A REVIEW OF DUAL-HAZARD EFFECTS ON BRIDGE SUPERSTRUCTURES AND THEIR PROTECTIVE PROVISIONS

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Abstract

This paper describes dual-hazard (earthquake/tsunami) effects on bridge superstructures and outline recommendations for protective measures to mitigate and/or withstand these effects. The paper aims to (1) recall damage of bridges involving superstructures under dual-hazard effects—with emphasis in the 2011 Japanese earthquake and tsunami, (2) highlight the effectiveness and limitations of mitigation strategies such as passive systems responding to dual-hazard effects, (3) recommend provisions to seismically isolated bridges to respond under uplifting effects, and (4) develop initial recommendations addressing design needs for protective provisions and practices required for dual-hazard mitigation.

Introduction

In the very recent Chilean and Japanese events, dual-hazard (earthquake/tsunami) effects led to the failure of many bridges. Bridge superstructures under the effects of earthquakes and tsunamis are subjected to longitudinal, transverse and vertical forces that in turn are transmitted to the substructure. These earthquake induced forces have different geneses, magnitudes, and characteristics than those generated by a tsunami. On bridge superstructures, however, damage resulting from earthquakes can be similar to damage resulting from tsunamis. Examples of this related damage are superstructure unseating, failure of horizontal and vertical restrainers, and damage to shear keys and abutments. For instance, superstructure unseating under seismic horizontal effects was one major cause of bridge collapse in the 1971 San Fernando earthquake, but it is still being reported as a cause of damage during recent events. In the 2010 Chilean and 2011 Japanese earthquakes and tsunamis, bridges equipped with deck tie-downs experienced unseating of their superstructures and damage to their restrainer systems due to horizontal and vertical tsunami effects. Recent events have tested superstructure to pier restrainer systems to their limits; damage of restrainer systems suggest the need to reinforce protective measures on bridge superstructures.

Some measures for the seismic resilience of bridges associated with superstructures include the provisions for (a) continuous superstructures using as few joints as possible, (b)

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increasing redundancy by implementing restrainers and enough seat-width at expansion joints and at the abutments, and (c) implementing passive devices, such as energy dissipation and isolation devices to reduce seismic effects. The first two measures help mitigate tsunami effects but can increase the demands in the substructures. However, implementing only seismically isolation devices, while reducing seismic horizontal seismic forces, may cause conflict withstanding vertical tsunami-lifting effects acting on the superstructure. The seismic isolators create a decoupling interface between the bridges super- and sub-structures and the most commonly used isolators do not offer uplift or tensile resistance; therefore, special provisions should be consider to mitigate and/or withstand the tsunami uplifting forces on seismically isolated superstructures.

The 2011 Japanese earthquake and tsunami exposed the vulnerability of non-integral bridges and of bridges built with mitigation mechanisms meant to reduce some level of seismic effects. Bridge damage due to seismic effects was less significant than those due to tsunami effects. Tsunami effects caused extensive bridge damage along the Japanese pacific coast where a large number of bridge superstructures were uplifted and swept away. The main failure mode of bridges under tsunami effects were caused by transverse drag and uplift effects on superstructures that overwhelmed the capacity of lateral and vertical restraints and anchorages, leading to lost superstructures. Examples of damage during the Japanese tsunami are: (a) the Kesen bridge—equipped with seismic elastomeric bearings and dampers yet lost the entire superstructure (Figure 1); (b) the Utatsu bridge—equipped with seismic cable restrainers, steel stoppers, and reinforced side blocks, yet sustained transverse deck movement and uplift; (c) the Numata bridge—equipped with longitudinal stoppers meant to prevent transverse movement of the deck, but had its deck uplifted away; (d) the Koizumi bridge—equipped with sliding bearings, dampers and cable restrainers, lost two three-bay-continuous spans, and (e) the Shin-Kitakami bridge—equipped with roller bearings, had two of its spans washed away (Kawashima, 2012). Failure of these restrainer systems may be attributed to underestimation or omission of earthquake-tsunami demands in the system design.

