SEISMIC LOW DAMAGE TECHNOLOGIES FOR BRIDGES IN NEW ZEALAND: FROM RESEARCH TO PRACTICE

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Abstract

Large earthquakes in Japan, U.S and New Zealand have demonstrated the economic and social costs of seismic induced bridge damage. Minimizing damage and maintaining functionality of important bridge structures following these events is critical in facilitating immediate emergency response and longer term recovery of the community.

Existing design solutions often rely on the formation of plastic hinges in monolithic concrete bridge substructure elements during earthquake events. This is economical and generally provides adequate seismic performance, but often results in residual deformation of the structure and substantial plastic hinge damage following earthquakes, which can be costly to repair and reduce post-earthquake functionality.

Recent research has investigated alternative design solutions for bridge structures, which improve on the seismic performance of traditional forms of construction, whilst also facilitating rapid methods of construction and post-earthquake repair. Based on the PRESSS hybrid system for building structures, these alternative design solutions use prefabricated elements connected together at rocking interfaces by un-bonded post-tensioned bars or tendons and energy dissipating components. The resulting system can accommodate large seismic displacements while providing significant energy dissipation, resulting in minimal residual deformation and limited, easily repairable damage.

This paper summarizes recent research into low damage technologies for bridges using prefabricated elements, including experimental testing that has been carried out at the University of Canterbury. A case study is presented where the technology was applied in the design of a bridge located in Christchurch, New Zealand by Opus International Consultants that utilizes external energy dissipation devices and un-bonded post-tensioned bars in the pier columns.

Introduction

Conventional design approaches for ductile concrete bridges typically rely on the formation of plastic hinges in the bridge substructure to dissipate energy during seismic events. Although this approach is economical and provides a robust structure that generally achieves the primary goal of ensuring life safety, it often results in the need for costly post-earthquake inspection, assessment and repair. In larger earthquakes, residual displacements and excessive plastic hinge damage can lead to replacement of the bridge structure altogether. Damage and residual displacement of bridges can result in substantial costs – both economically and socially – during immediate post-earthquake response and longer term recovery. Although the seismic performance of bridges was generally satisfactory during the Christchurch Earthquake, approximately 50% of the bridge stock required post-earthquake repair (Palermo et al., 2011). There was reduction in functionality of a large number of bridges, with bridges either having reduced load carrying capacity or being closed altogether while inspection, assessment and repair processes were carried out.

There has been substantial recent investigation into innovative designs for bridge substructures that achieve similar ductile response to conventional systems, but which avoid damage associated with formation of plastic hinges. A technique to achieve such outcomes is the use of jointed rocking connections, which combine energy dissipating components that control peak deformations with recentering components that minimize residual deformations. Consideration of post-earthquake repair processes and inclusion of appropriate connection detailing between substructure elements facilitates rapid post-earthquake assessment and repair, which helps to reduce the post-earthquake social and economic costs of recovery. Jointed rocking connections lend themselves well to prefabrication of substructure elements, which also facilitates accelerated bridge construction and the associated benefits including reduced construction times and disruption, improved construction quality and improved safety during construction.

This paper provides a summary of recent research into low damage connections for bridge substructures, including an overview of research conducted at the University of Canterbury. A case study is presented where low damage connections were applied to a bridge in Christchurch, New Zealand.

Innovative Bridge Substructure Design and Construction

Historically, bridges were designed with a focus on strength to resist seismic loading. Large earthquakes, particularly the 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes illustrated that strength alone will not ensure good performance, and highlighted the importance of ductility and capacity design for structures. As a result, significant changes to codes in the US, Japan and New Zealand were made to address the need for improved seismic performance of bridge structures, with the primary objective of ensuring life safety (Buckle, 1996). Ductile behavior is often obtained through reliance on the formation of plastic hinges. This approach provides robust structures, but relies on acceptance of the possibility of damage and residual deformation during large seismic events.

