DEVELOPMENT AND EXPERIMENTAL TESTING OF A NOVEL BRIDGE CONNECTION UNDER TSUNAMI LOADING

R PAGEL\(^1\); A PALERMO \(^2\); G DE FRANCESCO\(^3\); I ROBERTSON\(^4\)

\(^1\) University of Canterbury, Christchurch, New Zealand
\(^2\) University of California, San Diego, USA
\(^3\) California Polytechnic State University, San Luis Obispo, USA
\(^4\) University of Hawaii at Manoa, Honolulu, USA

SUMMARY

As highlighted by recent catastrophic events in Japan and Indonesia, tsunamis pose a serious threat to coastal infrastructure and bridges are especially vulnerable to this loading. Many critical bridges on key routes in New Zealand lie in tsunami-prone coastal areas. This research proposes a novel connection between the bridge deck and pier to provide vertical connectivity and investigates whether this connection can improve the resilience of bridges to tsunami events. An overview of the proposed detailing and experimental testing conducted at the University of Canterbury investigating the connection performance is presented.

INTRODUCTION

Tsunami events have devastated low-lying countries and communities internationally over the last 20 years. The widespread failure of bridges in the 2011 East Japan tsunami left many communities isolated, with limited access to essential post-disaster supplies. Over 300 bridges were destroyed or damaged beyond repair in the 2011 East Japan tsunami. The majority of these bridges survived the initial earthquake but failed under the tsunami loading (Akiyama et al. 2012; Yim et al. 2015).

Like other Pacific nations, New Zealand is at risk of a tsunami inundating the coastline, from local or global sources. According to Power (2013), regions including Northland, Hawkes Bay, and Canterbury, could be inundated by a wave of up to 12 metres in a 1/2500 year event. Many of the state highways connecting coastal communities in these regions are located within a tsunami inundation zone, and in several cases these highways are the sole route in and out of a community, leaving these communities particularly vulnerable to bridge failure.

Emerging out of the 2004 Indonesian and 2011 East Japan tsunami was research seeking to quantify the magnitude of tsunami forces on a bridge and the variation of these forces during inundation. This research found that tsunami waves impose hydrostatic, hydrodynamic, and impulsive lateral and vertical forces (Azadbakht and Yim 2016, 2015; Bricker and Nakayama 2014; Istrati et al. 2016, 2018; Istrati and Buckle 2019; Kosa et al. 2010; Seiffert et al. 2015; Winter et al. 2018; Yim et al.)
The hydrostatic and hydrodynamic forces act both laterally, on the pier and bridge deck, and vertically on the bridge deck. The short-duration impulsive force occurs when the wave first impacts the offshore side of the bridge (Livermore 2014). When the tsunami wave first impacts the bridge, the load acts on the offshore side of the bridge deck and an overturning moment about the onshore side is induced. The maximum loading on the structure usually occurs in this phase, except when there is a return wave which can create large forces in the opposite direction (Istrati and Buckle 2018).

While bridges, especially those located in seismic regions, are designed for lateral loads, typical bridge design does not account for large uplift forces (Robertson et al. 2007). Reconnaissance indicated that failure due to the bridge deck washing away in the flow of water was the most common, and coincidentally the most damaging, failure mode occurring during the 2011 East Japan tsunami (Bricker et al. 2012; Kosa 2011; Shoji et al. 2011). However, few studies have investigated methods to mitigate the failure of the connection between the bridge deck and pier.

This research proposes a novel deck to pier connection which aims to improve the bridge performance and prevent this failure mode from occurring. The first part of this paper provides details of the design philosophy and concept behind the proposed connection. The second part presents an overview of the experimental testing at the Structural Engineering Laboratory at the University of Canterbury to validate the expected performance of the novel connection under simulated tsunami actions.

**NOVEL DECK TO PIER CONNECTION**

**Design Concept and Philosophy**

The novel bridge deck-to-pier connection proposed in this study aims to improve the resilience of bridges to tsunami events by minimising both damage to the critical elements of a bridge and downtime following an event. This is achieved by connecting the bridge deck and pier with mechanical bars (structural fuses) that are designed (according to capacity design principles) to limit the forces and damage induced on the bridge superstructure and pier. The connection is designed to increase the displacement capacity of the bridge superstructure, relative to the pier, with the aim to (i) dissipate, by material hysteresis, part of the energy content imposed by the tsunami wave, and (ii) delay the washout of the bridge superstructure.

The bars are designed to yield and elongate under a design level tsunami, allowing the bridge superstructure to uplift and rotate about the pier cap as the wave impacts the offshore side of the bridge deck. Once the flow has subsided, the deck will return to its initial position, due to the stabilising effect of the superstructure dead load. In an extreme tsunami event, the bars are designed to rupture, and the bridge deck to be washed away in the tsunami flow. Following this scenario, the bridge deck and bars will need replacing, but this bar failure ensures minimal damage to the pier cap and foundation, which can be time-consuming and expensive to repair.

