MULTI-HAZARD (BLAST, SEISMIC, TSUNAMIS, COLLISION) RESISTANT BRIDGE PIERS

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ABSTRACT

Bridges are often built in locations susceptible to multiple extreme hazards. Meeting some or all of these constraints drives the development of innovative multi-hazard design concepts. This paper presents the results of research conducted to develop and experimentally validate such multi-hazard bridge pier concepts. The first concept is a pier-bent made of concrete filled steel tube columns. For comparison, the paper summarizes the results of other blast tests on ductile reinforced concrete (RC) bridge piers and non-ductile RC bridge piers retrofitted with steel jackets, both designed to be ductile from a seismic design perspective. LS-DYNA finite element results are presented to replicate and validate test results for the concrete filled columns. The second concept is a multi-hazard resistant steel plate shear wall (SPSW) box pier developed to provide satisfactory performance for earthquakes, vehicle collisions, tsunamis or storm surges, and blasts. All analyses show that the proposed concepts have superior multi-hazard performance.

INTRODUCTION

The emergence of new design objectives in bridge engineering always provides new opportunities to re-examine past design practices and explore the potential benefits of various alternative design solutions. Considered in this paper is the emerging topic of multi-hazard design, as it relates to bridges. Bridges are often built in locations susceptible to multiple extreme hazards (earthquakes, vehicle collisions, tsunamis or storm surges, and blasts as a minimum for some locations). Meeting some or all of these constraints drives the development of innovative multi-hazard design concepts.

Favorable features for design against one hazard may inevitably be unfavorable for other hazards, however, thus lending mismatched design solutions to the multi-hazard dilemma. Such conflicting design aspects are well illustrated elsewhere [1]. To make a design that is beneficial for one hazard while at the same time avoiding the possibility of making the structure vulnerable to other hazards, a system's approach to design must be undertaken. Such an approach necessitates designers to be knowledgeable of multiple hazards, and to consider the numerous and sometimes contradicting demands from the multiple hazards at the onset of the design process such as to avoid foreseeable mismatched design solutions. Such an approach should provide for a single cost single concept solution (not a combination of multiple design schemes), which aims to eliminate the potential incremental cost per hazard design.

This paper presents the results of a research project conducted to develop and experimentally validate such a multi-hazard bridge pier concept, i.e., a bridge pier system capable of providing an adequate level of protection against collapse under both seismic and blast loading, and whose structural, construction, and cost characteristics are not significantly different from those of the pier systems currently found in typical highway bridges in the United States. The proposed pier system is a pier-bent where concrete filled steel tube columns frame into beams made up of C-shape steel sections embedded in the concrete foundation and pier cap. For comparison, the results of another blast test series are presented to examine the blast resistance of ductile reinforced concrete (RC) bridge piers and non-ductile RC bridge piers retrofitted with steel jackets that are designed according to current seismic knowledge and that are currently applied in typical highway bridge designs.

Finite element studies were also conducted on the concrete filled columns to replicate the transient dynamic behavior observed during the blast tests previously described. Because of the complexity of the problem, the explicit solver in LS-DYNA which is built around the central difference scheme was adopted to solve the equation of motion that describes the problem. This solver is well suited to situations involving high impulsive loading, high strain-rate, contact and material non-linearities [2], which are all present in the FEM studies of the columns.

In addition, the development and design of a conceptual multi-hazard resistant steel plate shear wall (SPSW) box pier concept is discussed. The system development and design considered each of the four aforementioned hazards by use of simplified analyses for design, and the use of advanced nonlinear finite element analyses to confirm that the proposed SPSW box system provides adequate ductile performance and strength for each of the hazards.

BLAST RESISTANCE OF MULTI-HAZARD AND SEISMICALLY RESISTANT BRIDGE PIERS

A review of several different structural configurations of bridge piers and potential bridge bent systems was conducted to identify systems deemed most appropriate in meeting the objectives of multi-hazard design. It was found that concrete-filled steel shapes can be used as multi-hazard bridge piers capable of providing an adequate level of protection against collapse under both seismic and blast loading, and with member dimensions not very different from those currently found in typical highway bridges. These CFST columns are smaller than the typical 914 mm (3’) diameter reinforced concrete pier column, but expected to perform significantly better under blast loads. This type of structural member was deemed likely to be accepted in practice (and incidentally is helpful in fulfilling the objective of accelerated construction). This structural configuration was therefore selected for experimental verification of its blast resistance (seismic performance of such columns had already been demonstrated by researchers, such as Bruneau and Marson [3]).