With the issue of ensuring life safety generally considered to be adequately addressed, focus is now shifting towards further innovation and improvement of bridge design and construction processes including accelerating bridge construction, improving seismic performance and addressing issues relating to post-earthquake repair. Over the years, there have been a number of novel and innovative approaches to improve the seismic performance of bridges. Housner (1963) introduced the concept of pure rocking as a form of seismic isolation for structures. Beck and Skinner (1974) validated the concept through application on the South Rangitīkei Viaduct in New Zealand.

Expanding on the concept of pure rocking and hybrid connections for building structures (Priestley, 1991; Stanton et al., 1997), there has recently been substantial research into application of jointed rocking connections to bridge structures. Hewes and Priestley (2002) investigated seismic performance of pier columns which use post-tensioned tendons to clamp precast concrete pier column segments together. The resulting system utilizes gap opening between precast segments to accommodate large seismic displacements with little residual deformation of the structure following the earthquake.

Energy dissipation in post-tensioned rocking connections can be improved through the addition of supplemental energy dissipaters to form a hybrid or dissipative controlled rocking (DCR) connection (Figure 1) (Hieber et al., 2005; Mander and Cheng, 1997; Marriott, 2009; Palermo and Pampanin, 2008). Energy dissipation in DCR or hybrid connections can be provided through a number of mechanisms including hysteretic, friction and viscous damping. The combination of recentering and dissipating components usually results in a ‘flag-shaped’ hysteresis response which experimental testing has shown to provide excellent seismic performance.

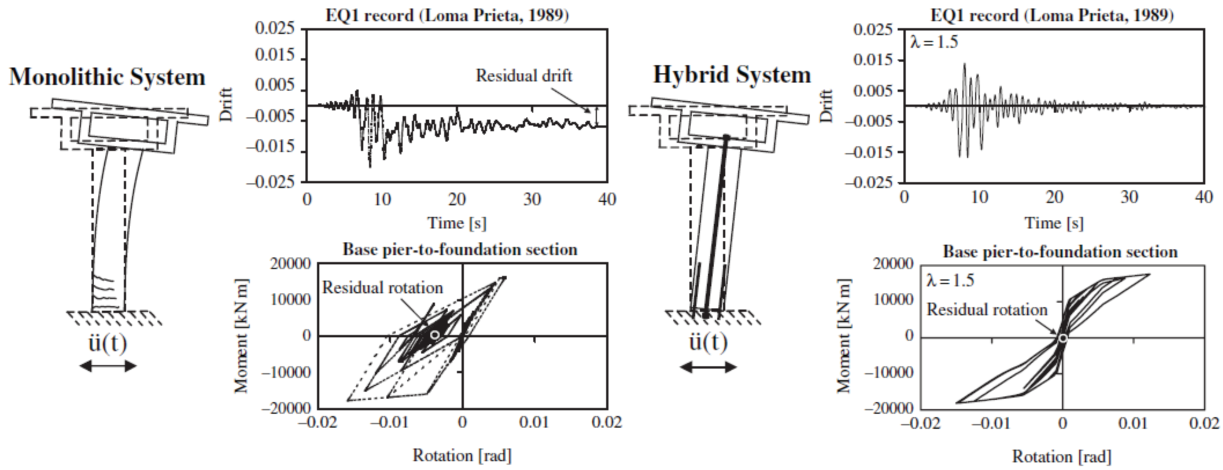


Figure 1. Comparison of the behavior of monolithic and hybrid systems (Palermo and Pampanin, 2008).