The unbonded bars were located within two vertical drossbach ducts in both the pier cap and deck beams, as shown schematically in Figure 1. Flange nuts and washers were used to anchor the steel and stainless bars (Figure 2), while the GFRP bars were epoxied over 300mm into a replaceable internal sleeve using HILTI RE500 V4. All bars were installed snug tight. The accessible detailing allows the yielded bars to be easily replaced, reducing the structure’s downtime. Likewise, the bars can easily be replaced if corrosion is detected inside the duct.
The tension-only bars are not designed for shear force and so the lateral component of the tsunami force is taken by traditional concrete shear keys integrated into the pier cap. This detailing primarily utilises conventional construction materials and can easily be integrated alongside standard bridge elements, resulting in minimal cost increases.

**Figure 1.** Side elevation at the pier showing the location of the threaded bars

**Figure 2.** Connection anchorages (left) at top of deck beams (right) at base of pier cap

**Materials Investigated**

Three types of fully threaded bars were investigated in this experimental programme: galvanised steel, stainless steel, and glass fibre-reinforced polymer (GFRP). These materials were chosen based on their large elongation capacities. To characterise the material properties of these bars, a series of uniaxial monotonic tensile tests were conducted to capture the axial stress-strain behaviour. The results in Figure 3 show significant differences in behaviour between the materials; the Grade 500 steel yielded at 0.3% strain and continued to elongate until rupture about 13.5% strain, while the Grade 650 stainless bars yielded at 0.6% strain but had a lower rupture strain (8%).
The tensile tests of the stainless bars show the presence of large non-linearities before the maximum stress is achieved. The GFRP bars exhibited a brittle behaviour, with a response essential linear up to rupture which was obtained at a strain of approximately 2.9%. However, as some slip was observed between the bar and the anchoring system, the strain at rupture could be overestimated and the modulus of elasticity underestimated.

![Stress-strain graph](image)

**Figure 3. Experimentally obtained stress - strain relationships**

**EXPERIMENTAL TESTING SET UP & PROGRAMME**

**Replicating Tsunami Actions**

Tsunami actions on a structure are typically experimentally simulated using a wave flume, and this approach is often used to capture the global response. However, experimental testing on small scale specimens may not accurately replicate the response of the structure's components. Large scale structural testing with hydraulic actuators to simulate the tsunami waves enables more accurate evaluation of the component response, and so this approach was used for this testing. Limited research has been conducted using a similar testing approach, so a novel experimental testing set up and loading protocol was proposed.

The experimental testing aimed to replicate the typical tsunami uplift and lateral force induced on a bridge. The relative magnitude of the horizontal and vertical actions depends on many site and case-specific factors (Qeshta et al. 2019), and different force resisting mechanisms are utilised within the structure to resist vertical and horizontal actions, so the assumed direction of loading was critical to this testing programme. Thus, to understand the expected performance of the bridge system under different assumed directions, an envelope of cases was considered. This included uplift only, lateral loading only and a combined uplift and lateral loading case.

Both the actions of an initial and return waves were simulated, and thus the loading protocol consisted of an initial loading phase and a return phase in the opposite direction, both which were applied monotonically. During tsunami events, many factors affect the magnitude of the actions imposed by the return wave, and these forces can vary greatly (Yeh et al. 2013). Thus, for simplicity, it was assumed that this return wave had equal forces to the initial wave.
Overview of Specimen and Test Set Up

The prototype structure was chosen to be representative of a modern, long-span, reinforced concrete, New Zealand bridge. It consists of two 30m simply supported spans; a single 1.5m diameter circular pier and straight pier cap beam. The prototype bridge deck has five 1225 mm deep super-tee beams with a nominal overall width of 10.35m. This design is consistent with the standard designs presented in the NZTA Research Report 364. This prototype bridge is designed using the method outlined in the AASHTO Guide Specifications (AASHTO 2022) alongside the design tsunami wave heights in Power (2013) for a coastal bridge located in Christchurch. The specimen was conceptualised as the central pier with an adjacent, shortened deck beam, to focus on the interface between the deck and the pier cap (Figure 4). These elements were designed in accordance with the relevant New Zealand standards (including NZS 3101 and NZS 3404).

![Figure 4. Top view of bridge testing set up](image)

Unlike the prototype, the specimen superstructure had no post-tensioning, so all tension capacity was provided by the steel reinforcing. As the superstructure was loaded under uplift, tension was induced on the top of the beam, so the flange was extensively reinforced compared with a standard bridge subject to primarily downward forces. Accommodating this additional reinforcement in the flange would likely require changes to the geometry of a standard bridge beam. Additionally, to minimise clashes with the web reinforcing, the ducts for the bars were positioned within the flange.