A series of blast experiments on 1/4 scale multi-hazard bridge piers was performed [4] [5]. Piers were concrete-filled steel tube columns (CFST columns) with different diameters [D = 102 mm (4”), 127 mm (5”) and 152 mm (6”)], connected to a steel beam embedded in the cap-beam and to a foundation beam. The bent frame was braced in what would correspond to the bridge longitudinal direction at the level of the cap-beams. A reaction frame was built for this purpose. Blast tests showed that CFST columns of bridge pier specimens exhibited a satisfactory ductile behavior under blast loading as shown in Figure 1a. The foundation connection concept applied in this experiment allowed to develop the composite strength of CFST column under blast loading.

Note that for comparison, another blast test series was conducted to examine the blast resistance of ductile reinforced concrete (RC) bridge piers [D = 203 mm (8”)] and non-ductile RC bridge piers retrofitted with steel jackets [D = 213 mm (8 3/8”)] that are designed according to current seismic knowledge and that are currently applied in typical highway bridge designs. Out of that test series, standard RC and steel jacketed RC columns were not found to exhibit a ductile behavior under blast loading, failing in direct shear at their base rather than by flexural yielding, as was the case with CFST columns (see a test result of the RC column in Figure 1b). Furthermore, this non-ductile failure occurred for a much smaller blast pressures than used for the comparable CFST [6]. Reinforced concrete details by current seismic codes and steel jacketing, known to be effective to provide satisfactory seismic performance, were thus shown to be ineffective for the blast loading cases considered.

(a) (b)

Figure 1. (a) CFST column (D = 127 mm) after the test; (b) RC column after the test

