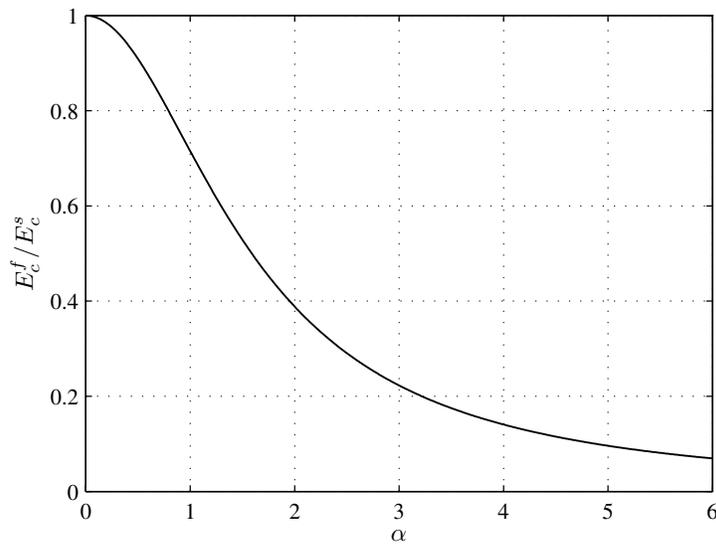


Figure 4. Dimensionless ratio of fiber-reinforced and steel reinforced compression moduli as function of parameter α .

$$\frac{E_c^f}{4GS^2} = \frac{3}{\alpha^2} \left(1 - \frac{\tanh \alpha}{\alpha} \right) \quad (3.4)$$

Where the dimensionless parameter α is defined through the tension elastic modulus of the fiber, E_f , and the thickness of the fiber reinforcement, t_f , in the following form

$$\alpha^2 = \frac{12Gb^2}{E_f t_f t} \quad (3.5)$$

The dimensionless ratio E_c^f / E_c^s for various values of parameter α is presented in Fig. 4.

4. ULTIMATE DISPLACEMENT OF UNBONDED BEARINGS

The highly favourable response of an isolator which is not bonded to the top or bottom plates is due to the elimination of tension in the elastomer. In a bonded bearing under the simultaneous action of shear and compression, the presence of an unbalanced moment at both top and bottom surfaces produces a distribution of tensile stresses in the triangular region outside the overlap between top and bottom, as shown in Fig. 5. The compression load is carried through the overlap area, and the triangular regions created by the shear displacement provide the tensile stresses to balance the moment. These tensile stresses must be sustained by the elastomer and also by the bonding between the elastomer and the steel reinforcement plates. These bonding requirements are the main reason for the high cost of current designs of isolator bearings for buildings. With the elimination of these tension stresses, the bonding requirements for this new type of bearing are reduced.

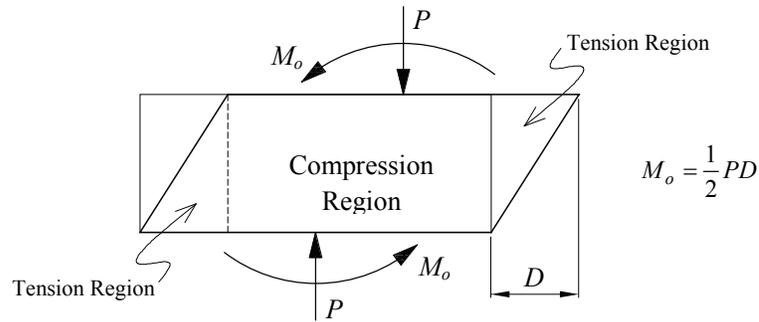


Figure 5. Offset of the compressive load due to horizontal displacement in a bonded bearing. The triangular stress regions are formed to balance the resulting moment.

In these bearings, the steel reinforcing plates are relatively thin as compared to the reinforcing in current designs of building seismic isolators. This flexibility allows the unbonded surfaces to roll off the loading surfaces and thus relieves the tensile stresses that would be produced if the top and bottom surfaces of the bearing were bonded; this in turn puts much lower demands on the internal bonding between elastomer and reinforcing.

