Experimental response modification of a four-span bridge retrofit with shape memory alloys

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SUMMARY

A unique shape memory alloy (SMA) restrainer cable is developed and tested to evaluate its effectiveness in limiting the hinge opening in bridges. The SMA cables, connected at the deck–abutment interface, are tested on a four-span, one-quarter scale, concrete slab bridge. The bridge is subjected to a suite of ground motion to assess the performance of the SMAs under different magnitudes of loading. The results of the experimental tests show that the SMA cables were effective in reducing the potential for unseating by reducing the as-built openings by 47 and 32% for low-level and high-level loading, respectively. In addition, the hinge displacements were also accompanied by reductions in column drift. A detailed finite element (FEM) model of the test setup is developed and comparisons are made with the experimental tests. The results of the FEM compare favorably with the experimental tests. Using the FEM, a suite of 40 ground motion records are used to compare the expected performance of the bridge with SMA cables. The results of the analysis show that the SMA cables reduce the mean hinge openings by 57 and 69% for the low-level and high-level loading, respectively. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: shape memory alloys; Nitinol; earthquakes; seismic; bridges; retrofit; testing

INTRODUCTION

Earthquakes have resulted in considerable damage to highway bridge infrastructure in events of past decades [1–4]. One of the most severe modes of failure includes unseating of bridge spans. This occurs due to excessive out of phase motion in multi-frame bridges or deck displacements...
that exceed support lengths at abutments or bent beams in simply supported bridges. While new design strategies aim to alleviate unseating potential, there are many existing bridges that may be susceptible to span unseating due to a lack of seismic detailing or potential for stronger ground shaking than considered in the original design. These structures require seismic retrofitting or rehabilitation. The primary objective of many bridge seismic retrofit programs is to avoid the loss of life due to collapse of bridges during earthquake events, which is often marked by unseating of bridge spans. More stringent performance goals may require some level of residual functionality or accessibility of the bridge, which is obviously inhibited should a span displace to the point of instability (Federal Highway Administration (FHWA) [5]).

Given the criticality of controlling deck displacements, a number of studies and applications in practice have addressed seismic retrofit devices modifying deck response or preventing unseating of bridge spans [6–8]. Despite these advances, some of the limitations of traditional approaches have been highlighted in past studies. Examples of device limitations noted include the fact that steel restrainer cables can transfer large forces to adjacent bridge components when elastic or upon yielding may accumulate plastic deformations in repeated loading cycles ultimately resulting in span unseating [9]; metallic dampers lack the ability to recenter, and must be replaced following an earthquake event [10]; and seat extenders avoid complete span unseating, yet have no effect on deck displacements that could lead to damage of other components [11]. Given these findings, new methods for modifying the seismic response of bridges have been proposed, including the use of smart materials in bridge retrofit [12–18]. Of interest in this work, shape memory alloys (SMAs) have been investigated for seismic response modification due to their advantageous properties, such as the ability to undergo large deformations with limited residual strain.

This paper presents the experimental results of a seismic response modification device for bridges using SMA cables at the deck–abutment interface, and complementary analytical studies conducted to refine finite element models (FEMs) of bridge systems with SMA-based devices. The testing was conducted as a part of the Network for Earthquake Engineering and Simulation (NEES) research program, using the quarter-scale, four-span bridge NEESR-0420347 test set up at the University of Nevada, Reno (UNR). Past studies of bridge retrofits have often been limited to component testing, given the large-scale specimen required to evaluate bridge systems and the former limitations of testing facilities. To the author’s knowledge, this provided the opportunity to conduct the largest-scale application of SMAs in a bridge to date. Moreover, it provided the first opportunity to investigate the effectiveness of the SMA-based devices within a bridge system, and validate past component-level tests.

