Controlled damage precast connections for Accelerated Bridge Construction in regions of high seismicity

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ABSTRACT: Bridge substructures are typically constructed using cast-in-place concrete components. During severe earthquake loading, these types of structures undergo inelastic deformation through the formation of plastic hinges. Although this type of approach has shown to be effective at achieving the base goal of ensuring life safety, there are some downsides relating to construction speed, quality and post-earthquake reparability. Controlled Damage Connections are a type of precast connection featuring a combination of post-tensioning and energy dissipation components based on the principles of Dissipative Controlled Rocking (DCR) or Hybrid PRESSS. The use of precast components allows for accelerated bridge construction with improved construction quality. The connections are detailed in a way that limits and constrains damage in bridge substructures during earthquake loading and minimises residual displacement of the bridge, meaning the bridge is more likely to be serviceable following an earthquake. Repair strategies are considered at the design stage allowing for rapid post-earthquake damage repair, minimising traffic disruption and repair costs. At the University of Canterbury, half scale testing of two precast columns and footings featuring Controlled Damage Connections was undertaken as part of the New Zealand National Hazard Platform research programme titled Advanced Bridge Construction and Design (ABCD). The columns were subjected to displacement controlled biaxial loading. Following initial tests, the columns were repaired and re-tested to demonstrate the repair strategies and effectiveness. This paper presents findings of this experimental testing.

1 INTRODUCTION

This paper presents the design and testing of two half scale bridge piers featuring Controlled Damage Connections (CDCs). This connection type builds upon developments in Dissipative Controlled Rocking (DCR) or Hybrid PRESS connection types (Priestley, 1991, 1996; Palermo, 2004; Marriott, 2009; Pampanin et al,. 2010) and Accelerated Bridge Construction (Billington et al., 1999; 2004; Ralls et al., 2004; Stanton et al., 2005; Marsh et al., 2011)

CDCs offer the advantages associated with precast construction, notably increased construction speed and quality. However, they also limit damage during seismic events and provide simple and pre-planned cost-effective repair options. This is achieved through the provision of unbonded post-tensioned steel tendons or bars to limit residual drifts in the structure, combined with energy dissipation components which are easy to replace. Consideration of the full life cycle costs of the structure is required when comparing CD connections in order to account for all benefits associated with the system, rather than focusing only on initial construction cost. This includes using a reasonable discount factor when undertaking a benefit cost analysis to appropriately account for future benefits of the system.

Two columns featuring Controlled Damage Connection types are discussed in this paper. The first is Column CDC featuring the Controlled Damage (CD) Member Socket Connection (MSC) which is similar to the High Damage (HD) MSC presented in previous publications (Mashal, White & Palermo, 2013). The second is Column CDS featuring the CD Coupled Bar Connection (CBC). This connection uses replaceable segments of longitudinal bar. Both connections were tested, repaired and retested to demonstrate the application and effectiveness of the repair strategy in each case.

This paper gives an overview of each connection type along with results of construction, testing and repair of the two test columns featuring CD connections.

2 PROTOTYPE STRUCTURE AND TESTING ARRANGEMENT

The prototype structure (Figure 1) is based on the Port Hills Overbridge in Christchurch, with a normal importance level, zone factor of 0.3, soil type C and no near field effects. A ductility of 3 was adopted for design with a design drift of 3%.

The test setup and loading protocol is shown in Figure 2. Each drift cycle consisted of a uniaxial push and pull in each direction followed by a clover shaped displacement path.

During testing, a 50mm post-tensioned bar was used to represent both the post-tensioning and gravity loads in the column.