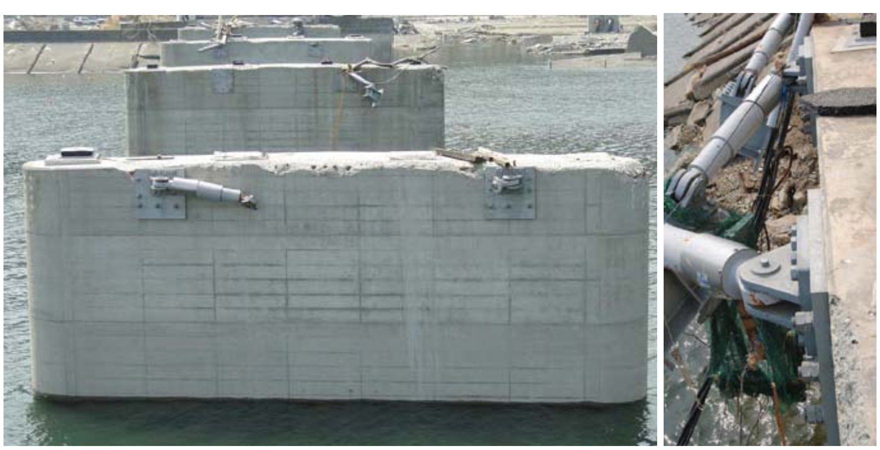


Figure1. Kesen bridge failure (Courtesy of Keigo Suzuki)

Summarizing performance of bridges to the 2011 Japanese earthquake and tsunami

The 2011 Japanese earthquake and tsunami, an extreme dual-hazard sequence with a very strong and long duration shaking followed by tsunami impact, tested the effectiveness of the Japanese bridge provisions for both hazard effects. Seismic retrofit programs and seismic design principles for bridges were proven effective in Japan. On the other hand, underestimations of tsunami effects and the omission of tsunami design provisions on the Japanese bridge specifications were reflected on the extensive tsunami-induced-damage on bridges (Hoshikuma et al., 2012). In particular, the vulnerability of bridges to the effects of both hazards was concentrated on bearings, laterals and horizontal restrainers and shear keys. Bridge performances under the effects of both hazards are summarized below.

Seismic design and retrofit of bridges:

a. Bridges built according to the post-1990 Japan Road Association's (JRA) design code sustained minor seismic damage. The implementation of seismic isolators and improvement of ductility of piers, foundations, unseating preventive systems, and the enhancement of shear and bending capacity of piers were effective in most cases for the ground shaking level experienced by the bridges (with spectral accelerations smaller than those for the type II Japanese design spectrum, Kawashima, 2012).

b. Bridges built according to the pre-JRA 1990 code and non-retrofitted sustained significant damage.

c. Elastomeric bearings performed satisfactorily and better than traditional steel bearings, with the exception of the rupture of several bearings that were reported at the Tobu and Rifu viaducts (Sandai)—designed according to the 1996 JPA code. Initial speculation suggested that the interaction between adjacent bridge decks with different periods of vibration caused the bearings' rupture (Takahashi, 2012). Under ground motion, multi-segment isolated viaducts may develop relative displacements between adjacent bridge segments that can cause damage on decks and isolators.

d. Some bridges in the Sandai area, designed according to the 1996 JPA code, experienced damage on connections of superstructures to dampers (Takahashi, 2012).