SHAPE MEMORY ALLOYS

While traditional applications of SMAs have been in the commercial, biomedical, or aerospace fields, advantageous properties of SMAs for use in the field earthquake engineering have been noted in past studies [19–26]. In particular, the distinguishing feature of SMAs that has made them attractive for applications in bridges under earthquake loads is their ability to undergo large deformations while reverting back to their undeformed shape through the removal of stress. This superelastic effect, illustrated in Figure 1, may be exploited for unseating prevention and reducing the vulnerability of bridges in seismic regions. Previous work has shown that nearly ideal superelastic properties can be exhibited in nitinol SMA bars and wires with proper
heat treatment [26,27], and has focused on optimization of alloy properties for use in seismic
applications [21]. Given these advances, some of the additional characteristics of nitinol SMAs
that are conducive to restraint of bridge decks, include the large elastic strain range, leading to
excellent potential as a recentering device; damping associated with the flag-shaped hysteresis;
and excellent low- and high-cycle fatigue properties. Moreover, the formation of a stress plateau
at intermediate strains can assist in limiting transfer of forces to adjacent members, while strain
hardening or stiffening at large strains limits excessive displacements at high loading levels.

Previous work has analytically evaluated the use of SMA restrainer cables in bridges, with
results showing that not only were they effective in reducing hinge openings between adjacent
frames [10] but they were superior to traditional steel restrainer cables or metallic damper retrofits
in reducing hinge openings with similar impacts on column demands [28]. Very few studies,
however, have assessed the viability of using SMA cables as response modification devices for
bridges through experimental testing. Recent shake table testing by Johnson et al. [29] evaluated
nitinol SMA cables in a representative in-span hinge within a multi-frame concrete box girder
bridge, using an elastomeric bearing concrete block test setup. They found that the SMA
restrainer cables were more effective than equivalent steel restrainer cables at reducing hinge
openings and block accelerations, with minimal residual strain after repeated loading cycles. These
types of response modification devices have yet to be evaluated, however, within bridge system-
level tests. This scale of testing is critical for further validation of the novel SMA-based device and
for evaluation of the impact on bridge system response. Additionally, since in-span hinges are not
the only potential application zone of SMA restrainers, additional configurations of the cables are
of interest, particularly for bridge types other than multi-frame concrete box girder bridges.

**EXPERIMENTAL TEST SETUP**

*Large-scale four-span bridge*

The SMAs restrainers were tested on a one-fourth scale, four-span, concrete slab bridge
designed as a part of the NEESR-0420347 project, and constructed at the NEES equipment site.
at the University of Nevada, Reno [30]. The bridge deck was 2.388 m wide, 356 mm thick and 32.6 m long. The two outer spans were 7.47 m and the inner spans were 8.84 m in length. The four spans were made continuous through the use of a post tensioning system and tensioned to the bent cap at the top of the columns. Each of the three bents had two, 305 mm diameter columns with heights of 1.52, 2.13, or 1.83 m. An additional 800 kN of loading was imposed on the bridge deck to simulate a realistic mass to stiffness ratio and period of the bridge. The superstructure of the bridge is supported on rollers, or guided sliders, at the abutment seats, and the abutments were locked using actuators for the purposes of the restrainer tests. Furthermore, they were pulled back to avoid pounding which may have compromised the actuators and abutment test setup for the other tests. The bents were supported on three bi-axial shake tables, capable of simulating seismic shaking. Figure 2 shows an overall view of the test setup, indicating the location of the nitinol SMA cable devices located at the deck–abutment interface, and Figure 3 shows the constructed test setup. The same instrumentation that was used for the

Figure 2. Test setup indicating: (a) SMA restrainer locations in the four-span bridge and (b) restrainer details.
bridge system test was utilized for the SMA restrainer evaluation. Namely, those exploited for the retrofit evaluation included displacement transducers for measuring column drift; accelerometer and displacement transducers for measuring deck displacements and accelerations, hinge openings, and cable elongation; and a load cell for measuring cable forces.

**SMA restrainers**

The response modification device was composed of nitinol SMA cables that were connected between the underside of the deck and the abutment face. The cables were composed of bundled 0.584 mm diameter wires, which were made of superelastic nitinol having a composition of 51% atomic weight of nickel. The 559 mm long design cables had a total of 645 mm$^2$ cross sectional area of alloy distributed equally in five cables symmetrically connected across the hinge at each abutment. This design targeted a 50% reduction in hinge openings, based on preliminary analytical modeling. Each of the five cables was connected to the deck–abutment face using u-bolt and 12.7 mm thick steel plate bracket assemblies bolted and grouted to the abutment face and underside of the deck slab, as further detailed in Figure 2(b). The photograph in Figure 3(c)

![Figure 3. (a) Experimental test setup; (b) SMA restrainer locations in the four-span bridge; and (c) SMA restrainer bundle.](image-url)
shows a sample SMA cable consisting of 480 SMA wires threaded around a thimble and clamped. The wires were subsequently encased in a thin-walled latex tubing.