The aforementioned tests have shown that the roll-off response is limited by the fact that the free edge of the bearing rotates from the vertical towards the horizontal with increasing shear displacement, and the limit of this process is reached when the originally vertical surfaces at each side come in contact with the horizontal surfaces at both top and bottom. Further horizontal displacement beyond this point can only be achieved by slip. The friction factor between the elastomer and other surfaces often can take very large values, possibly as high as 1, and slip can produce damage to the bearing through tearing of the surface distortion of the reinforcing steel and heat generated by the sliding, as witnessed

by Konstantinidis et al. (2008). Tests conducted by Toopchi-Nezhad et al. (2009b) on FREI bearings also noted damage at large displacements past the full rollover point. Thus, for design purposes, the maximum displacement for a bearing of this type can be specified as that which transforms the vertical free edge to a horizontal plane. In the normal situation, where the bearing thickness is small in comparison to the plan dimension in the direction of loading, this can be estimated by studying only the deformation of one side and neglecting the interaction between the deformations at each end.

The basic assumptions used in the development of the prediction of the limiting shear deformation are

1. the material is incompressible,
2. the reinforcement is completely flexible, and
3. the free surface of the roll-off portion is stress free.

The first two are reasonable for the elastomer and reinforcement of these bearings, and the third means that the displacement when the vertical surface touches the horizontal support is the length of the curved arc of the free surface.

The geometry assumed in the derivation is shown in Fig. 6. The thickness of the bearing is 1. We assume that the curved free surface is a parabolic arc, then in the coordinate system x, y shown in the figure, the curved surface is given by

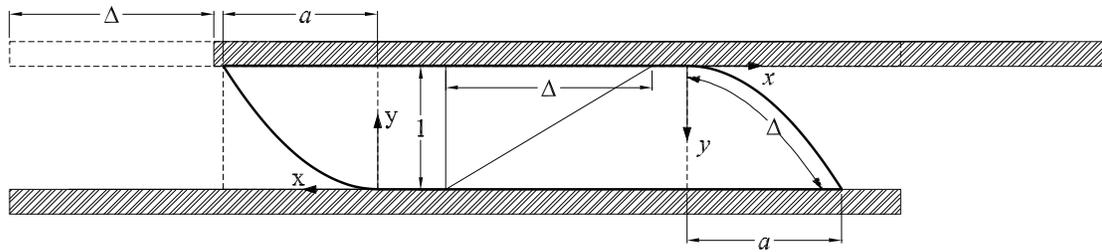


Figure 6. Schematic of the deformed bearing

$$y = \frac{x^2}{a^2}; \quad x = a\sqrt{y} \quad (4.1)$$

The area of the region enclosed by the curved arc of length Δ is

$$A = \int_0^1 \int_0^{a\sqrt{y}} dx dy = \frac{2}{3} a \quad (4.2)$$

The requirement of compressibility means that the volume before deformation and after is preserved, thus

$$\frac{1}{2} \Delta = \frac{2}{3} a \quad \text{or} \quad a = \frac{3}{4} \Delta \quad (4.3)$$

The curved arc length Δ is given by

$$d\Delta = \sqrt{dx^2 + dy^2} \quad (4.4)$$

where

$$dy = \frac{2x}{a^2} dx \quad (4.5)$$

So

$$\Delta = \int_0^a \sqrt{1 + \left(\frac{2x}{a^2}\right)^2} dx \quad (4.6)$$

Using the change of variable $u = 2x/a^2$, we have

$$\Delta = \frac{a^2}{2} \int_0^{2/a} \sqrt{1+u^2} du \quad (4.7)$$

Let $u = \sinh t$. Then

$$\Delta = \frac{a^2}{2} \int_0^{\sinh^{-1} 2/a} \cosh^2 t dt \quad (4.8)$$

Since $\cosh^2 t = (\cosh 2t + 1)/2$, this leads to

$$\Delta = \frac{a^2}{4} [\sinh t \cosh t + t]_0^{\sinh^{-1} 2/a} \quad (4.9)$$

and with $\cosh t = \sqrt{1 + \sinh^2 t}$, we have

$$\Delta = \frac{a^2}{4} \left(\frac{2}{a} \sqrt{1 + \frac{4}{a^2}} + \sinh^{-1} \frac{2}{a} \right) \quad (4.10)$$