Tsunami provisions:

e. Tsunami induced damage on bridges was widespread along the Japanese pacific coast. The predominant failure mode of bridges was the loss of superstructures. Superstructures of 12 bridges on route 45 were washed away, and at least 91 highway bridges in Iwate, Miyagi, Fukushima, Ibaraki and Chiba areas sustained the same fate. (Hoshikuma et al., 2012). Hydrodynamic uplift forces due to wave action and hydrostatic uplift forces due to buoyancy coupled with entrapped air tested superstructures to pier restrainer systems to their limits, causing deck rotations, rupture of restrainers, bearings, and dampers.

f. At least 105 short and integral bridges survived the tsunami even though the superstructures of these bridges were fully inundated (Hoshikuma et al., 2012). This

happen to the Yanoura bridge, which was inundated by the tsunami but only experienced slight damage on hand rails. Its resiliency is attributed to the low lying profile and robust restrainer system (Takeda et al., 2012).
g. Deep foundations prevented failure mechanisms due to scouring.

Bridge damage due to the 2011 Japanese earthquake and tsunami emphasize what was already known about the common deficiencies of bridges at their bearings, support lengths, restraints, and shear keys due to dual-hazard effects—the type of deficiencies that can lead to loss of support and superstructure collapse. The satisfactory performance of non-integral bridges under both hazards greatly depends on the good performance of bearings, tensile and uplift resistance restrainers and damping devices. These traditionally well-known deficiencies were in part the foundation for seismic retrofits specifications such as the FHWA, 2006. To alleviate this type of deficiencies, measures such as the lateral load path enhancement of superstructures and the reduction of seismic effects that are transmitted to the superstructure are reinforced in the retrofit specifications. These retrofit measures include: (1) strengthening of deck to girder connections; (2) implementing restraining devices and bearing seat extensions; (3) strengthening and replacing bearing and anchorages and (4) implementing energy dissipating devices and/or isolation bearings, just to name a few.

The implementation of most of the seismic measures associated with load path enhancements of superstructures mentioned above are also useful to withstand tsunami effects at the superstructure level, at the expenses of increasing the demands in the substructures. On the other hand, the implementation of seismically isolation devices can significantly reduce horizontal seismic forces and may require provisions to mitigate and/or withstand vertical tsunami-lifting effects. The next section is focused on the implementation of passive system such as seismic isolation, together with energy dissipation mechanisms for dual-hazard mitigation.

Passive systems mitigating dual-hazard effects on bridges

As a result of past earthquakes and the collapse of a large number of bridges, passive protective systems, such as seismic isolation bearings together with energy dissipation mechanisms, have emerged to protect bridges. Seismic isolation bearing are being implemented in new and retrofitted bridges. For seismic retrofit, seismic isolators can have a twofold benefit: replacing a weak link while reducing seismic effects—mitigating potential damage to other structural bridge components. Seismic isolation is a flexible way to control or avoid earthquake damage on structures by reducing accelerations and controlling deformations and displacements, an effectiveness that has been extensively established. In the 2011 Japanese earthquake, passive systems that were implemented to protect bridges performed very well—with a localized exception which required further conclusive studies as previously mentioned (Buckle et al., 2012).

Seismic isolation and damping devices are essential for seismic protection of bridges. However, their implementation on bridges for near-field tsunami prone-areas requires provisions to mitigate and/or hold out the uplift tsunami forces. What needs especial considerations when designing bridges to withstand dual- hazards effects are the limited tensile or uplift resistance of seismic isolators, the decoupling of bridge components due to the isolation interface, and the potential amplification of seismic accelerations due to restrainers implemented on isolators. Some of these challenges associated with the implementation of seismic isolators for tsunami and seismic protection are presented below:

Limitation in the mitigation/isolation of vertical effects*:* Current seismic isolation bearings only provide isolation for ground motions in the horizontal direction. Vertical ground motions are not isolated and in some cases may be amplified. Commercially available seismic isolators are confirmed to be efficient at reducing horizontal ground accelerations that are transmitted to the superstructures. None of the currently available seismic isolators are able to mitigate the transmission of vertical ground accelerations to the superstructures. Therefore, a seismically isolated superstructure is directly exposed to vertical ground accelerations. This absence of vertical isolation was confirmed in instrumented seismic isolated building in the 2011 Japanese earthquake. Further, the vertical and horizontal accelerations may be amplified at the superstructure level if a stiff vertical restraint or tie-down is incorporated at the isolation interface. The potential amplification is due to both lack of ductility and energy dissipation capacity of commonly use restrainer systems and to high-short period characteristics of vertical ground accelerations.