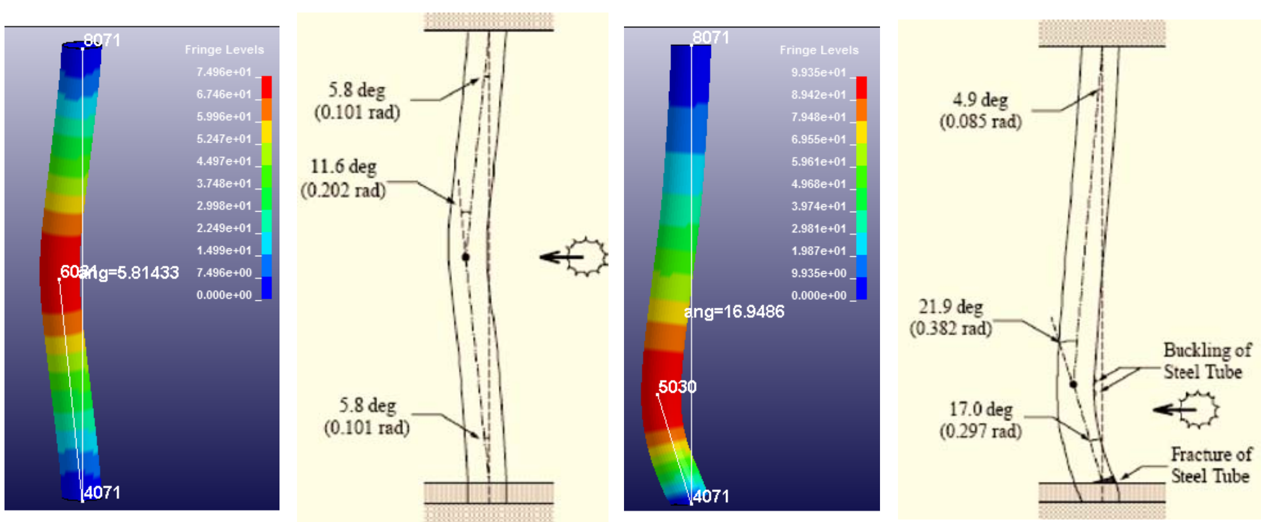
FINITE ELEMENT BLAST ANALYSIS OF CONCRETE FILLED TUBE

To model the steel tube, fully integrated 4-noded shell elements were used whereas 8-noded tetrahedron solid elements with reduced integration for the concrete core were deemed appropriate to capture with sufficient accuracy the behaviour of the core. Since the steel stress-strain curves for the experiments were available, they were directly input in the material model considered for the steel. This material coded in LS-DYNA as Material Model 24 is a Von-Mises based plasticity material model in which damage is considered intrinsically using ultimate strain as failure criterion. Moreover, strain rate effect was accounted for using the Cowper-Symonds model which scales the yield stress by a factor which varies with the actual strain rate [2]. For the concrete core, the model opted for was Mat72 REL3 in LS-DYNA whose formulation draws upon the William-Warnke three-invariant plasticity concrete material model as described in Malvar and Simons [7]. This model uses three shear failure surfaces to represent the behavior of the concrete material. It can account not only for confinement of the core, but also for strain-rate effects via a tabulated-function derived from experimental data. The model considers both shear and volumetric damage in the concrete. However, an erosion algorithm available in LS-DYNA has to be appended to the concrete model to physically display damage.

Fully fixed conditions were assumed to allow progressive hinging at the base and top of the specimens, thus no embedment length was considered. No slip was visible during the experiments at the interface between the steel tube and the concrete core, it can be assumed then that perfect bond exists between the tube and the core. Thus their corresponding nodes can simply be constrained to each other. Contact between the two elements was still modelled to avoid mesh penetration; the contact model used allows separation between the steel and the concrete when damage is taking place.

Blast overpressure was applied to the model using the airblast function of LS-DYNA which is an implementation of the airblast pressure data available in ConWep, a collection of conventional weapons effects calculations from the equations and curves of the U.S. Army technical manual TM 5-855-1. Since in the version of LS-DYNA used reflection of blast wave is not included in the computation of the peak overpressure and impulse, a factor was applied to the resulting pressure history so that the resulting peak impulse matched the peak reflected impulse predicted for the tests using the program BEL and the correction method presented by Fujikura and Bruneau [4] to account for the reduction in impulse due do the roundness of the section.

LS-DYNA captured satisfactorily the ductile sequence of limit states (yielding-plastification-fracture) experimentally observed. Figure 2a & Figure 2b below respectively show plastic deformation as measured in Test 5 and test 10 described in [5]. In particular, the angles of rotation from the finite element model match exactly the ones measured after the tests. The displacement fields (see fringe levels) match also the ones measured in the test. In test 10 the partial fracture of the shell and the concrete core is well captured.



(a) (b)

Figure 2. Plastic Deformation in Test 5 and Shell Fracture in test 10

In Figure 3, the finite element model captured the fracture observed for the specimen of test 7. It can be seen that the bottom part of the specimen blows away as seen in the test while the columns fracture at its top and its base