**Loading and test cases**

The ground motion used for testing the effectiveness of the SMA devices was the same as the record selected for the NEESR-0420347 project, incrementally scaled for excitation of the four-span bridge. This motion is a modified version of the 1994 Northridge, California earthquake record from Century City station, and has been used in past shake table testing of a two-span bridge [31]. Figure 4 shows the ground motion scaled to a peak ground acceleration of 0.60g. The test specimen was subjected to the longitudinal component of the motion to evaluate the dynamic response of the as-built bridge system relative to the bridge retrofit with SMA cables. This set of runs was conducted at a low- and high-level ground motion of 0.09 and 0.6g, for a total of four shake table excitations. The test matrix is summarized in Table I. It is noted that this is not the full test matrix conducted for the NEESR-0420347 project testing, in which there were biaxial and white noise simulations conducted prior to and following the SMA test matrix. This is of note, given that slight evolution of structural damage is expected throughout the process. Based on a frequency response evaluation of the structure using the white noise

![Ground motion time history used in shake table excitation, scaled to a peak ground acceleration of 0.60g.](image)

**Figure 4.** Ground motion time history used in shake table excitation, scaled to a peak ground acceleration of 0.60g.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Peak ground acceleration (g)</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.09</td>
<td>As-built bridge</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
<td>Retrofit with SMA cables</td>
</tr>
<tr>
<td>3</td>
<td>0.60</td>
<td>As-built bridge</td>
</tr>
<tr>
<td>4</td>
<td>0.60</td>
<td>Retrofit with SMA cables</td>
</tr>
</tbody>
</table>

Table I. Shake table test matrix for evaluating four-span bridge retrofit with shape memory alloy devices.
simulation from the full testing paradigm, it is estimated that the initial natural period of the bridge in the longitudinal direction is approximately 0.67 s.

**EXPERIMENTAL RESULTS**

The experimental program was conducted and each of the four runs presented in Table I were simulated with the shake table on a four-span bridge test setup to evaluate the SMA devices. However, due to unforeseen spalling on the underside of the bridge deck during intermediate testing conducted throughout the NEESR-0420347 test program, two of the five cables were not used for the upper-level test to avoid any further damage of the test specimen. Thus, the lower-level runs at 0.09g peak ground acceleration (pga) were conducted with the design retrofit of five cables with a total 645 mm² cross sectional area of SMA at each abutment; however, the upper-level runs at 0.60g pga were conducted with a reduced number of cables (3) and a 40% reduction in cross-sectional area of alloy. The higher level of forces transferred to each cable and connection element was sufficient to cause damage to the connections and reduced the effectiveness of the originally designed retrofitted system. The results will be presented below for both sets of tests, and further analytical studies will evaluate the system response anticipated with the full SMA design of five cables at each abutment hinge.

**Hinge opening**

The north and south hinge opening in the multi-span continuous bridge is defined as the relative displacement of the bridge deck away from the abutment. The hinge opening was measured with displacement transducers on the east and west side of each abutment, and are presented as an average value. It is noted that slight out-of-plane motion occurred in some runs due to imperfect in-lab conditions (i.e. variable friction in rollers/sliders, etc.). This resulted in slight rotation of the deck about a vertical axis. The time history for the hinge opening at the north abutment of the quarter scale four-span bridge is shown in Figure 5(a) for the ground motion scaled to 0.09g pga. It is apparent from this plot that the five SMA cables were effective in reducing the potential for unseating by reducing the openings by 52% compared with the case without restrainer cables. Table II compares the peak hinge openings for the four runs in the upper- and lower-level events, noting the location abutment at which the peak hinge opening occurred in the as-built bridge. For the as-built bridge subjected to the 0.60g motion (also shown in Figure 5(b)), the deck displacements resulted in peak hinge openings at the south abutment on the order of 55.9 mm. It is noted that even when using 40% fewer cables than originally designed, there was a reduction in deck displacements of over 30%.