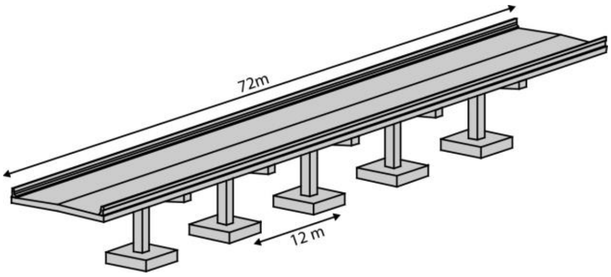

Figure 1a. Prototype bridge system

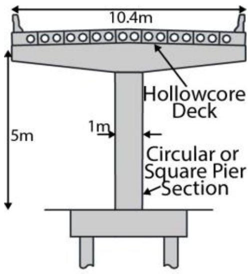

Figure 1b. Prototype transverse configuration

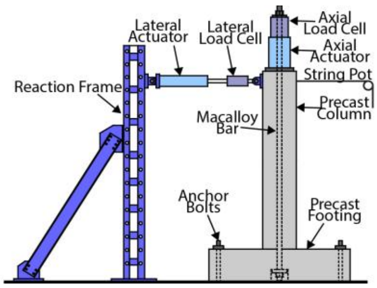

Figure 2a. Elevation of test setup

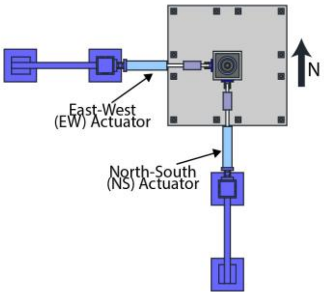

Figure 2b. Plan of test setup

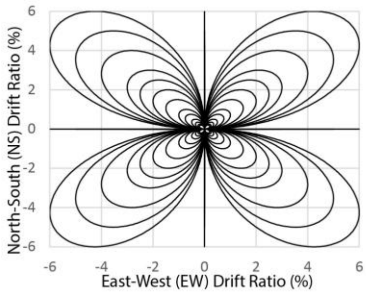

Figure 2c. Displacement input

3 CONNECTION OVERVIEWS AND REPAIR STRATEGY

Both half scale columns had a section depth of 500mm and a total height of 3.2m. Square precast footings of 500mm depth and 2.1m length were used in both cases. Concrete with strength of 50MPa was specified for both columns and Grade 300 steel used for all components that are designed to yield as part of the energy dissipation system or provide armouring protection to the concrete. Grade 500 steel was specified for all other steel components. The design of both columns was based on the PRESSS design handbook adopting a re-centering ratio of 1.5 (Pampanin et al., 2010).

3.1 Controlled Damage Member Socket Connection

The Controlled Damage (CD) Member Socket Connection (MSC) (Figure 3) features a Member Socket Connection (Mashal, White & Palermo, 2013) with post-tensioning to limit residual drifts in the structure. Cover confinement limits spalling damage. Threaded anchors are cast into the precast components allowing for simple mounting of external dissipators for repair of the connection. The longitudinal bars were debonded over a length of 50mm at the connection interface, localising yielding of the bar and encouraging a rocking interface to form. The repair strategy is illustrated in Figure 4 and construction and repair photos are shown in Figure 5.

For repair of the connection, a novel dissipator design known as the Grooved Bar dissipator was used. This dissipator features a plain steel bar with grooves milled along the length of the dissipator, reducing the section to localise yielding in the bar. A steel confining tube surrounds the dissipator to prevent buckling under compressive loading without the need for filler material such as epoxy or grout as used in BRF style dissipators (Sarti, 2013).

