SEISMIC DESIGN OF A FERRY TRANSFER SPAN BASED ON TWO PERFORMANCE LEVELS

Henry Huang[1], Markus Wernli[1], Matt Donahue[1], Lee Marsh[2], and Mike Wray[2]

ABSTRACT

Washington State Ferries (WSF) has recently initiated a new hydraulic lift transfer span (H-span) system to replace an existing counterweighted cable and winch system. The motivation for this change stems in part from failure of a pulley cable, resulting in the transfer span and its operator falling into the water, at a WSF ferry terminal. The new H-span consists of multiple steel boxes with an orthotropic steel deck and provides adequate stiffness and strength to safely support live load if one of the two cylinders fails. The H-span is simply supported by bridge seats on the shore side and by two hydraulic cylinders on the offshore side. In the horizontal direction, the H-span reacts like a cantilever beam fixed at the shore side by the two bridge seats. The bridge seats are rigidly linked to the concrete trestle span supported on numerous piles. From the dynamic response spectra analysis, it was found that the response of the H-span along the transverse direction is substantially magnified due to a "whipping" effect triggered by the massive trestle structure. The resonant amplification was more than five times that of the AASHTO design spectra. To limit the structural response, the H-span was designed to meet two seismic performance levels. The bridge shall perform linear-elastically up to a defined Operational Earthquake (50 percent of design earthquake) before a fuse-mechanism reduces the fixity of the shore side of the bridge, allowing the bridge to slide at the bridge seat and sway horizontally offshore to contact a bumper system. This paper discusses the design considerations for the two performance levels and the consequential detailing of fuse and bumper systems. The dynamic impact on the bumper system is also discussed.

Introduction

The lift bridges serving auto ferries in the Puget Sound region have been running successfully since the 1930s. The general mechanism for lift bridges since that time has been a single winch mounted on the transfer span that operates a cross-reeve cable and features cable-supported counterweights. After an accident in 2001, when a cable failed, dropping both transfer span and its operator into the water, Washington State Ferries (WSF) initiated a review of the existing transfer span system that included investigation of the existing structural, mechanical, and electrical systems.

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[1] Project Engineers, BERGER/ABAM Engineers Inc., Federal Way, WA 98003
[2] Project Managers, BERGER/ABAM Engineers Inc., Federal Way, WA 98003

Prior to this project, the WSF standard design for a transfer span, commonly referred to as the M-span, consisted of a cable hoist and counterweight system with live load pins and hanger bars. The transfer span of the M-span is supported by either a rigid pin support or sliding energy dissipating pin support located at the shore side bridge seats. The offshore end is attached to lift cables that run through the reeved winch system that in turn is attached to a pile-supported headframe.

The town of Sydney in British Columbia, Canada, owns a ferry terminal bridge system operated by hydraulic actuators. Engineers from BERGER/ABAM Engineers Inc.visited the Sydney terminal and conducted a feasibility study on whether such a hydraulic system would be suitable for WSF transfer span system (BERGER/ABAM, 2004). The results of this study showed that a hydraulically actuated transfer span a hydraulically actuated transfer span (H-span) could be designed to have low vulnerability of a hydraulic oil leak, increased vessel and bridge operator visibility, reduced maintenance cost, and increased structural efficiency by using a torsionaly stiff deck system. Overall, the BERGER/ABAM study showed that the hydraulically actuated transfer span design is more economical, more practical, and simpler than the existing cable-operated systems. The H-span is designed to be rigidly connected to the approach trestle that connects the entire structure to shore. The study showed that the seismic behavior of the H-span is largely dependent on the dynamic response of the trestle structure. This paper investigates the link between the dynamic behavior of the H-span and the dominant trestle dynamic response. Also further explored is the design approach with two earthquake performance levels, the corresponding fuse-mechanism, and the impulse impact on the offshore bumper system.

Hydraulic Transfer Span Description

The hydraulically actuated transfer span (H-span) consists of a superstructure, two A-shaped frames with hydraulic lift cylinders, an apron deck, and support frames fitted with pressed bearings at the bridge seats (see Figures 1a and 1b). The multibox superstructure is composed of welded steel boxes with an orthotropic steel deck and is designed to provide adequate stiffness and strength to safely support the design live load, while accommodating failure of one of the two lift cylinders. The two A-frames are supported by pinned-end hydraulic cylinders located near the span's seaward end, which are designed to lift the entire superstructures along with vehicle loads. Bearing of the H-span on the inshore end is provided by steel frames rigidly weld-connected to steel plates embedded in the bridge seats. With such a configuration, the superstructure can redistribute the loads such that one lift cylinder and the bridge seat bearings can support the entire structure. The bearings are configured to resist both the normal operational loads and the uplift loading that accompanies the one cylinder faulted arrangement. This provides life-safety redundancy and simplicity of design.