**Stress–strain of SMA restrainer**

The response of the cables themselves is of interest to evaluate whether the hysteretic characteristics observed during the testing, the residual strain, and level of force transferred through the cables are representative of what we expect from typical SMA materials. Figure 6 plots the stress–strain response of the SMA cables for 0.09 and 0.60g events. The flag-shaped hysteresis is exhibited at the upper-level event, while at the lower-level event the displacements are not large enough to reach the forward transformation stress. For the upper-level event, the
Figure 5. Comparison hinge openings for (a) the north abutment at the 0.09g motion and (b) the south abutment at the 0.60g pga motion, where the largest openings occurred in the as-built bridge.

Table II. Comparison of the peak responses from each test and percent change of the responses with retrofit relative to the as-built bridge.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Peak hinge opening (mm)</th>
<th>Reduction from as-built (%)</th>
<th>Peak SMA strain (mm/mm)</th>
<th>Peak SMA stress (MPa)</th>
<th>Peak column drift (in/in)</th>
<th>Reduction from as-built (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.2 (N)</td>
<td>—</td>
<td>N/A</td>
<td>0.0030</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>6.86 (N)</td>
<td>52%</td>
<td>0.012</td>
<td>119</td>
<td>0.00158</td>
<td>47%</td>
</tr>
<tr>
<td>3*</td>
<td>55.9 (S)</td>
<td>—</td>
<td>N/A</td>
<td>0.0365</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4*</td>
<td>38.1 (S)</td>
<td>32%</td>
<td>0.068</td>
<td>610</td>
<td>0.0249</td>
<td>32%</td>
</tr>
</tbody>
</table>

* = 3 cables at each hinge; S = south; N = north.

Figure 6. Stress–strain response of the south SMA cables from the shake table test with the 0.09 and 0.60g pga earthquakes.
cables load and unload along the plateaus, and recenter with little to no accumulated deformation.

For the upper-level event approximately 236 kN was transferred through the cables to the abutments. This value corresponds to the forward transformation stress level for the SMA cables. The tests also reveal, however, that the SMA cables exhibit the classical loading and unloading plateaus, negligible residual strain, and strain hardening around 8% strain, all critical to effectively reduce the hinge openings presented in the previous section. A modest amount of energy dissipation is also provided by the hysteresis of the SMA cables for the upper-level event, totaling to approximately 6138 kNmm for the six cables.

**Impact on column demands**

The largest column demands in the as-built bridge were measured at the bottom of the columns in the first bent—the shortest bent. It is noted that in the longitudinal direction the columns undergo single curvature due to a pinned connection between the superstructure and substructure. In addition to reducing the potential for span unseating, the use of the SMA cables also translated into a reduction in demands placed upon the column, as measured by column curvature or column drift. Table II compares the peak column drifts for the four test cases. As shown in this table for the lower-level event, the five SMA cables at each abutment led to a 47% reduction in peak column drift. At the upper-level event, with three SMA cables, the column drifts reduced from approximately 3.65 to –2.49%, representing a 32% reduction in drifts. These comparisons further reveal the potential benefit of SMA cables in improving the local and global performance of bridges. While reducing the column demands was not the primary design objective of the SMA response modification system, this is an additional benefit of incorporating the system in the multi-span continuous bridge.

These large-scale bridge tests revealed that the use of SMA cables for response modification is effective within a bridge system. They reduced both the potential span unseating, measured in terms of the hinge opening at the deck–abutment interface and column demands. Though the test setup did not explicitly permit experimental evaluation, the associated reduction in deck displacements would also reduce the potential for pounding and abutment damage when retrofit with the SMA cables. While this study emphasizes assessment of the feasibility of using the SMA cables in a large-scale test and comparison of system performance with the as-built condition, past experimental and analytical studies have illustrated the benefits of SMA versus steel restrainer cables. For example, Johnson et al. [29] found that SMA restrainer cables were more effective in reducing both deck accelerations and displacements than equivalent steel restrainers in a multi-frame box girder bridge test; Andrawes and DesRoches [28] also performed an analytical study and concluded that superelastic SMA restrainers were more effective in reducing maximum hinge displacements and residual displacements at the hinges of multiple frame bridges.