Limited tensile or uplift resistance of isolators. The most commonly used isolation systems do not offer tension or uplift resistance. Earthquake and tsunami effects combined with unfavorable bridge geometries might produce localized uplift (in the absence of restraint) or tensile forces in isolation bearings. Under seismic effects, bridges with irregular curved or skewed spans, bridges having a relatively large vertical distance from the superstructure center of mass to the horizontal line of action of the bearings, and bridges with an unfavorable spacing of bearings, might have isolators that uplift or experience tensile forces. Under tsunami effects, hydrodynamic and hydrostatic uplift forces coupled with entrapped air can produce localized uplift or tensile forces on the isolators.

Friction Pendulum^{TM} (FP) bearings do not offer tensile strength; instead, they uplift and lose contact with the sliding surface. In rubber type bearings, the tensile strength is similar to compressive strength at low tensile levels, but when tensile stresses increase at to approximately three times the effective shear modulus rubber, (1.5 to 2.5 MPa, which varies with the rubber compound) the rubber develops small cracks. Rubber cracks lead to loss of both bearing confinement and tensile strength; only very high quality bearings are able to cope with significant extension without rupture (Constantinou et al., 2007).

Depending on the global system redundancy, sometimes uplift is allowed for some of the FP bearings, or specific tension is allowed for some rubber type bearings. However, the isolators' re-engagement just after uplift or tension may involve significant impact, rupture of bearings and/or stability problems of the bridges superstructures due to the redundancy restrictions of most base isolated bridges.

Decoupling of superstructures and substructures due to isolation interface. Seismic isolators in bridges are usually implemented between the superstructure and substructures, creating in that way a decoupling interface between both bridge components. The isolation interface offer limited uplift-tensile strength to the superstructures under extreme vertical load conditions.

Failure of restrainers and damping devices on some Japanese bridges illustrated the manner in which the tsunami demands overpassed the tensile capacity of the restrainers. Tensile and lifting forces acting on bridge restrainers are one of the main causes of bridge failure in Japan. For instance, the Kesen Bridge, although equipped with seismic elastomeric bearings and dampers, lost the entire superstructure (Figure 1). While the Koizumi Bridge, although equipped with sliding bearings, dampers and cable restrainers, lost two three-bay continuous spans in the 2011 Japanese tsunami.

Strategies to reduce the magnitude of tsunami forces as an alternative of providing restraints mechanisms to resist them may be an optimal measure to mitigate tsunami induced damage to seismically isolated superstructures. Provisions such as (1) open vents on the superstructure (girders and parapets) to alleviate buoyancy effects by reducing the vertical projected area of bridge deck to prevent uplift and (2) defining aerodynamic geometries to mitigate drag forces should be explored (Buckle et al., 2012). A current limitation for engineers to implement this option is in establishing capacity/demands estimates with current specifications and design tools; the lack of tools to estimate the tsunami demands on bridges superstructures is currently a major limitation.

The implementation of mechanisms to withstand the uplift forces such as tie downs or uplift restrainers may prevent tsunami-induced failures and could simultaneously be utilized for seismic mitigation on isolated bridges. For example, seismic isolators coupled with energy dissipation devices such as fluid viscous dampers, metallic dampers, etc., can mitigate seismic effects and also serve as unseating and uplift preventative devices. Implementing uplift-tensile restrainers for isolated structures can also serve as an approach to accomplish the AASHTO requirement (AASHTO, 2010) related to the provision of establishing a clear and direct load path.