Experimental Testing at the University of Canterbury

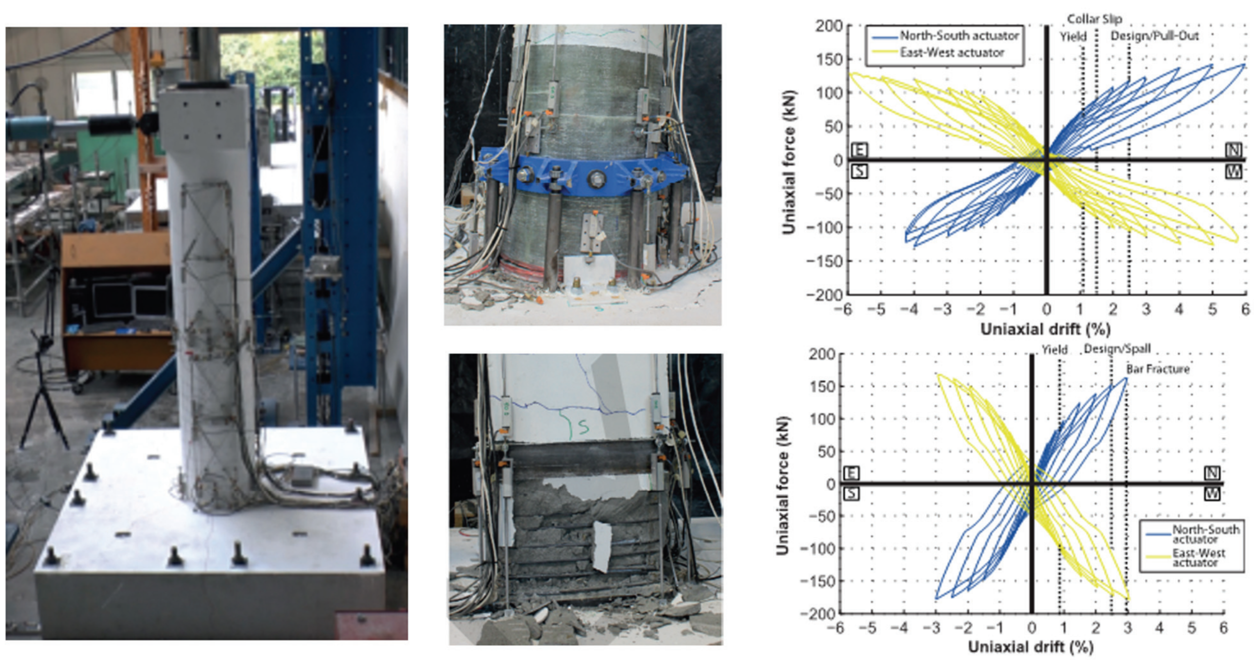
Research has recently been completed at the University of Canterbury into development of innovative approaches for design and construction of precast concrete bridge substructures. Two categories of connections were investigated. Emulative connections (also referred to as 'high damage') are intended to behave in a similar manner to conventional monolithic columns that form plastic hinges and offer a cost-effective approach for the use of precast concrete substructures in regions of moderate to high seismicity. Non-emulative connections (also referred to as 'controlled damage' or 'low damage') aim to improve on the performance of precast concrete substructures through the use of jointed rocking behavior where damage to the core elements of the substructure is limited or avoided altogether and residual deformations are minimized. Low damage connections constrain inelastic behavior to externally mounted dissipaters which can be easily accessed and replaced. Little to no damage is expected to occur in the concrete elements of the joint. Controlled damage connections permit limited damage to joint components to occur, but ensure that the damage is controlled and easily repairable using predetermined methods. Cost effective repair strategies are developed during the design phase of the structure, and implemented following the earthquake. Post-earthquake inspection and assessment processes can be reduced and repair work can be carried out more rapidly when compared to conventional approaches.

Half scale quasi-static testing was carried out to investigate the performance of controlled and low damage connection details. A single column pier arrangement was used to biaxially test controlled damage column-footing connections (Figure 2). A multi-column bent arrangement was used to uniaxially test low damage column-footing and column-cap beam connections (Figure 3). The models were subjected to increasing magnitudes of cyclic displacement applied using lateral actuators. Axial actuators with post-tensioned bars were used to apply axial loads representing both gravity and post-tensioning loads. Both the controlled damage and low damage connections were repaired following initial testing, and retested to validate the repair process. A range of energy dissipation devices were tested. The general goal was to achieve effective dissipater activation in both tension and compression without relying on grout or epoxy fill to resist buckling. Dissipaters with longitudinally milled grooves to provide a fused length and steel buckling restraint sleeves showed excellent performance (White and Palermo, 2016).