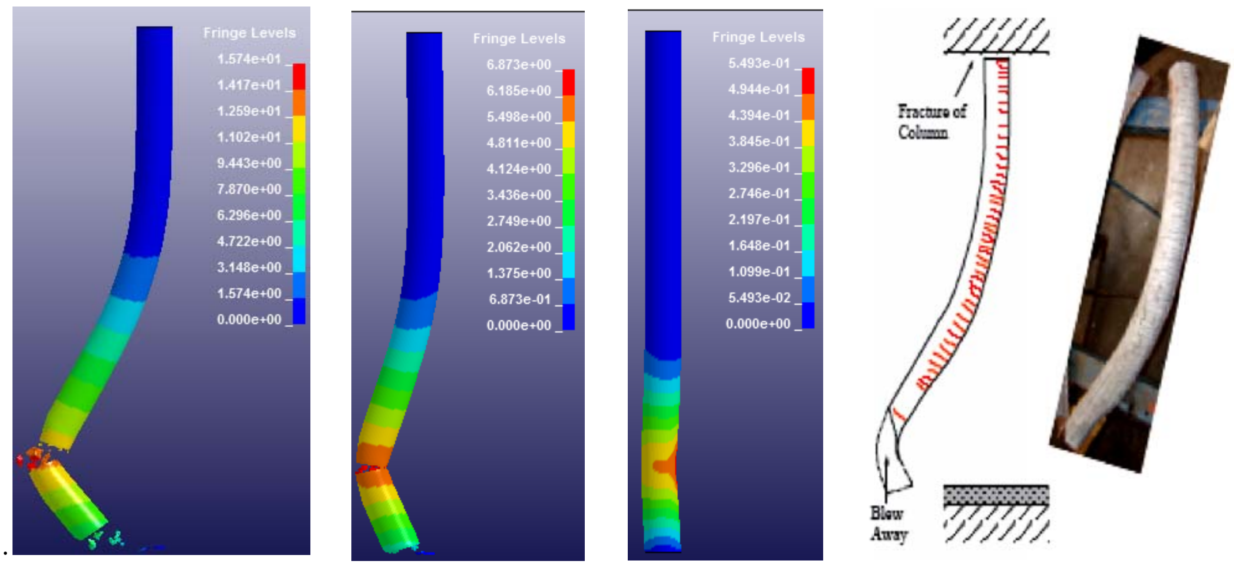


Figure 3. Sequence of Failure in Test 7

MULTI-HAZARD SPSW BOX-PIER CONCEPT DEVELOPMENT

Given that the objective of this research, designing a bridge pier system from a multi-hazard perspective, is a wide-reaching proposition, the scope was narrowed by focusing on developing a pier system that incorporated concepts from SPSW design. A system incorporating SPSWs was sought because of their ductile nature, because of the redundancy they offer, and because they are easy to repair. Such qualities of SPSWs make them a resilient structural system that suggested at the onset of the study that they should be capable of resisting multiple hazards. However, SPSW concepts, while already implemented in buildings, have never been incorporated into bridges, which posed an additional challenge. Hazards considered included earthquakes, vehicle collisions, tsunamis, and blast.

In considering the seismic hazard, comparable resistance from the piers in each of a bridge's principal directions was desired while at the same time being redundant enough to sustain gravity loads and maintain its integrity after occurrence of any of the other hazards. Additionally, a design that had aesthetic appeal was sought. To visualize and explore various concepts, a generic pier bent and superstructure (at first, one composed of reinforced concrete girders, but ultimately one with steel plate girders) was chosen. Figure 4 illustrates conceivable retrofit concepts (a & b) and new construction concepts (c - e) as they would appear looking longitudinally down a bridge. Arbitrary sizes for the cap beam and columns were chosen and were not designed for the purpose of this preliminary investigation. Figures 4a & 4b show the pier bent with SPSW assemblies that could be inserted as either retrofit solutions or new construction measures, and Figures 4c - 4e show the superstructure completely supported by SPSW assemblies, which would be implementable into new bridges. Note that foundation and connection details were not developed for these preliminary concepts.