**ANALYTICAL VERIFICATION**

**FEM of retrofitted bridge**

A FEM of the bridge retrofit with SMA cables was developed in the computation platform OpenSees [32]. The deck and bents are approximated as rigidly connected. Elastic beam–column
elements are used to model the four-span continuous concrete deck slab. The bent beams and columns are modeled with displacement beam–column elements discretized into fiber sections. In this fiber model, uniaxial material models are assigned for the reinforcement steel, confined, and unconfined concrete which comprise the column or bent beam cross sections. The sliding supports provided at the abutment seats are idealized as rollers. The additional blocks used in the experimental test setup to simulate realistic mass to stiffness ratio were modeled as additional superstructure masses. Rayleigh damping of 5% in the first two modes is assumed. For the upper-level tests, which were conducted later in the test matrix, a reduced moment of inertia for the columns of 15.7% was considered to emulate the progressively damaged condition revealed in the experimental tests. The reduction was targeted to achieve improved matching with the dynamic characteristics of the structure, where the period was estimated at 0.67 s from the dynamic response for the upper-level tests. This corresponds to a moderately cracked column conditions or an equivalent cover loss of approximately 12.7 mm at the plastic hinge region of the columns.

The SMA cables are modeled as tension only springs between the deck and fixed abutment. The superelastic behavior of the SMA restrainer is obtained by using a modified constitutive model implemented in OpenSees by Auricchio et al [33]. This uniaxial material model is an extension of the model proposed by Auricchio and Saco [34]. It is capable of capturing sub-hysteresis loops, which may occur in non-uniform loading such as earthquake loading, as well as the complete transformation pattern characteristic of superelastic SMAs. Assumptions include the fact that strength degradation is minimal and the modulus is the same for the austenite and martensite branches, which have been found to be of little impact when analyzing global system response [35]. The robustness and simplicity of implementing the model adopted are complemented by the ease of obtaining material parameters from the test data. Five cables totaling a cross section area of 645 mm² of SMA material were included at each abutment in the lower-level simulations, while three cables giving 387 mm² were used in the upper-level runs to maintain consistency with the experimental tests.

Comparison with experimental results

The finite element model was refined and validated against the experimental data from the large-scale testing, in order to further extrapolate the results to other cases. The fundamental period of the structure from the finite element model is 0.62 s for the upper-level runs—a 7.5% difference from the estimated period of 0.67 s for the test specimen. Non-linear time history analysis was conducted by applying the ground motion as a synchronous input acceleration at the base of the bridge model. A range of parameters are used to compare the ability of the model to predict bridge system response, given that this is the first opportunity to evaluate SMA response modification devices within a large-scale bridge system. In addition to the fundamental period, these parameters include the hinge opening at the abutments, force in the cables, stresses and strains in the cables, and column drifts.

Figure 7 shows a comparison of the time history of south hinge openings for the 0.09 g earthquake for the as-built bridge. The comparison reveals that the model performs relatively well at capturing the dynamic response and peak hinge opening. The analysis does not compare as well with the experimental tests after the peak displacements are reached (around 6 s). This is due to the inability of the model to capture some of the damage in the columns that was observed during testing. Table III further presents a comparison of peak quantities from the
Figure 7. South hinge openings from the model relative to the experimental data from the $0.09g$ motion for the as-built bridge.

Table III. Peak responses for the analytical model and percent change relative to the experimental results (shown in parentheses).

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Peak hinge opening (mm)</th>
<th>Peak SMA strain (mm/mm)</th>
<th>Peak SMA stress (MPa)</th>
<th>Peak column drift (in/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.7 ($-4%$)</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0068 ($+127%$)</td>
</tr>
<tr>
<td>2</td>
<td>5.90 ($-14%$)</td>
<td>0.0106 ($-12%$)</td>
<td>127 ($+7%$)</td>
<td>0.0033 ($+109%$)</td>
</tr>
<tr>
<td>3*</td>
<td>59.3 (+6%)</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0304 ($-17%$)</td>
</tr>
<tr>
<td>4*</td>
<td>41.8 (+10%)</td>
<td>0.0748 (+10%)</td>
<td>730 (+20%)</td>
<td>0.0217 ($-13%$)</td>
</tr>
</tbody>
</table>

* = 3 cables at each hinge.