Brief findings from the controlled low damage tests are provided below. Further details on the controlled damage and low damage connections can be found in White and Palermo (2016) and Mashal and Palermo (2014).

The controlled damage socket connection (Figure 2b - top) featured a variant of the standard socket joint (Marsh et al., 2011) with post-tensioning for improved seismic performance. A natural rocking interface occurred as a result of the formation of a single wide crack at the base of the column. The formation of a single crack was encouraged by the addition of connection confinement at the base, which terminated above the rocking interface and the debonding of the longitudinal bars at the rocking interface. Regular reinforcement was used for energy dissipation, with no reduction in bar diameter at the rocking interface. Repair of this connection involved intentional severance of the damaged internal reinforcement, followed by installation of external dissipation devices. Testing showed good damage control with low residual deformations. Improvement of the repair process is required to avoid mounting collar slip and pull out of dissipaters. This could be achieved through the use of cast-in anchorages for the external dissipaters, rather than post-installing the dissipaters into damaged concrete.

The controlled damage coupled connection (Figure 2b - bottom) used replaceable dissipating reinforcing bar segments with mechanical couplers, de-bonded with grease-tape, to form a dissipative rocking connection between the column and footing. Steel plates surrounded the bottom of the column and were used as formwork to enclose the replaceable reinforcing bars in cast-in-place (CIP) grout that was cast during column assembly. The connection was designed to behave in a rocking manner during a seismic event, with damage limited to yielding of the dissipaters and spalling of the CIP grout. All other connection components were designed to remain elastic. The connection showed good damage control and energy dissipation. The post-tensioning force was not sufficient to achieve full recentering of the connection following testing, but residual deformations were significantly smaller than would be achieved by a conventional monolithic joint. It is expected that increasing the post-tensioning force would have improved recentering. The connection was successfully repaired through replacement of the coupled bars and re-casting the grout at the base of the column. The repair process was effective at reinstating the strength and ductility of the column.

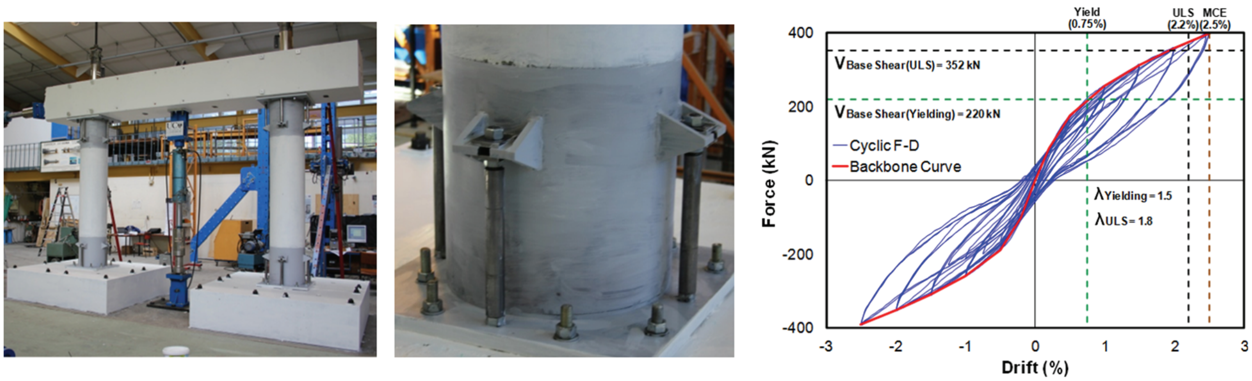


(a) Testing arrangement

(b) Results from testing of repaired socket connection (top) and coupled connection (bottom).

Figure 2. Controlled damage testing (White and Palermo, 2016).

The low damage test models (Figure 3) comprised precast concrete columns with steel armoring at both ends to prevent damage and unbonded post-tensioned bars located at the center of the columns for recentering. Energy dissipaters were mounted to cleats on the exterior of the casing and anchored into the footings and cap beams. A range of energy dissipation devices and varying amounts of post-tensioning force were tested. In all cases, the testing showed that the low damage connections sustained no damage to precast elements, even after being subjected to a force level corresponding to the structure's ultimate limit state. External mounting of the dissipaters and full recentering of the connection allowed for straightforward removal and replacement of the energy dissipaters to reinstate the full strength and ductility capacities of the columns.