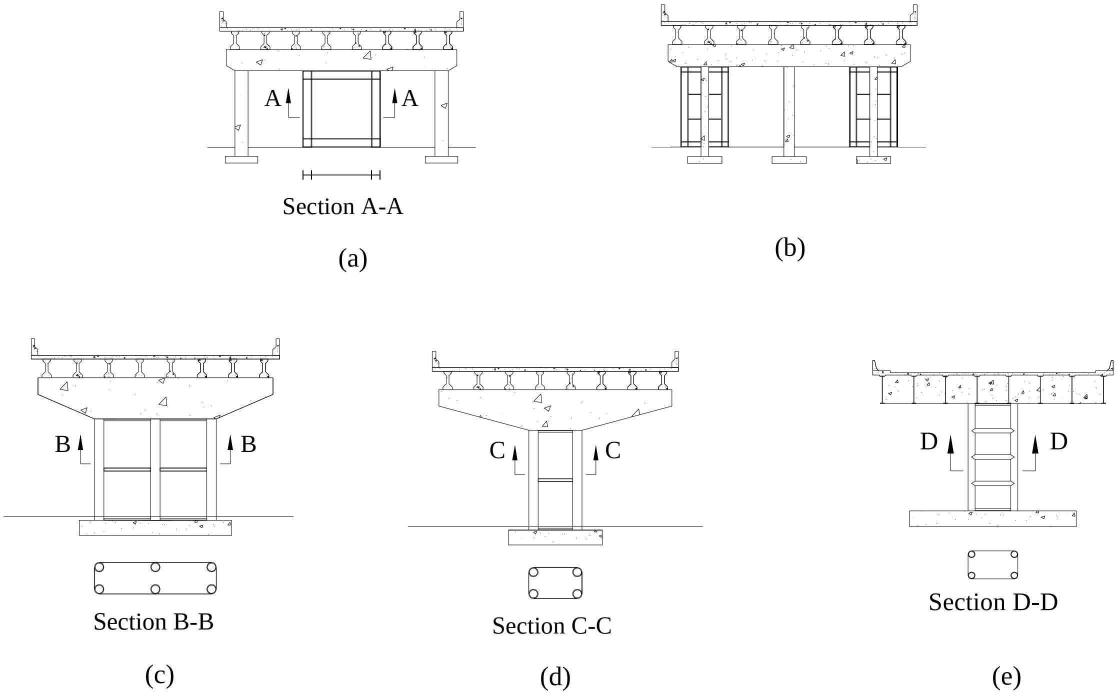


Figure 4. Progression of multi-hazard resistant SPSW bridge pier concept

Keller & Bruneau [8] describe short-comings of concepts (a) & (b) by discussing specific aspects of these concepts that fail to adequately coalesce favorable design features for each hazard into a single multi-hazard solution. This, in addition to the limited freedom of design for retrofits and the potential difficulties of anchoring SPSW assemblies to existing bridge piers, shifted the focus to concepts for implementation into new bridges where the pier is completely composed of steel in the form of a SPSW box assembly (c - e) aimed at providing significant redundancy and comparable strength in a bridge's transverse and longitudinal direction. Note from the sections in these figures (B-B, C-C, and D-D) that the vertical boundary elements (VBEs) are hollow circular tubes. The use of tubes was preferred over the use of wide flange shapes, as is typical with SPSWs (e.g. Section A-A in Figure 4a) due to their cross-sectional symmetry about any axis. Similarly, the horizontal boundary elements (HBEs) are hollow circular tubes. Note that the elevations in Figure 4 show the pier without plates attached, thus revealing the boundary frame, when in fact the pier's boundary frame is wrapped with plates that are assumed welded to the HBEs and VBEs allowing the inside to remain dry.

After due consideration of each concept's benefits, the four-column box pier concept was retained as worthy of further development. In addition to its seismic resistance in each direction, which can be adjusted by simply changing plate thickness, the plates are anticipated to be sacrificial for the other hazards. This is an important point considering the premise behind multi-hazard design is to be conscious of design solutions with favorable features for one hazard that may be detrimental for other hazards. The plates, in particular, are an important feature to any SPSW system for seismic resistance, but at the same time provide surfaces that collect pressure loads from other hazards (e.g. tsunamis and blast). This undesirable design feature provided for seismic resistance, however, is not destructive for the other hazards if the plates are indeed sacrificial without consequence to the boundary frame.

The section in Figure 4e and the rendering in Figure 5 illustrate the final concept that was developed in this research where the pier is attached to a pier cap that is integral with the bridge superstructure, which was found to be advantageous. Note that the three-span steel plate girder prototype bridge was adapted from a seismic design example developed for the Federal Highway Administration [9]. Also, the pier assembly was made reasonably narrow in the longitudinal direction to with the intent of reducing the plate surface area subject to wave loads arising from surging water transverse to the bridge's deck.