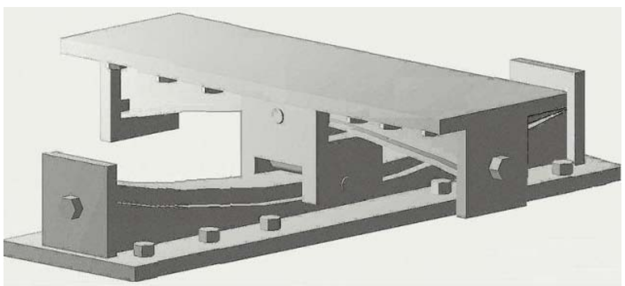
Uplift-tensile restrainers for isolated structures

This section presents some potential options to provide uplift or tensile resistance to seismically isolated structures. Uplift- or tensile-resistance mechanisms of isolation systems can be the key at preventing damaging effects due to buoyant and hydrodynamic forces acting on bridges equipped with isolators. However, these mechanisms may increase the tsunami induced forces in the substructures as they provide the reaction force to counteract the uplift and/or tensile effects. Detailed analysis are required to ensure that the failure mode does not change from the deck uplift to piers, abutments and/or foundations damage, because such failure mechanism implies costly and cumbersome repairing. Figures 2, 3 and 4 present a set of uplift restrainers for seismic isolators that are introduced below:

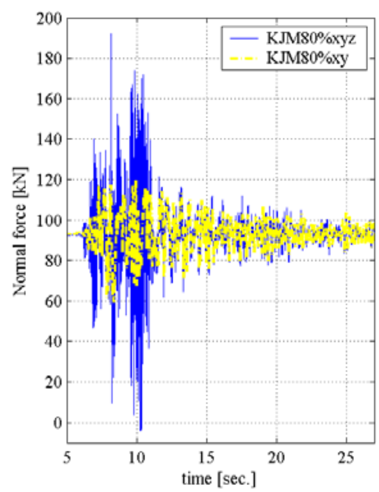
The XY-FP Friction Pendulum (XY-FP) bearing: this is a modified FP bearing that consists of two perpendicular steel rails with opposing concave surfaces and a connector. The connector resists tensile forces, slides to accommodate translation and provides rotation capacity about a vertical axis. Numerical and experimental studies on an isolated truss-bridge model were conducted to study both the behavior of an XY-FP isolated system under three-directional excitation and the potential uses of XY-FP bearings for the seismic isolation of bridges. Two of the key features of these bearings for the isolation of bridges are their resistance to tensile axial loads and the opportunity to provide a different period of isolation in each principal direction of the isolated structure. Figures 2a and 2b show an schematic of the XY-FP bearing and the testing setup, respectively (Marin-Artieda et al., 2009). A 1/4-length-scale truss-bridge model supported on XY-FP bearings was tested on a pair of earthquake simulators at SUNY-Buffalo. The effectiveness of XY-FP bearings resisting tensile axial loads during three-directional shaking was evident during testing. The XY-FP isolated truss-bridge model was subjected to earthquake shaking that induced overturning moments and vertical accelerations capable of overcoming the compressive loads, generating tensile axial loads in some of the XY-FP bearings. The vertical components of the earthquake history led to tensile loads on the isolators in three of the five earthquake histories used in testing. During three-directional testing, the largest peak horizontal accelerations on the simulators were obtained for the 80% Kobe KJMA station earthquake histories. The maximum accelerations of the earthquake simulator were 0.6 g, 0.47 g and 0.27 g, in the x, y and z directions, respectively, and the corresponding base shear of the isolation system in both horizontal directions was 7% of the total weight. For this test, the maximum compressive load on one of the bearings was 198 kN and the maximum tensile axial load was -4 kN. The normal response for one of the isolators on this case is illustrated in Figure 2c. The XY-FP bearings simultaneously resist tensile loads and function as seismic isolation. The experimental results demonstrated the effectiveness of the XY-FP bearings as an uplift-prevention isolation system. The construction detail of the small-scale connector of the XY-FP bearings and misalignment of the isolators on the test fixture did not permit fully uncoupled orthogonal responses. Some recommendations to improve the performance of the connector were reported (Marin-Artieda et al., 2009, 2010).