(a) Testing arrangement (b) Typical results

Figure 3. Low damage testing (Mashal and Palermo, 2014).

Case Study Application of Low Damage Connections

The Wigram-Magdala Bridge in Christchurch, New Zealand offers a case study to demonstrate implementation of low damage jointed rocking connections in an actual bridge. The bridge was designed by Opus International Consultants with input from the University of Canterbury and is currently under construction (Routledge et al., 2016). The bridge comprises three spans of 32m, 35m and 32m length, giving an overall length of approximately 99m. The east abutment and east pier are skewed at an angle of 30 degrees with respect to the bridge to accommodate the underlying road alignment (Figure 4).

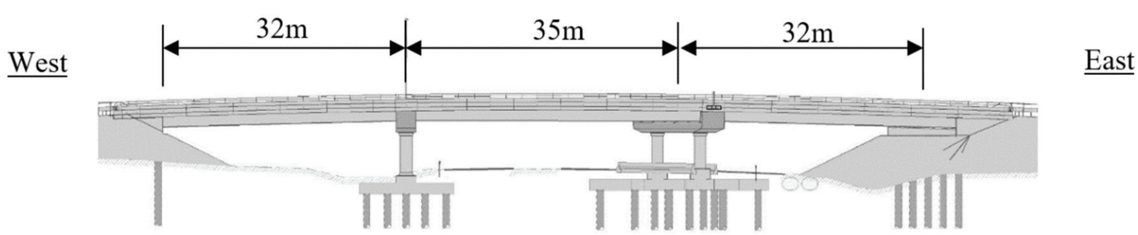
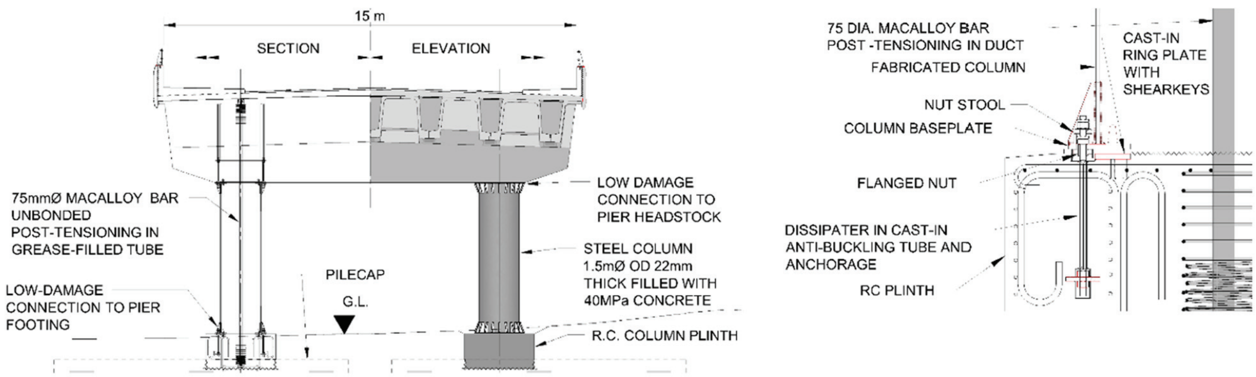


Figure 4. Elevation on Wigram-Magdala Bridge (Routledge et al., 2016).

The superstructure comprises simply supported 1525mm deep prestressed concrete Super Tee beams with a 200mm thick in-situ deck. The two piers each comprise a headstock beam supported by two 1500mm diameter columns. The pier columns are supported on relatively stiff piled footings which ensures hinging occurs within the columns. The abutments comprise spill-through piled bank seats. This case study will focus on the design on the columns, which incorporate low damage hybrid rocking joints, enabling straightforward replacement of energy dissipating components that may be damaged during a major earthquake.