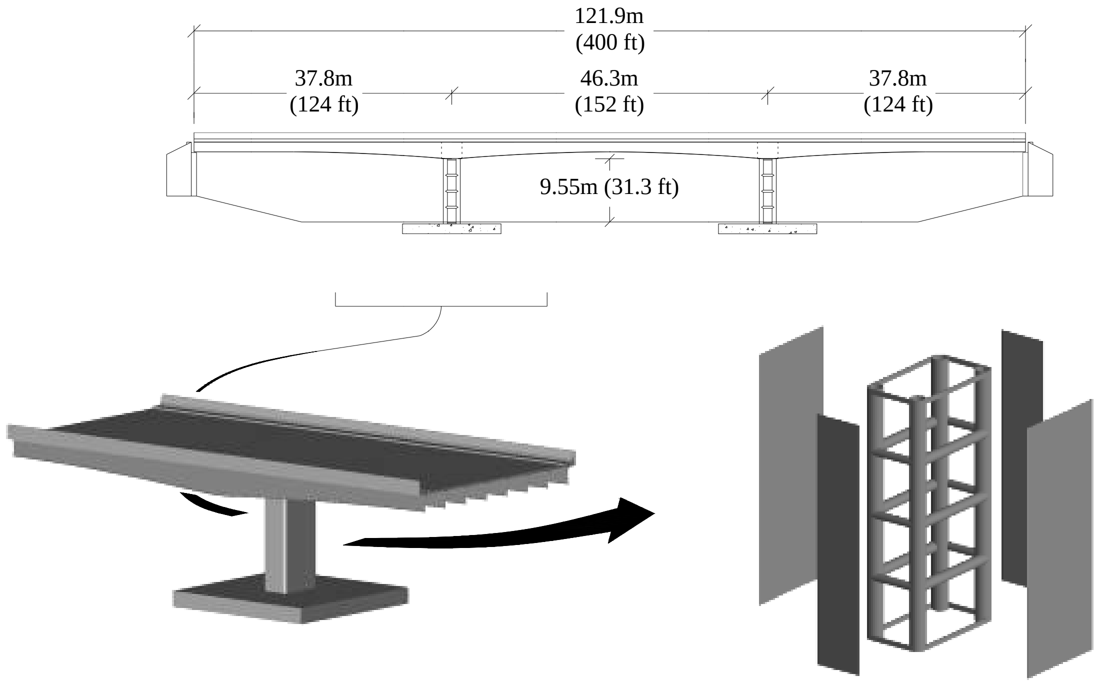


Figure 5. Final multi-hazard resistant bridge pier concept

ASSESMENT OF PIER TO MULTIPLE HAZARDS

EARTHQUAKES

In general, the system was designed for a given seismic hazard and then analyzed for the other hazards. This was only possible because of the multi-hazard approach taken in conceiving a concept at the onset. The seismic hazard was also used as the starting point of the detailed design because proven methods for the design and analysis of SPSW for seismic hazards are available in codes and design guides.

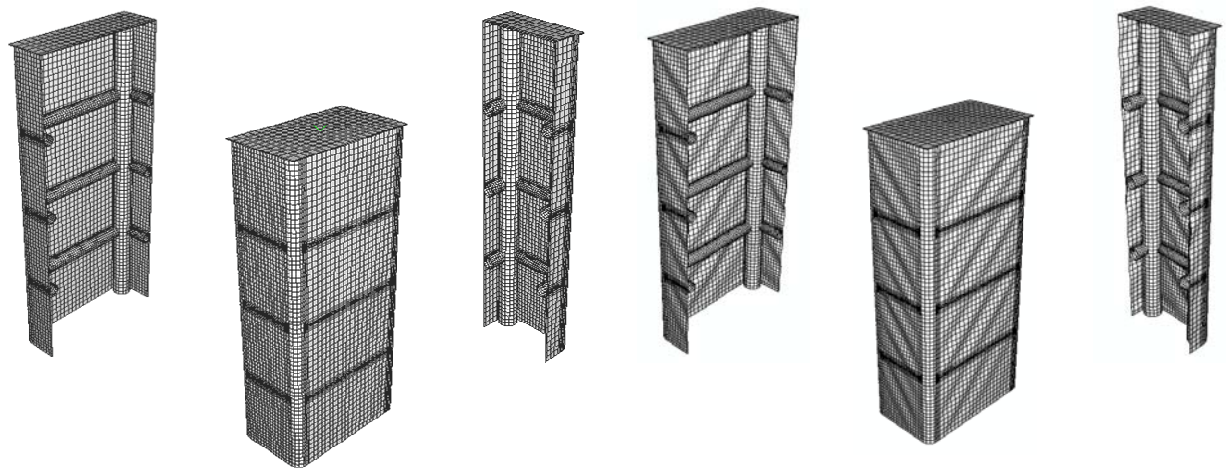
For the purpose of design, in accordance with AASHTO [10], the seismic acceleration coefficient was chosen to be 0.20 placing this bridge in seismic performance zone III, the bridge was classified as “regular”, and its importance classification was chosen to be in the AASHTO category of “other bridge”. The response modification factor, R, was chosen to be 5, and based on recommendations from AASHTO (Article 3.10.5.1) when the soil profile is unknown, the site coefficient was chosen to be 1.2. In analysis, movement of the superstructure in the longitudinal and transverse direction was assumed to be resisted by the two piers acting in parallel, the superstructure was assumed to be rigid, and it was assumed that there would be sufficient space for movement at the abutments so that the piers could develop their ultimate strength (the abutments were assumed to offer no resistance). In both directions, the top and bottom of the pier was assumed rigidly attached to the pier cap and foundation, respectively.