For the H-span case described in this paper, the bridge seats are monolithically part of the massive trestle span that is supported by numerous piles for the Bainbridge Island Ferry Terminal located near Seattle, WA. Overall dimensions for the H-span of Bainbridge are as follows.

- Transfer span total length (ramp hinge to apron hinge): 90'-8"

- Apron length (apron hinge to finger lip hinge): 15’-9”
- Structural deck width (from edge to edge of steel deck): 23’-0”
- Road width (edge of curb distance): 20’-1”
- Steel deck depth: 3’-3”
- Distance of lift A-frame (ramp hinge to actuator): 74’-8”
- Bridge seats cross distance: 30’-0”
- Actuators cross distance: 31’-6”
- Ramp motion range: +11.4% to -15.4%

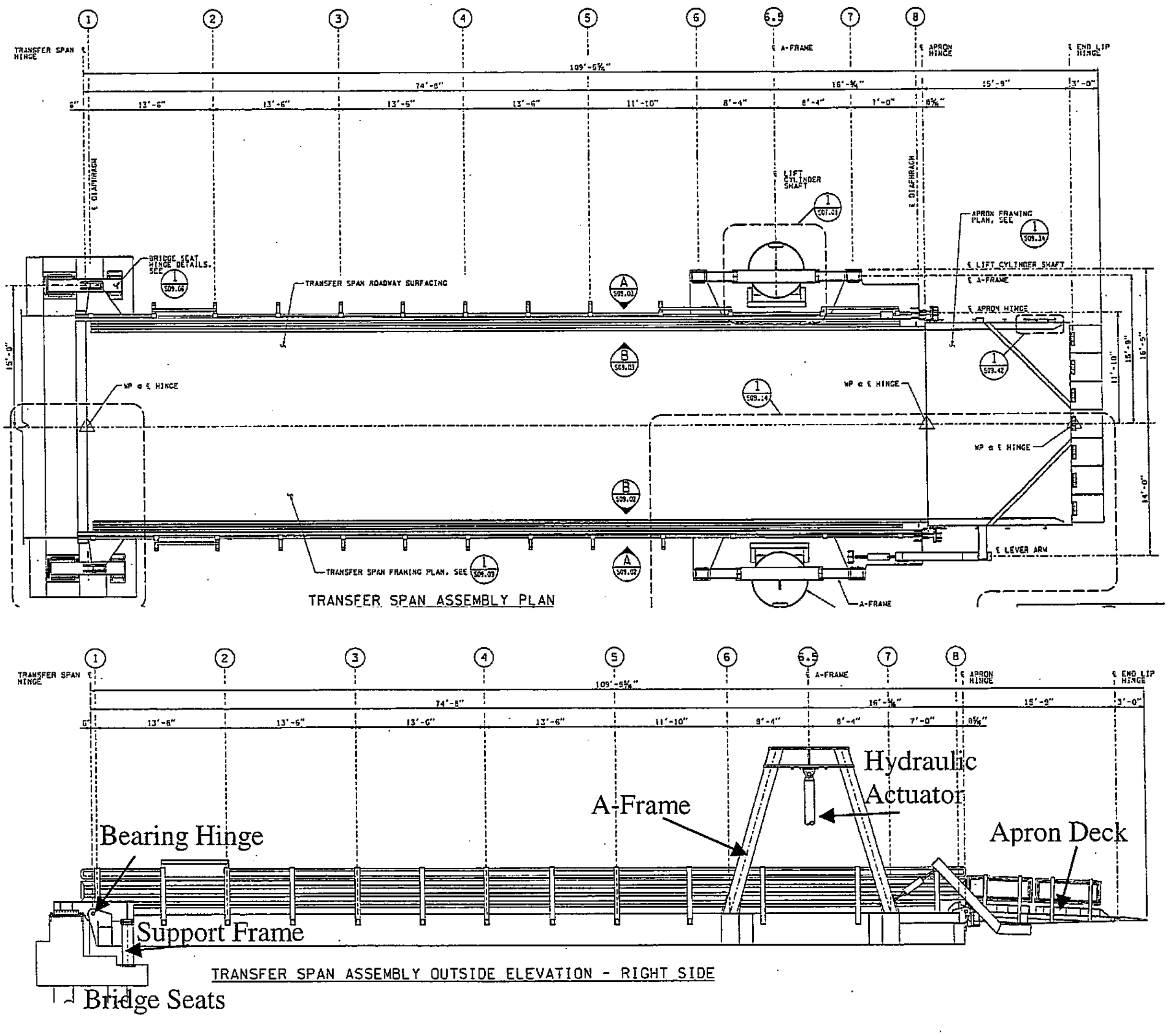
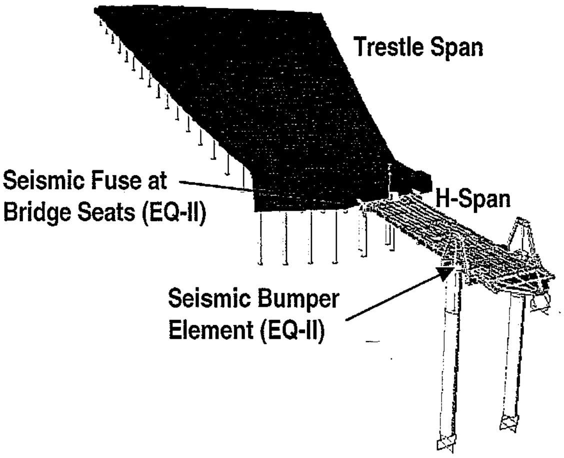