Uplift restrainer for elastomeric bearings: Experimental studies were undertaken on an uplift restrainer-displacement-control device for elastomeric bearings

(Griffith et al.,1990). The device was installed in a central hole in the elastomeric bearing. Figure 3a presents the bearing-device configuration. The device consisted of two bolts contained within a cylindrical sleeve that allowed an elongation of the device. After the bearings were displaced horizontally, the bolt heads were constrained by the ends of the sleeve, and the horizontal stiffness of the bearings was increased. Experimental studies in a scaled nine-story steel frame demonstrated the effectiveness of the device. In some tests, the uplift restrainers were fully engaged and the horizontal stiffness of the bearings was increased. The shear forces in the isolators with the restraint devices fully engaged were significantly larger than those forces in the isolation system that used regular elastomeric bearings and that were free to uplift (without the devices). The horizontal accelerations in the superstructure were up to 100% greater with the restrainer devices fully engaged than those accelerations in the structure equipped with regular elastomeric bearings only.



a. XY-FP bearings detail



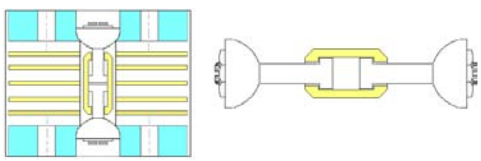
b. Testing setup with XY-FP bearings

c. Normal loads on a XY-FP

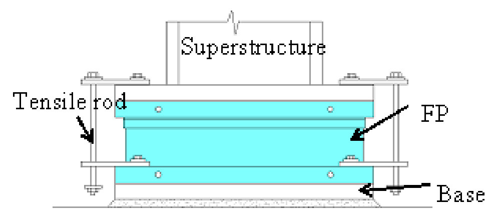
Figure 2.The XY-FP Friction Pendulum (XY-FP) bearing

Uplift restrainer for FP bearings: Figure 3b shows the uplift restrainer for FP bearings (Zayas et al., 1989), consisting of rods to resist tensile axial loads and to limit vertical displacements while allowing the lateral displacement of the isolator. This type of uplift restrainers was implemented on FP bearings to retrofit an elevated water tank.

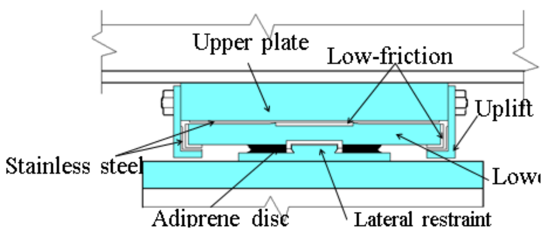
Uplift restraint for flat sliding (FS) bearings: Figure 3c presents the construction of flat sliding (FS) bearing with the uplift restraint device that was experimentally studied for applications to medium-rise buildings (Nagarajaiah et al., 1992). The inner part of the uplift restrainer was faced with polished stainless steel, while the side and bottom surfaces of the lower plate (in contact with the uplift restraint) were faced with a low-friction composite material. The purpose of the friction interface of the uplift restraint device is to mitigate horizontal movements during the activation of the uplift restraint system. Experimental results demonstrated the effectiveness of the sliding isolation system in reducing both the lateral accelerations and overturning moments and in preventing uplift. A similar uplift restraint system was implemented in FP bearings at the San Francisco abutment in the Oakland-Bay-Bridge in San Francisco.