The incompressibility condition requires that $\Delta = 4a/3$, leading to an equation for a in the form

$$\sinh^{-1} \frac{2}{a} = \frac{16}{3a} - \frac{2}{a} \sqrt{1 + \frac{4}{a^2}} \quad (4.11)$$

Replacing $2/a$ by t and inverting the equation leads to a transcendental equation for t in the form

$$t = \sinh \left[\left(\frac{8}{3} - \sqrt{1+t^2} \right) t \right] \quad (4.12)$$

which after solving for t gives a and in turn Δ . The solution to a high degree of accuracy is $t=1.60$, $a=1.25$ and $\Delta=1.67$. This is the overall shear strain. Since the reinforcement will not deform in shear, the shear in the elastomer is increased by the ratio of the total thickness (reinforcement plus elastomer) to elastomer thickness. For typical thermal expansion bridge bearings, the elastomer and steel thicknesses are 12 mm and 1.9 mm respectively. Thus the limiting shear strain based on the thickness of elastomer is 1.92.

The conclusion is that in broad terms these bearings with small thickness compared to their plan dimension can experience a displacement of twice the thickness of elastomer before they run the risk

of damage by sliding. This is quite comparable to the shear maxima usually imposed on building bearings in current practice in North America although it is somewhat less than that permitted in Japan. It is also worth noting that this is a lower bound to the maximum displacement of the second type of isolator since in that case the reinforcement is not completely flexible, and the small but finite bending stiffness will allow the bearing to displace further.

5. STABILITY OF HORIZONTAL DISPLACEMENT

The basic premise for the analysis of these bearings is that the regions of the bearing that have rolled off the rigid supports are free of all stress and that the volume under the contact area has constant shear stress. Under this assumption, the active area that produces the force of resistance F to displacement Δ , is $2b - \Delta$ and thus the force (per unit width of the bearing) is $F = G\gamma(2b - \Delta)$, but $\gamma = \Delta/t_r$, thus

$$F = \frac{G}{t_r}(2b - \Delta)\Delta \quad (5.1)$$

and consequently the force displacement curve has zero slope when

$$\frac{dF}{d\Delta} = \frac{G}{t_r}(2b - 2\Delta) = 0, \quad \text{i.e., when } \Delta = b \quad (5.2)$$

where, recall, b is half the width of the bearing. The implication of this result is that the bearing remains stable in the sense of positive tangential stiffness so long as the displacement is less than half the width in the direction of the displacement. For a bearing with a low profile, the ultimate displacement limit computed in the previous section will be reached before $\Delta = b$. After this displacement the bearing will stiffen up as witnessed by Konstantinidis et al (2008) for thermal expansion bridge bearings and by Toopchi-Nezhad et al. (2008b) for FREIs. On the other hand, for a bearing with a slender profile, instability will arise before $\Delta = b$.

6. DESIGN CRITERIA FOR A BEARING WITH FLEXIBLE REINFORCEMENT

As a result of the two limiting displacement criteria outlined in the previous two sections, it is possible to determine a simple design criterion for this type of bearing. We need only to determine a maximum required design displacement which normally would depend on the site, the anticipated isolation period and damping. If we denote this by Δ then the requirement for positive incremental horizontal stiffness requires that the width $2b$ of the bearing in the direction of the displacement be at least twice the displacement, i.e. $2b \geq 2\Delta$ and the requirement that the vertical faces should not contact the horizontal support surfaces means that the total elastomer thickness t_r should be not less than half of the displacement, i.e. $t_r \geq \Delta/2$.