Figure 8. Comparison of experimental and analytical stress–strain response of the north SMA cable for the $0.60g$ pga ground motion.
experimental and analytical studies for all cases considered. The stress–strain plot for the hysteresis of the north SMA restrainer is presented in Figure 8 for the upper-level event. The analytical model is able to capture the initial stiffness, sub-looping, loading, and unloading plateau of the SMA cable. The model assumptions of zero residual strain and equivalent elastic modulus for the martensite and austenite branch reasonably represent the lab performance of the SMA cables.

Additional analytical studies

The refined analytical models are used to extrapolate the results beyond the single modified Century Station record used in the experimental loading protocol, in order to assess the performance of the retrofitted system for a suite of ground motions.

An extended evaluation of the two configurations of the bridge retrofit with smart materials is conducted for a suite of ground motions to improve understanding of the behavior of these systems under different hazard levels and to verify that the findings of the testing are consistent over a suite of excitations. The peak hinge opening is used as the primary measure of system performance comparison for ground motion suites corresponding to two hazard levels.

![Graph](image)

Figure 9. Peak hinge opening of the as-built and retrofitted bridge for the (a) 10% and (b) 2% in 50 year ground motion suite.
A total of 40 records from the FEMA/SAC Project [36] are used in the analysis, consisting of recorded and simulated ground motions for the Los Angeles area for use in seismic performance assessment. Twenty of the motions are representative of 10% probability of exceedance in 50 year events and 20 are 2% probability of exceedance in 50 year events. Figure 9 shows the peak hinge openings for the two suites of ground motion for the case with and without SMA restrainer cables. In all cases, the SMA reduces the hinge opening in the bridge. Table IV compares the mean and standard deviation of the peak hinge opening for the 2 and 10% in 50 year suites for each bridge configuration. For the larger return period events (2% in 50), the mean peak hinge opening for the suite of motions decreases from 172 to 54 mm, and by using the SMA cables the variability about that mean decreases for the uniform hazard motions. These trends are consistent for the upper- and lower-level suites.

It should be noted that the properties of shape memory alloys are dependent on the ambient temperature in which they are being used. In the applications presented in this paper, the SMA restrainers are designed to exhibit superelastic properties for a range of temperatures from approximately 45–100 F. Below 45 F, the material begins to lose its ideal superelastic properties, thereby reducing their effectiveness in recentering. Previous studies have shown, however, that at higher temperatures, the effectiveness does not change significantly [28]. In cases where exposure to extreme low temperatures is possible, the material properties can be adjusted to exhibit superelasticity at a lower temperature.

## CONCLUSIONS

SMAs are a unique class of materials that have the ability to undergo large deformations, while reverting back to their undeformed shape through the removal of stress (superelastic effect) or heating (shape memory effect). This unique superelastic property results in recentering capability coupled with energy dissipating properties. In this study, bridge restrainer cables made of SMAs are developed and tested on a four-span, one-quarter scale, concrete slab bridge to determine their effectiveness in limiting hinge opening. The model bridge is subjected to a suite of ground motion with a range of pga values. The results show that the SMA cables reduce the as-built hinge openings by 52% and reduce the column drifts by 47%. A FEM of the test setup is developed to enable the assessment of the performance of the bridge for a broader suite of inputs. The results for a suite of 2% in 50 year ground motion records show that, on average, the SMA cables reduce the hinge opening by 69% compared with the as-built bridge. In addition to the reductions in hinge displacement, the SMA cables also reduce the column drifts. This study further supports the case for using SMAs for improving the entire system-level response of bridges.

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**Table IV. Mean and standard deviation of the peak hinge opening for the 2% and 10% probability of exceedance in 50 year records.**

<table>
<thead>
<tr>
<th></th>
<th>10% in 50 years</th>
<th>2% in 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (mm)</td>
<td>Standard deviation (mm)</td>
</tr>
<tr>
<td>As-built</td>
<td>85.8</td>
<td>34.2</td>
</tr>
<tr>
<td>SMA</td>
<td>36.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Percent reduction</td>
<td>57</td>
<td>36</td>
</tr>
</tbody>
</table>

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