Design relied on use of nonlinear pushover analysis. Beam-column elements representing the boundary frame, and “tension-only” strips representing the plates, were used as is commonly done for SPSW design [11]. Plastic hinging was allowed only at the ends of the boundary frame members. Hinging was modeled using discrete nonlinear “Fiber P-M2-M3” hinges displaying elastic-perfectly plastic behavior placed at the ends of the boundary frame elements, and using discrete “Axial P” hinges at the strips’ centers also exhibiting elastic-perfectly plastic behavior. The steel assumed for the tubular sections was A500 Gr. B (Fy = 290 MPa (42 ksi)) and the material assumed for the plates was A36 (Fy = 248 MPa (36 ksi)) steel.

Critical loading was assumed as occurring if the pier were to be pushed simultaneously (or bi-directionally) in the transverse and longitudinal directions, where all strips in the perpendicularly oriented plates yield. The design was then checked to ensure that hinges had formed only in the intended locations, that the members were not shear critical, and that the assumed stiffness in the transverse and longitudinal direction (used, with the reactive mass, to compute the seismic demand on the pier required for sizing the plates) matched that of the design. This approach was iterated until a satisfactory design was converged upon.

The final boundary frame design consisted of VBEs having an outer diameter of 609.6 mm (24 in) with a wall thickness of 46.0 mm (1.812 in), longitudinal HBEs having an outer diameter of 323.9 mm (12.75 in) with a wall thickness of 12.7 mm (0.5 in), and transverse HBEs having an outer diameter of 406.4 mm (16 in) with a wall thickness of 21.4 mm (0.843 in). The transverse plates were each 1.588 mm (0.0625 in) thick, and the longitudinal plates were each 3.175 mm (0.125 in) thick.

This design was further assessed with non-linear finite element modeling using the graphical interface program ABAQUS [12]. Figure 6 shows the model of the pier both prior to and following a pushover analysis being carried out. Notice that the plates buckle in compression and develop tension field action, as is characteristic of SPSW systems.



Before After

Figure 6. Finite element model before and after the pushover analysis

VEHICLE COLLISION AND TSUNAMI

The pier's design also considered the vehicle collision hazard by way of statically applying a 1780 kN (400 kip) concentrated load at 1200 mm (4 ft) above the ground, per AASHTO [10] requirements, to one of the VBEs in a linear elastic analysis. Not being captured in simplified analyses, advanced, finite element analysis was used to assess the impact the plates have on the global behavior of the system to this hazard, and it was found that the plates aided in resisting load in a way similar to how they resist the seismic hazard – through the development of tension field action (Figure 7).

Tsunami preliminary design considered loads that were obtained from FEMA 55 [13] and the City and County of Honolulu Building Code (CCH) [14], and assumed an event corresponding to a 3 m design stillwater depth with water flow having a computed design velocity of 10.8 m/s (35.4 ft/s) in the direction perpendicular to the bridge's deck. Design considered the following two load cases: (1) surge forces and debris impact forces, and (2) hydrostatic, hydrodynamic and debris impact forces. While the plates were expected to yield in response to being loaded, the boundary frame was expected to remain undamaged.

Further analysis with a finite element model similar to that used in analysis of the seismic and vehicle collision hazards, considered only hydrostatic and hydrodynamic forces, but for four different water depths; the fourth depth very conservatively considered the pier to be fully submerged (Figure 7). It was found that (even for the fourth load case) while the plates did yield and act as sacrificial elements for this hazard, the boundary frame was observed to remain stable and not develop any plastic hinges following each finite element analysis, per conceptual intent at the onset of design.

BLAST

In initial design, the plates and VBEs were assessed separately in a decoupled analysis being subject to a blast load having a peak reflective pressure of 29.2 MPa (4228 psi) and a reflected impulse of 9.7 MPa-msec (1407 psi-msec). Design considered this load to act uniformly over the bottom plates and the bottom (up to the first HBEs) of the VBEs; these elements would have the least standoff to an explosion occurring at the base of the pier and would therefore be the most severely loaded.

Simplified analysis revealed that the plates would likely offer little resistance against the threat considered and would thus be sacrificial assuming the boundary frame remained stable. Accordingly, the VBEs of the system were assessed to validate this assumption. It was found that the VBEs would be sufficiently strong to resist the loads imposed by simultaneous yielding of attached plates. Likewise, it was found through a separate SDOF flexural analysis that the VBEs would also likely remain elastic if subject to the design blast loads acting over their own surface.