7. CONCLUSIONS

This paper has described two potential approaches to the provision of low-cost, light-weight elastomeric isolation systems. Both types have been extensively tested in laboratory test programs and have also been verified by finite element studies (Kelly and Konstantinidis 2007, Konstantinidis et al. 2008, Toopchi-Nezhad et al. 2011). They both have much less severe bonding requirements than conventional isolators and have the potential of lending themselves to mass production manufacturing, which will be required for any type of retrofit of vulnerable buildings in the urban environment.

The most important aspects of both types of these bearings are that they do not have thick end plates,

they are not bonded to the top and bottom support surfaces, and their reinforcement mechanisms are very flexible. These aspects at first sight might seem to be deficiencies of their design, but they in fact have the advantage that they eliminate the presence of tensile stresses in the bearing by allowing it to roll off the supports. This reduces the costly, stringent bonding requirements that are typical for conventional isolation bearings. The weight and the cost of isolators is reduced by using fiber reinforcement or very thin steel reinforcing plates, no end-plates and no bonding to the support surfaces, thereby offering a low-cost, light-weight isolation system for retrofit in large cities and also for new housing and public buildings in developing countries.

REFERENCES

- Kelly, J.M. (1999). "Analysis of Fiber-reinforced Elastomeric Isolators." *Journal of Seismology and Earthquake Engineering*, **2**(1): 19–34.
- Kelly, J.M. and Konstantinidis, D. (2007). "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*. Istanbul, Turkey, May 28–31, 2007.
- Kelly, J.M. and Konstantinidis, D. (2011). *Mechanics of Rubber Bearings for Seismic Isolation and Vibration Isolation*. Chichester, UK: John Wiley & Sons.
- Kelly J.M., Takhirov S.M. (2001). "Analytical and Experimental Study of Fiber-Reinforced Strip Isolators," *Report No. PEER 2001/11*, Pacific Earthquake Engineering Research Center, University of California, Berkeley.
- Kelly J.M. and Takhirov S.M. (2004). "Experimental Study of Steel Reinforced Rubber Bearings with Various Shim Thicknesses." *SEM X International Congress and Exposition on Experimental and Applied Mechanics*. Costa Mesa, California, June 7–10, 2004.
- Konstantinidis D., Kelly J.M., and Makris N. (2008). "Experimental Investigation on the Seismic Response of Bridge Bearings," *Report No. EERC 2008/02*, Earthquake Engineering Research Center, University of California, Berkeley.
- Toopchi-Nezhad, H., Tait, M.J., and Drysdale, R.G. (2008a). "Testing and Modeling of Square Carbon Fiber-reinforced Elastomeric Seismic Isolators." *Structural Control and Health Monitoring*, **15**(6): 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., Tait, M.J., and Drysdale, R.G. (2009a). "Shake Table Study on an Ordinary Low-Rise Building Seismically Isolated with SU-FREIs (Stable Unbonded-Fiber Reinforced Elastomeric Isolators)." *Earthquake Engineering & Structural Dynamics*, **38**(11): 1335–1357.
- Toopchi-Nezhad, H., Drysdale, R.G., and Tait, M.J. (2009b). "Parametric Study on the Response of Stable Unbonded-Fiber Reinforced Elastomeric Isolators (SU-FREIs)." *Journal of Composite Materials*, **43**(15): 1569–1587.
- Toopchi-Nezhad, H., Tait, M.J., and Drysdale, R.G. (2011). "Bonded versus Unbonded Strip Fiber Reinforced Elastomeric Isolators: Finite Element Analysis." *Composite Structures*, **93**(2): 850–859.
- Van Engelen, N.C., Tait M. J., and Konstantinidis, D. (2012a). "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.
- Van Engelen, N.C., Tait M. J. and Konstantinidis, D. (2012b). "Horizontal Behaviour of Stable Unbonded Fiber Reinforced Elastomeric Isolators (SU-FREIs) with Holes." *15th World Conference on Earthquake Engineering*. Lisbon, Portugal, September 24–28, 2012.