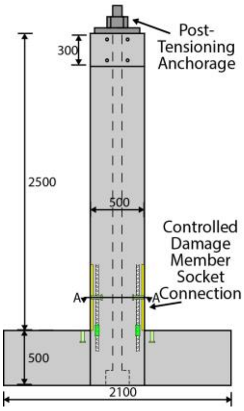

Figure 3a. Column CDC

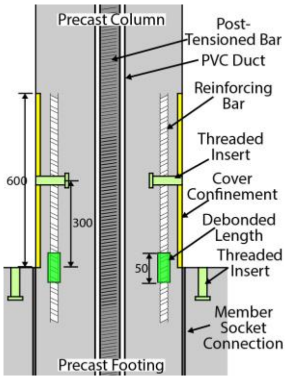

Figure 3b. Controlled Damage Member Socket Connection

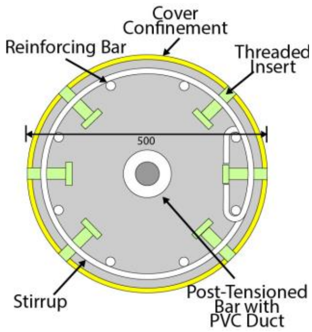

Figure 3c. Section A

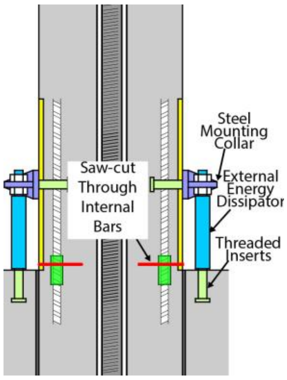

Figure 4a. Repair strategy for CDC

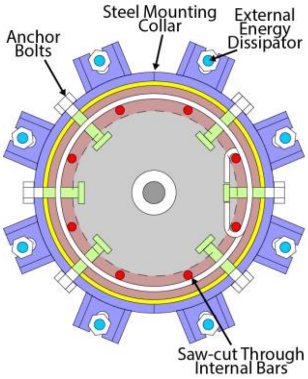

Figure 4b. Section A after repair

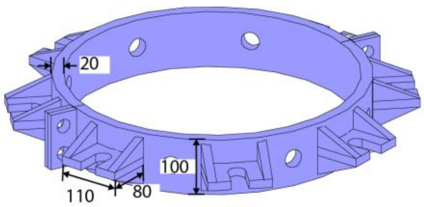

Figure 4c. Dissipator mounting collar

Figure 5a. Placement of column

Figure 5b. Application of FRP

Figure 5c. Column after repair

3.2 Controlled Damage Coupled Bar Connection

The second connection type is the Controlled Damage (CD) Coupled Bar Connection (CBC) (Figure 6). Replaceable segments of longitudinal bar are used, connected to threaded studs formed in the ends of permanent reinforcement using threaded bar couplers. The replaceable segments of bar are located in a recess in the precast column element which is filled with cast-in-place concrete or grout during construction. Steel armouring is used to protect the precast concrete core, meaning all damage is constrained to the cast-in-place material and replaceable dissipators. Figures 7, 8 and 9 illustrate the

construction and repair methods.

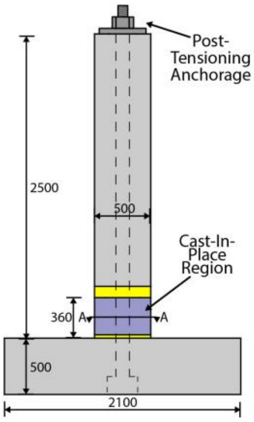

Figure 6a. Column CDS

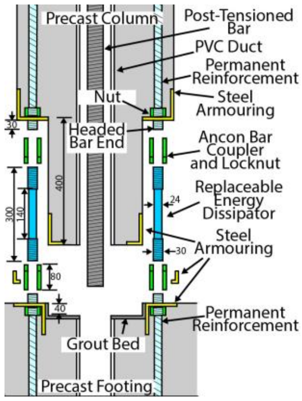

Figure 6b. Controlled Damage Coupled Bar Connection (exploded view)