Nonlinear static analyses were also conducted in an effort to uncover unanticipated behavior when the pier is locally subject to larger pressures loads, and in a manner that simulated the likely failure sequence of pier elements, the plates being assumed to fail first. Of primary concern was how the VBEs would behave under large compressive forces, so the finite element analysis considered a uniform pressure loading over the bottom quarter of one of the VBEs (Figure 7). Ultimately, this study uncovered the potential need to locally reinforce the cross-sections of any hollow structural shape, and that the VBEs could undergo significant flexural deformations without apparent consequence to the pier's global behavior. As such, a revised and final multi-hazard concept suggests the use of concrete-filled steel tubes instead of hollow ones. The design concept remains identical otherwise.

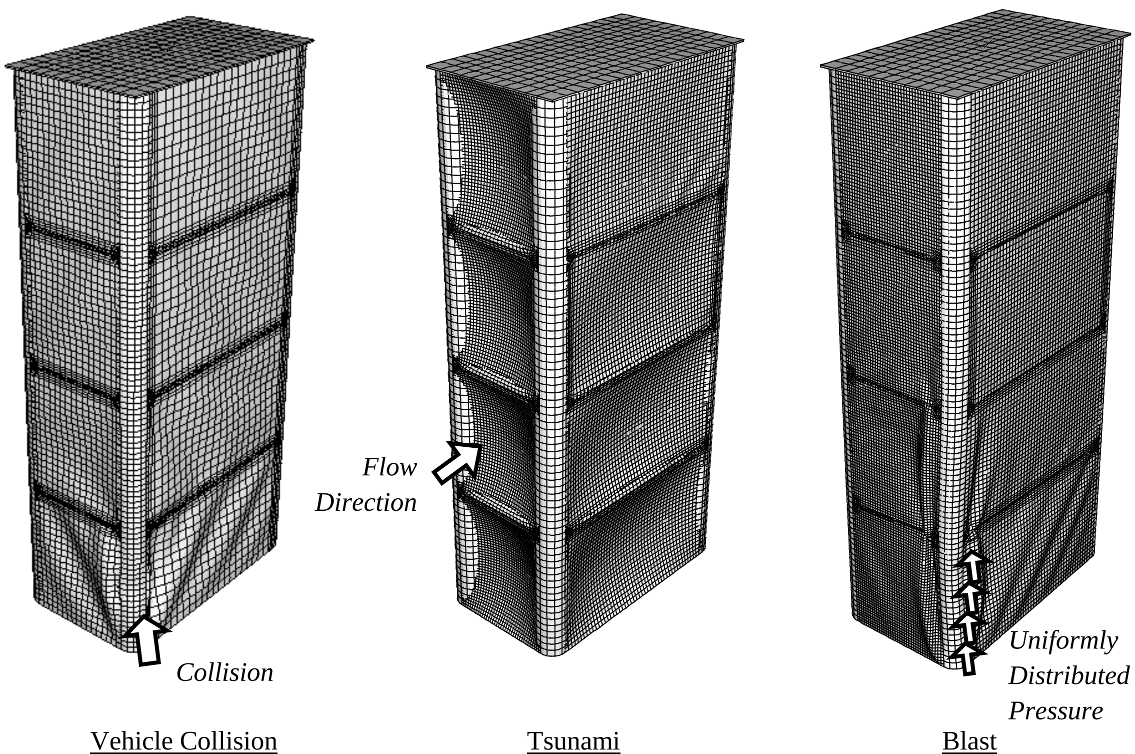


Figure 7. Finite element model following analysis for vehicle collision, tsunami and blast

CONCLUSION

Two innovative bridge bent concepts have been proposed to meet the objectives of multi-hazard design, namely: (i) a pier-bent made of concrete filled steel tube columns intended to resist blasts and earthquakes, and; (ii) a multi-hazard resistant steel plate shear wall box pier developed to provide satisfactory performance for earthquakes, vehicle collisions, tsunamis or storm surges, and blasts. Experiments and finite element analyses conducted to validate and verify these concepts demonstrated their superior multi-hazard performance, particularly (in some instances) compared to piers only designed to resist earthquakes. These results also support the benefits of approaching multi-hazard design in a holistic way during the conceptual design stage.

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