The seismic behavior of the joints is intended to be similar to that of the low damage connections that were testing at the University of Canterbury. The joint detail (Figure 5) comprises:

- Circular steel-cased columns filled with unreinforced concrete.
- Replaceable dissipater bars connecting the stiffened column endplates to anchorages cast into the footing and headstock.
- Vertical unbonded post-tensioned bars that extend the length of the column and cross both joints.



(a) Elevation and section on typical pier showing low damage details

(b) Enlarged view of low damage connection to pier footing

Figure 5. Low damage joint details (Routledge et al., 2016).

The local city council required the appearance of the low damage details to be improved over that which was tested at the University of Canterbury (Figure 3). The visible externally mounted dissipating bars with steel cleats and shear keys were considered unsightly. The use of a removable shroud to hide the low damage details was initially considered but resulted in making the columns appear overly stocky and was consequently rejected. As a result, the dissipating bars were embedded in the concrete plinths at the base of the columns and in the headstock at the top of the columns. By hiding the dissipaters in the footing and headstock, access for removing and replacing them would only be available from one end of the dissipater and hence a blind connection was introduced.

While improving the aesthetics, the blind connection led to a number of design, detailing and construction challenges which are further discussed in Routledge et al. (2016). These challenges included:

- Availability of large diameter dissipating bars with high strength, good ductility, well defined limits on strength and the ability to be machined without modifying mechanical properties.
- Detailing of the dissipater profile and anti-buckling tube to allow for yielding and extension of the dissipating bars while resisting buckling and avoiding damage to threaded anchorage regions.
- Allowing for replacement of the bars from one side of the connection only.
- Anchorage of dissipaters to the endplates of the column to ensure activation of dissipaters in both tension and compression with access for nut tightening from one side of the connection only.
- Corrosion protection of the connection to achieve a 100 year design life.
- Complex connection detail with small construction tolerances.
- Issues with distortion of dissipating bars during milling of longitudinal grooves.

The low-damage details have now been installed (Figure 6), providing an opportunity to review the success and constructability of these details. The detailing associated low damage and with burying the dissipaters for aesthetic reasons has increased the cost compared to a reinforced concrete column with conventional plastic hinges. While being more expensive to construct, the benefits associated with ease of repair and the importance of aesthetics should be considered

There is potential for a number of optimizations to the detail presented, including:

- The use of alternative steel grades (to 500E) for fabrication of the dissipating bars to enable more economic machining and allow the use of fewer larger diameter bars.
- Increasing the area of the fused region of the dissipating bars relative to the threaded region to increase the efficiency of the dissipaters.
- Altering the ratio of moment contributions from energy dissipaters and post-tensioning.

Figure 6. Construction of Wigram-Magdala Bridge pier with low damage joints.

Conclusion

This paper has given a brief overview of low damage connections for bridges and how recent research at the University of Canterbury led to New Zealand's first implementation of low damage joints in an actual bridge.

Conventional approaches for design and construction of bridges lead to robust and economical structures which generally achieve the primary goal of ensuring life safety, but can result in plastic hinge damage, residual deformations and reduction in functionality with significant social and economic costs, should a large seismic event occur.

Recent research has focused on ways of improving seismic performance, including the use of hybrid or dissipative controlled rocking joints to reduce damage and residual damage and facilitate straightforward and cost-effective repair. Testing of controlled and low damage connections at the University of Canterbury has demonstrated construction and repair methodologies for controlled and low damage connections, and provided validation of their seismic performance. Application on Wigram-Magdala Bridge has provided an example of real world use of low damage connections and has helped to identify design, detailing and construction challenges associated with full scale construction of low damage joints.

While there are still challenges to be overcome and optimizations to be made, testing and application of low damage connections has shown the potential for improvement over conventional methods of bridge construction. With further research and application of low damage technologies, it is believed that low damage joints will offer a cost competitive alternative to reliance on plastic hinges for energy dissipation in structures, while offering benefits including reduced damage and residual deformations and straightforward approaches for post-earthquake repair.

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