Figure 1 Hydraulic Transfer Span Plan and Elevation

Dynamic Amplification of the H-Span

As per WSF requirements, the AASHTO LRFD Bridge Design Specifications (2004), is applied to the H-span seismic design. An acceleration coefficient of 0.3 is used for the location of the Bainbridge Island Ferry Terminal, which falls into seismic Category C with soil Type II.

No vertical acceleration was considered. Modeling of the H-span configuration as described above shows that the fixed bearings at the bridge seats tend to attract a significant portion of the seismic load. The bridge seat is part of the pile-supported concrete trestle, which becomes increasingly more flexible toward the seaward end (see Figure 2). The H-span comprises less than 3 percent of the total mass of the concrete trestle. Therefore, the trestle will dominate the dynamic response of the H-span in the longitudinal and transverse directions. Amplification of the dynamic response beyond the bridge seats, which can be termed a "whipping" effect, is anticipated and depends on the stiffness of the superstructure and the connections at the bridge seats. From the dynamic response spectra analysis, it was found that the response of the H-span in the transverse direction is substantially magnified by the dynamic response of the comparatively massive trestle structure. The amplification resulted in a spectral response more than five times larger than that given by AASHTO (see Figure 3).



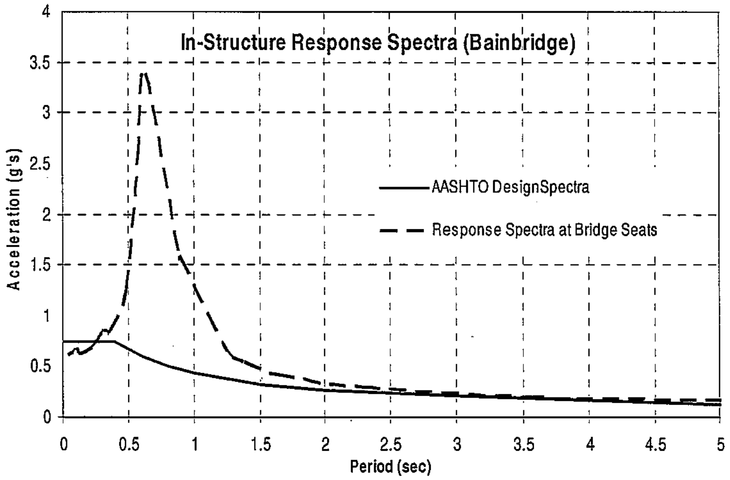


Figure 2 H-Span Analysis Model

Figure 3 Floor Response Spectra at Bridge Seats

Two-Level Earthquake Performance Design Consideration

AASHTO publishes two standards for movable bridges: AASHTO LRFD Movable Highway Bridge Design Specifications, First Edition, 2001 and the Standard Specifications for Movable Highway Bridges, 1988. These two standards specifically address bascule, swing, and vertical-lift bridge criteria for electrical and mechanical design and refer to the AASHTO LRFD Bridge Design Specifications for structural design. Engineering judgment has been used for establishment of the design criteria where AASHTO standards were found not to apply. The operational level earthquake design concept defined by AASHTO LRFD Movable Highway Bridge Design Specifications is adopted as seismic design criteria for the H-span to ensure that the H-span remains operational subjected to a low or moderate seismic event.