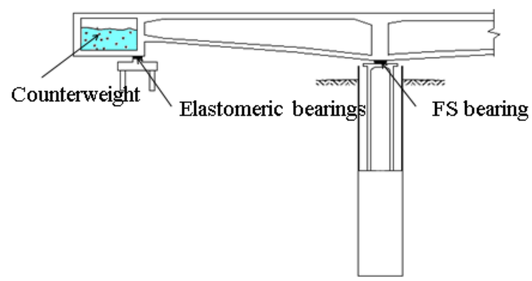
a. Uplift restrainer for elastomeric bearings



b. Uplift restrainer for FP bearings



c. FS bearing and uplift restraint



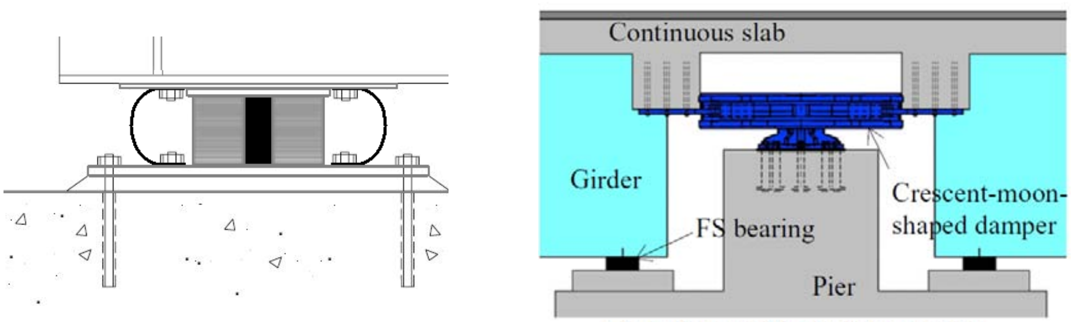
d. Counterweights

Figure 3: Uplift restrainers for seismic isolators

Pre-stressed isolators: Pre-stressing tendons were experimentally studied to prevent either uplift or tension loads in FS bearings, FP bearings, and in elastomeric bearings. The purpose of the pre-stressing tendons is to provide additional compressive force to counteract the tension or uplift effects on the isolation bearings, minimizing the development of additional forces on both the bearing and the structure as a result of geometrical changes of the tendons during horizontal displacements (Kasalanati et al., 1999). The effectiveness of the pre-stressing strategy in preventing uplift or tensile axial loads on the bearings was illustrated by displacement-control tests using the tendons with isolation bearings and by imposing horizontal displacement histories. The vertical load on the bearings was increased by the tendons. At the same time the tendons introduced additional lateral stiffness. Pre-stressing of isolation bearings was described as one option to prevent uplift or tension, regardless of the state of deformation of the bearing. Further studies were recommended to improve the understanding of the behavior of pre-stressed isolation bearings.

Counterweights to prevent uplift: A pair of seismically isolated highway bridges over the Corinth Canal in Greece is described in the literature. Each bridge consists of a continuous pre-stressed concrete box girder supported at each abutment by six elastomeric bearings and at each pier by one FS bearing. Counterweights were implemented at the abutments to avoid uplift and tension loads on the isolation system (Constantinou, 1998). Figure 3d shows an elevation of the bridge.

Tension-compression damper devices: Energy dissipation devices such as fluid viscous dampers and shaped metallic dampers implemented to mitigate seismic effects may also serve as unseating preventative and tension resistance devices. They may offer ductility and/or energy dissipation capacity in the vertical direction. The structural configurations need to provide a clear vertical and lateral load path between the superstructures and the substructure. The isolators may disengage from the superstructure to a specific tensile level to avoid undesirable tensile stresses when dampers are implemented with rubber isolators. Careful capacity-demand estimations on the dampers are required to determine the feasibility of these options. Figure 4 illustrates configurations using seismic isolation devices coupled shaped steel dampers.



a. Installation of the isolation system

a. U-shaped steel dampers b. Crescent-moon shaped damper of the Bolu viaduct

Figure 4: Tension-compression damper devices as uplift restrainers

Some of the uplift- or tensile-resistance mechanisms presented above can be key for preventing dual-hazard damaging effects on bridge superstructures. However, potential amplification of acceleration due to some of uplift- or tensile- mechanisms to isolation systems needs careful considerations. It is necessary to explore and develop uplift/tension resilient devices for seismic isolation that prevent the amplification of accelerations during tensile engagement under earthquake effects and also are able to engage when the superstructures are subjected to significant uplift forces such those due to tsunamis. Further, additional research is needed to refine prediction tools to enhance existing models that address tensile force-displacement relationships for seismic isolator coupled with uplift-tensile restrainers.