The test set up consisted of four hydraulic actuators that load the underside of the bridge deck vertically and two hydraulic actuators that load the bridge deck transversely (Figure 5 and Figure 6). The positioning of these vertical actuators offset from the bridge centre line allowed for the overturning moment to be simulated, providing sufficient capacity to yield and deform the bars. Torsion of the bridge deck was restricted using shear keys installed against the free end of the deck.
Experimental Testing Programme

The full testing programme consists of four phases which aim to investigate the performance under a range of potential tsunami actions, and with varying boundary conditions (Table 8). All tests are conducted using the same loading protocol, which consists of the initial loading and the return wave loading in the opposite direction.
Table 1. Testing programme

<table>
<thead>
<tr>
<th>Phase</th>
<th>Test ID</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Uplift loading</td>
<td>P1-1</td>
<td>Galvanised steel bars</td>
</tr>
<tr>
<td></td>
<td>P1-2</td>
<td>Stainless steel bars</td>
</tr>
<tr>
<td></td>
<td>P1-3</td>
<td>GFRP bars</td>
</tr>
<tr>
<td>2: Lateral loading</td>
<td>P2-1</td>
<td>Galvanised steel bars</td>
</tr>
<tr>
<td></td>
<td>P2-2</td>
<td>Stainless steel bars</td>
</tr>
<tr>
<td></td>
<td>P2-3</td>
<td>GFRP bars</td>
</tr>
<tr>
<td>3: Combined lateral – uplift</td>
<td>P3-1</td>
<td>Galvanised steel bars</td>
</tr>
<tr>
<td></td>
<td>P3-2</td>
<td>Stainless steel bars</td>
</tr>
<tr>
<td></td>
<td>P3-3</td>
<td>GFRP bars</td>
</tr>
<tr>
<td>4: Boundary conditions</td>
<td>P4-1</td>
<td>Vertical flexible (spring)</td>
</tr>
<tr>
<td></td>
<td>P4-2</td>
<td>Pinned (spherical bearing)</td>
</tr>
<tr>
<td></td>
<td>P4-3</td>
<td>Fully fixed (grouted)</td>
</tr>
</tbody>
</table>

TESTING RESULTS

Preliminary testing in the uplift only experimental configuration (Phase 1) validated the material behaviour under the uplift and overturning moment loading. The bars were all subjected to the same maximum displacement so their performance could be compared. Both the stainless steel and galvanised steel bars yielded within the vertical displacement range, while the glass fibre reinforced polymers (GFRP) bars exhibited largely elastic behaviour for the entirety of the test (Figure 7).

![Figure 7. Global behaviour of the system for the three materials](image)

Pinching was observed at the end of the first cycle for all materials. The galvanised Grade 500 bars yielded at 0.3% and the stainless steel bars yielded around 0.6% which resulted in large residual displacements following completion of the test for these materials (Table 2). Unlike the two metallic materials, the non-linear elastic GFRP bars...
exhibited small residual deformations, which were primarily attributed to bar slip within the anchorage.

Table 2. Residual deformation of the bars under uplift loading

<table>
<thead>
<tr>
<th>Material</th>
<th>Approximate Residual Deformations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After Initial Wave</td>
</tr>
<tr>
<td>Grade 500</td>
<td>3mm</td>
</tr>
<tr>
<td>Stainless</td>
<td>1.5mm</td>
</tr>
<tr>
<td>GFRP</td>
<td>1.5mm</td>
</tr>
</tbody>
</table>

DISCUSSION

The initial phase of testing of the connection under tsunami uplift loads verified that the mechanical bars could provide vertical displacement capacity to the bridge superstructure. Likewise, it verified that implementing the bars would not create significant damage to the pier cap and superstructure (for the vertical displacement range tested).

The Grade 500 bars and stainless steel bars dissipated the applied tsunami energy due to material hysteresis, however, also exhibited residual deformation. This residual deformation meant the bar was not initially engaged when the return wave loading was applied, and thus this system was weaker in this direction. The non-linear elastic GFRP bars exhibited minimal energy dissipation and residual deformation.

CONCLUSION

This research proposed and investigated a novel bridge deck to pier connection for use in tsunami-prone bridges. These mechanical bars were designed to increase the displacement capacity of the bridge superstructure, as to dissipate some of the tsunami wave energy and delay the washout of the bridge superstructure under alternate direction tsunami waves. Preliminary testing has indicated that these bars perform as anticipated.

A novel approach to replicate the actions induced by tsunami waves on large scale bridges was also proposed and applied to assess the performance of the proposed connection to tsunami-induced uplift action. Future research within this project aims to experimentally investigate the connection performance under a wider variety of loading cases.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the University of Canterbury and Precast NZ for their financial support, and Ramset Reid, BBR Contech, Pultron, GPIL and Freyssinet for their material donations. Thanks go to Busck Prestressed Concrete Ltd for manufacturing the specimens. Lastly, the authors would like to acknowledge the support of the University of Canterbury structural laboratory technicians: Alan Thirwell, Dave Carney, John Maley and Matthew Robinson.
REFERENCES