Initial design for the H-span assumed all lateral loads would be resisted at the bridge seat and the transfer span would cantilever offshore. From the examination of the output response spectrum at the bridge seats, it was found that the dominant period of the swing mode for the trestle span is about 0.7 seconds and is longer than that of the H-span. The response acceleration of the H-span for fixed bearings at the bridge seat would be about 1 g what is 35 percent higher than that prescribed by the AASHTO design spectrum. A further concern was that this amplification effect would be even more significant if the bearing connections become flexible due to slippage or deformation. To avoid the large amplification, it was decided to reduce the fixity of the bridge bearings once the acceleration response of the H-span exceeds 50 percent of the theoretical design earthquake demand. This "seismic fuse" allows the period of the H-span to shift beyond the high amplification peak of the spectrum for earthquakes larger than 50 percent of the design earthquake. The H-span was then designed to accommodate the acceleration and displacement demands of the design earthquake with the new constraints of reduced bearing fixity and the H-span impacting the bumpers for offshore support.

Therefore, the H-span was designed for two earthquake performance levels. Up to an Operational Level Earthquake of 50 percent of the design earthquake, the bridge responds linear elastically and is laterally restrained only at the bridge seat. For larger earthquakes up to the Design Level Earthquake, the bridge responds nonlinearly allowing for controlled minor damage at the bridge seat – the breaking of the seismic fuse and nonlinearly support at the offshore bumper system. The definition of the Operational Level Earthquake is according to AASHTO LRFD (2002) "Moveable Highway Bridge Design Specification", Section 3.4. No live load is considered for a design level earthquake and 50 percent of the live load is applied for an operational level earthquake.