Tsunami demand evaluation on superstructures

Tsunami-demands estimates are required to decide on the provisions needed to mitigate and/or withstand the tsunami forces on bridge superstructures. Strategies involving superstructure geometry to reduce the magnitude of tsunami effects and the validation of uplift-tensile restrainers systems require accurate demand estimates. Further, appropriate combinations of tsunami-induced forces should be considered when estimating the total tsunami forces acting on the bridge, given the location and type of structural elements. Current literature suggests a lack of procedures to define tsunami-induced-loads and load combinations.

Wave height and period, topography, geology, and roughness are general quantifications that characterize tsunami hazard and that directly affect the estimation of forces generated by tsunamis. Further, three basic parameters for estimating the magnitude, direction and implementation of tsunamis induced forces on the bridge components are: (a) depth of flooding, (b) flow velocity, and (c) direction of flow. However, in the United States there are no approved tsunami run-up maps that could be used to estimate the risk and reliability of coastal bridges (Thompson, 2010). The assessment of tsunami-risk, reliability studies and estimation of tsunami forces should be based on the characteristics of each specific project. But bridge engineers lack specific analysis and design guidelines. Although tsunami provisions for loading were initially developed for Hawaii in the 1980's and subsequently used in other design guidelines for coastal construction (Robertson, 2011), most of the current guidelines are limited to design provisions for evacuation of buildings, while bridge engineers are currently extrapolating force coefficients defined for buildings in their designs relying on their judgment and intuition in their analysis.

Recently, Oregon DOT and Oregon State University (OSU) made a preliminary effort to develop guidelines for estimating tsunami forces on bridges. OSU developed numerical models to estimate the tsunami impact on bridge superstructures on four specific bridges located on the Oregon Coast. The numerical results were used to formulate a simplified methodology for estimating tsunami forces on bridge superstructures. This approach is recommended only for preliminary estimates until validation of results on realistic bridge models are completed (Yim et al., 2011).

Conclusions remarks

The recent earthquake and tsunami in Japan in March 11, 2011 illustrated the need for reinforcing the dual-hazard (tsunami/earthquake) resilience of bridges. Factors affecting bridge vulnerability includes the lack of dual-hazard resilience of bridges, of knowledge for adequate dual-hazard assessment, and that of specific provision that combine dual-hazard measures on current codes, guidelines and regulations. The 2011 Japanese tsunami vastly exposed this vulnerability where several bridges that were designed to mitigate some level of damage induced by both earthquake and tsunami effects were severely damaged, collapsed, or were swept away.

The 2011 Japanese earthquake and tsunami demonstrate that underestimation of dual-hazard effects can lead to unacceptable performance of seismically isolated and conventional bridges under extreme effects. Currently in the United States, there is limited information and specific guidelines for local coastal areas to estimate tsunami load parameters, and basic research to understand the relationship among multiple variables controlling tsunami effects on bridges is scare. Testing, experimentation, and rigorous analysis are at initial stages.

Some of the uplift- or tensile-resistance mechanisms mentioned herein can be key at preventing dual-hazard damaging effects on bridge superstructures. However, potential amplification of acceleration due to some of uplift- or tensile- mechanisms to isolation systems needs careful considerations. It is necessary to retake the study and validate uplift/tension resilient devices for seismic isolation that prevent the amplification of accelerations during tensile engagement under earthquake effects and that are also capable of engaging when the superstructures are subjected to significant uplift forces such those due to tsunamis. Further, additional research is needed to refine prediction tools to enhance existing models that address tensile force-displacement relationships for seismic isolator coupled with uplift-tensile restrainers.

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