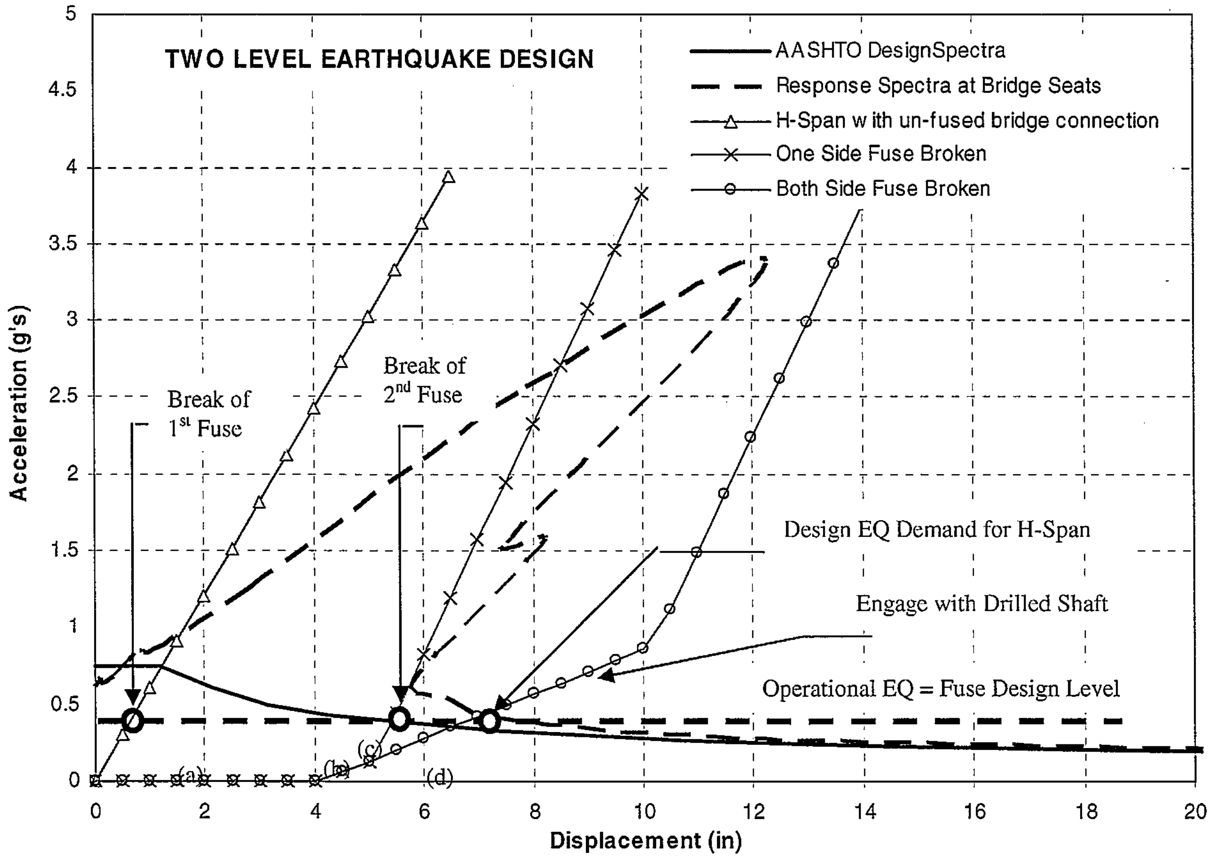


Figure 4 Two-Level Earthquake Design

The effect of the fuse mechanism is shown in a displacement/acceleration diagram in Figure 4. The design spectrum for the H-span is the amplified AASTHO design spectrum of the bridge seats. The linear-elastic response of the fixed H-span intercepts the design spectrum of the bridge seats at 1 g. A first fuse at one of the bridge seat dislodges at 50 percent of the theoretical demand from the design spectrum and allows the bridge to sway about 4 inches before the bridge impacts the seismic bumper at the drilled shaft (segment (a) in Figure 4). After contact with the drilled shaft, the bridge responds laterally as a simply supported beam, being effectively isolated from the "whipping" effect of the trestle. The fused bearing eventually engages stops at a displacement of 5 inches and stiffens the bridge's response back to a value similar to the un-fused stiffness (segment (c)). Having shifted the bridge response further into the peak demand of the design spectrum, the second fuse dislodges almost simultaneously, allowing the bridge's response to shift away from the design peak response. The final bridge response intercepts the design spectrum now at an acceleration that is even lower than the operational earthquake level but at a much higher displacement demand (Approximately 7in in Figure 4, point (d)). The gaps of the fuses have to be designed large enough, so that, once the bridge seat engages again, the bridge response is not intercepting the design spectrum peak. The strength and displacement demand of the seismic fuse is thus strongly dependent on the amplification effect of the trestle.

Seismic Design Details

The analysis provides a force and displacement demand for both the operational and design earthquake levels. The demand from operational earthquake is directly applied to design the seismic fuses and the H-span is modeled as a cantilevered structure. The demand of the remaining superstructure and reaction at the trestle is given by the demand from either the design earthquake or the operational earthquake. Thereby, the operational earthquake is multiplied by an overstrength factor of 1.25. This capacity design approach ensures that the fuse is the weakest link during an earthquake. Finally, the drilled shaft and the attached bumper system need only to be designed for the design earthquake demand. The details for the bridge bearing with seismic fuse and for the drilled shaft with bumper are shown in Figures 5 and 6.

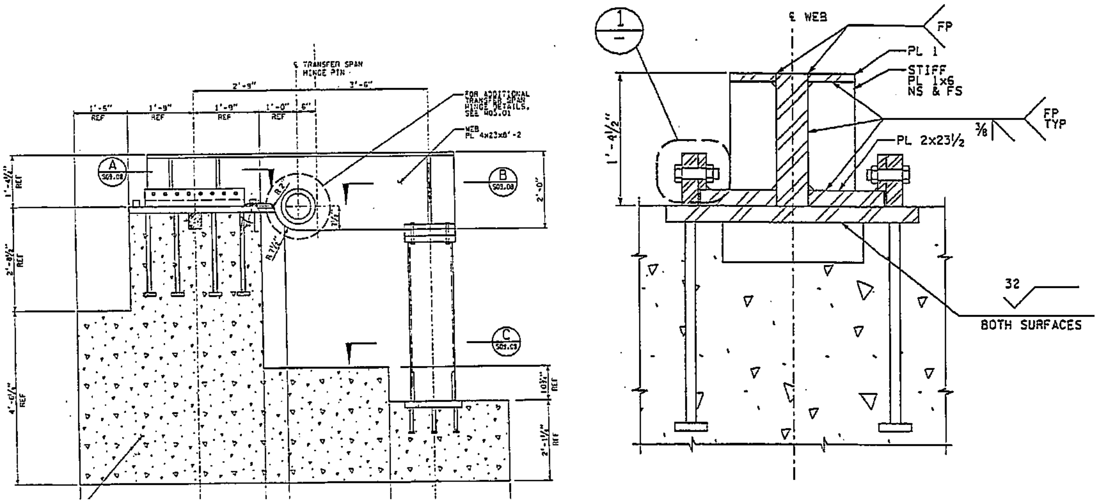


Figure 5 Seismic Details at Bridge Seats

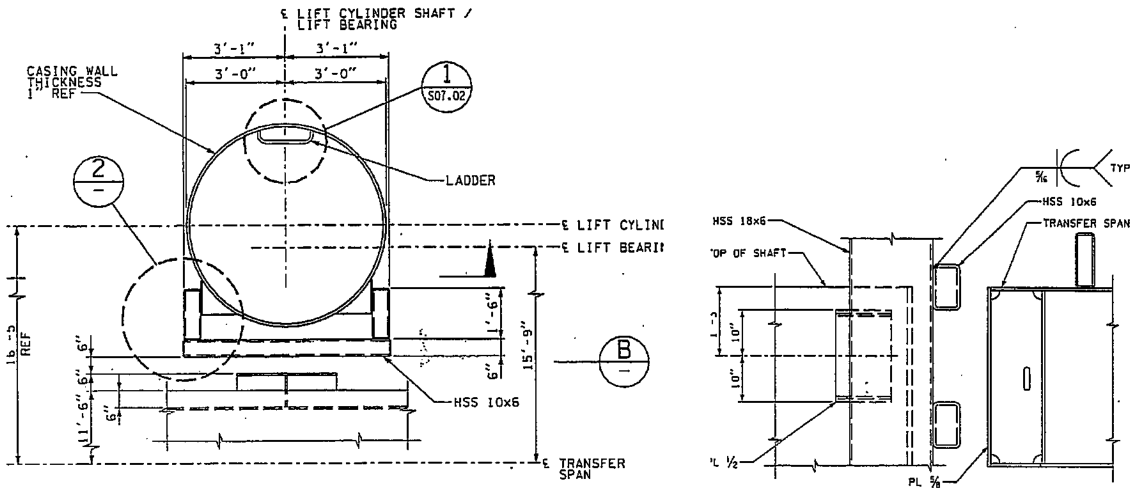


Figure 6 Seismic Bumper Frame at Drilled Shaft

Once the load has reached the defined fuse load level, the fuse is designed to allow the bridge supports to slide longitudinally. The motion range of the sliding support is limited by stops, so that a longitudinal motion of the bridge would eventually be hindered, but the bridge is still free to rotate horizontally for several degrees before hitting the bumpers at the shafts and finally engaging the stops. The gap at the bridge seat is sized for the minimum gap that will allow the bridge to sway and thus shift the bridge response within the design spectrum while avoiding an acceleration demand larger than the defined operational acceleration demand.

The gap between the bumper and the bridge is designed as the minimum distance so that the bridge does not touch the bumper under any operational conditions, including the operational earthquake. Force amplification due to impact is considered as explained below.

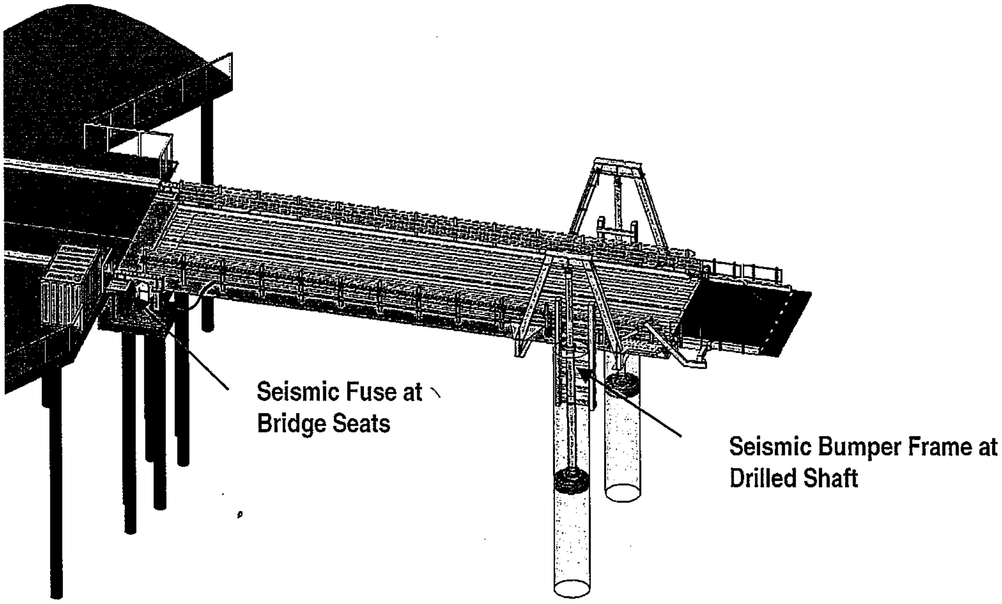


Figure 7 Seismic Fuses and Bumper Frames (Courtesy of Lund Engineering)

Impact for Design Earthquake Load

After the fuse breaks under a design earthquake load, the H-span is modeled as a simple beam horizontally supported at the bridge seats and seismic bumper frames. The movement of the H-span is nonlinearly restrained within the gap of the bridge seats and the gap of the seismic bumper frames (see Figure 8). The impacts occur due to the opening and closing of the gaps. In order to investigate the impact, the H-span in the transverse direction is represented as a generalized single-degree-of-freedom (SDOF) model that is excited by harmonic input at the dominant frequency of the trestle structure. The model has a stiffness given from the drilled shaft and is equipped with gap elements to address the nonlinearity.

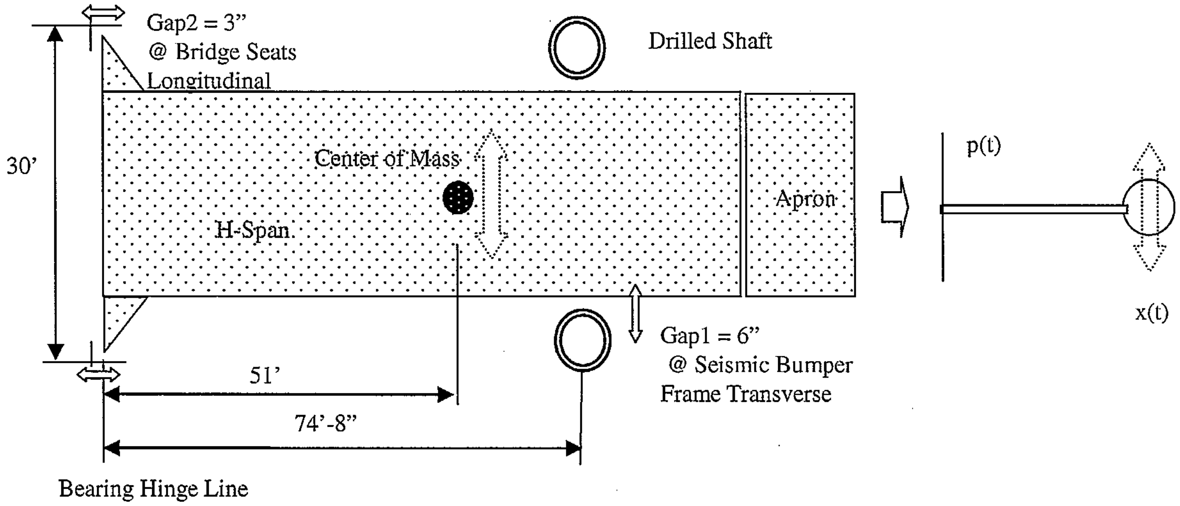


Figure 8 Pounding Impact Effect of SDOF Model

The equation of motion of the model can be written as,

$$m\ddot{x} + C(\dot{x}, x) + F(x) = -p(t) \qquad \text{Eq. 1}$$

where the *m* is the mass of the H-span, the restoring forces *F(x)*, and the damping forces *C(x',x)* can be expressed as,

$$F(x) = \begin{cases} 0 & if\ \lfloor x \rfloor \le open1 \\ \omega h^2 [x - open1 \cdot sign(x)] & if\ open1 \le \lfloor x \rfloor \le open1 + open2 \\ \omega h^2 [x - open1 \cdot sign(x)] + \omega c^2 [x - (open1 + open2) \cdot sign(x)] & if\ |x| > open11 + open2 \end{cases} \qquad \text{Eq. 2}$$

$$C(\dot{x}, x) = \begin{cases} 0 & if\ \lfloor x \rfloor \le open1 \\ 2 \cdot \xi \cdot \omega h & if\ open1 \le \lfloor x \rfloor \le open1 + open2 \\ 2 \cdot \xi \cdot \omega c & if\ |x| > open11 + open2 \end{cases} \qquad \text{Eq. 3}$$

where the ωh is the circular frequency of the drilled shaft and ωc is the circular frequency of the H-span with a fixed bearing connection, both of which can be obtained from modal analysis.

The function $sign\ (x) = 1$ for $x>0$ and -1 for $x<0$ controls the sign. The damping ratio is defined as ξ and is typically two percent for steel structures. The *open1* term is calculated from *gap1* and the *open2* term is the effective gap calculated as *gap2-gap1*. The nonlinear restoring force function with gaps is pictured in Figure 4 as *line (a)-(b)-(d-(c)*. The dominant excitation $p(t)$ is produced by the trestle structure at the frequency (f_t). For simplicity, the excitation can be expressed $p(t) = p0\ sin(2\ \pi f_t\ )$ with harmonic excitation having an intensity of $p0$. The dynamic response of the nonlinear gap element and comparison to the response without the gap are shown in Figure 8 where the input harmonic excitation has the amplitude of 2g; the H-span weight is 340 kips; the gap at the bumper frame and bridge seats is 6 and 3in respectively; the excitation frequency from the trestle structures is 1.36 Hz; the frequency of the drilled shaft is 1.20 Hz; and the frequency of the H-span fixed connection conditions is 2.44 Hz.

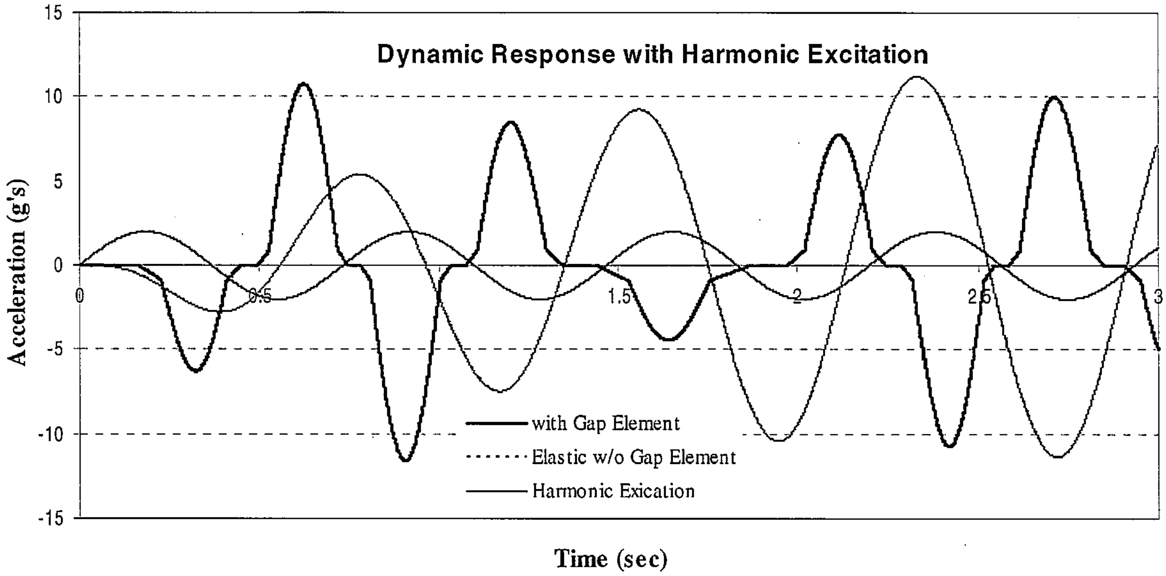


Figure 9 Comparison of Linear and Nonlinear Responses with Harmonic Excitations

The amplification due to the gap pounding impact is less than two percent because the drilled shaft frequency is smaller than the excitation frequency. If the gaps at the bridge seats closed before the seismic gap at the bumper frame, this impact could go as high as three times the linear dynamic analysis. Therefore, the seismic gap at the bridge seats should have sufficient distance to avoid a pounding impact.

Conclusions

The low mass of the transfer span compared to the trestle structure subjects the transfer span to a highly amplified acceleration spectrum due to a "whipping" effect of the trestle. The high amplification can be avoided by allowing a seismic fuse to shift the response of the transfer span beyond the dominant response of the trestle once an earthquake exceeds the operational earthquake level. Such a two level earthquake design is a prudent and effective measure to limit seismic design forces to a reasonable range for design.

The two-level earthquake design requires the application of the principles of capacity design to ensure that the seismic fuse is the weakest link. That is achieved by designing the seismic fuse for the operational level earthquake, whereas the remainder of the structure, including its reaction points, are designed to the operational level multiplied by an over strength factor. In addition, all structural elements have to be checked for the design earthquake level response of the structural system that has been altered due the dislodged seismic fuse.

The gaps of the seismic fuse have to be designed large enough so that once the fuse engages again the bridge response is not intercepting the amplified design spectrum peak. This requirement can be checked by comparing the nonlinear static response of the structure with the amplified design spectrum within an acceleration/displacement diagram. The strength and displacement demand of the seismic fuse is thus strongly dependent on the dynamic amplification effect of the trestle.

Besides meeting the seismic force and displacement demands, a seismic fuse can be economical, as well as meeting the requirements for practicality during construction, easy maintenance, and simple repair.

The bumper system is not intended to be a seismic damper, but rather simply limits the lateral displacement of the structure during an earthquake. The bumper does not need any compliance to reduce the impact reaction as long as the drilled shaft period is somewhat larger than the dominant period of the trestle. However, it is important that the stops at the bridge seat are not engaged during the seismic event, as otherwise the impact load could go as high as three times the linear dynamic response.

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References

BERGER/ABAM Engineers Inc., 2004. *Hydraulically Actuated Transfer Span System,* Technical Report to Washington State Ferries, Seattle, WA

SAP2000, 1996, *Analysis Reference*, *Volume 1*, Computers and Structures, Inc., Berkeley, CA