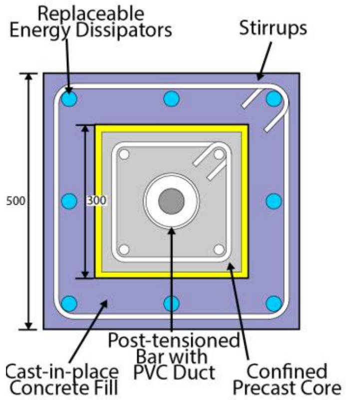

Figure 6c. Section A

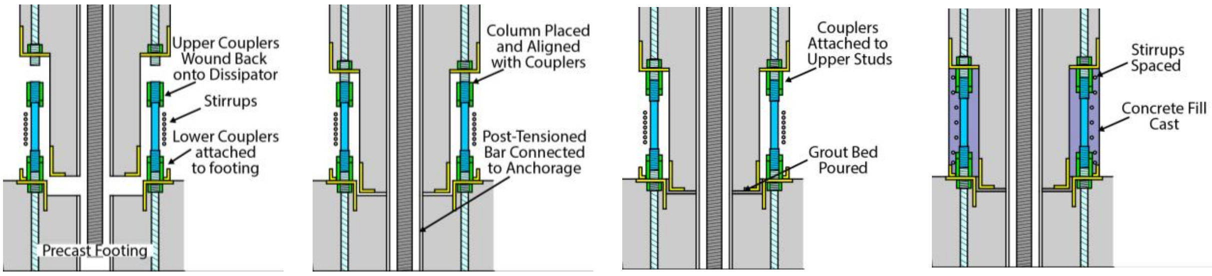

Figure 7. Controlled Damage Coupled Bar Connection assembly process

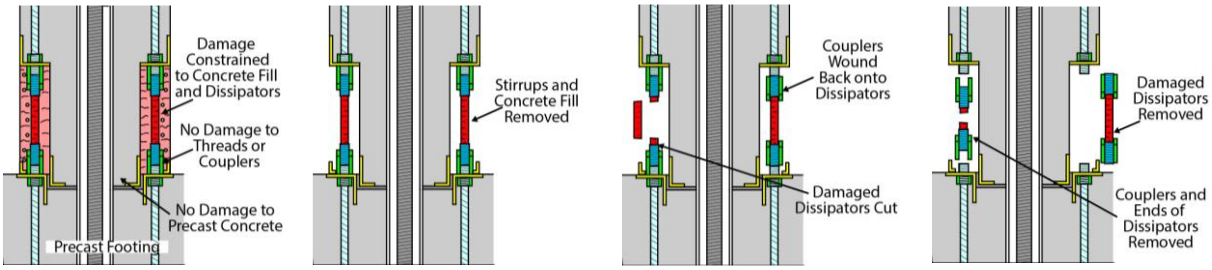

Figure 8. Controlled Damage Coupled Bar Connection repair process

Figure 9a. Dissipators and couplers

Figure 9b. Placement of column

Figure 9c. Construction complete

4 TESTING AND REPAIR

4.1 Controlled Damage Member Socket Connection

Figure 10 shows benchmark testing of Column CDC, Figure 11 shows testing following application of the repair strategy and Figure 12 gives the uniaxial force-drift behaviour observed in each test.

Figure 10. Column CDC benchmark testing

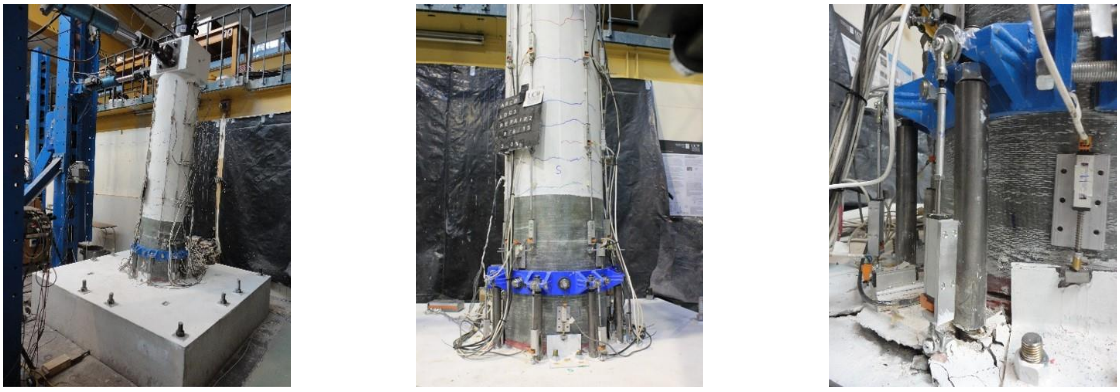

Figure 11. Testing of repair strategy

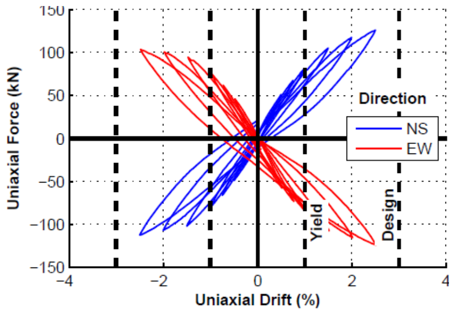

Figure 12a. Benchmark force-drift behaviour

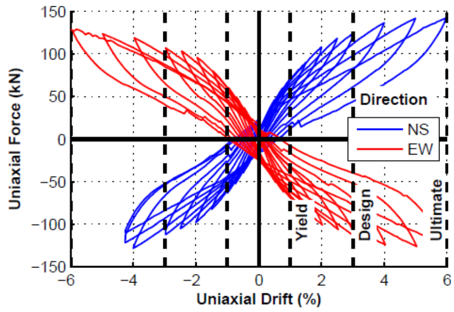

Figure 12b. Repaired force-drift behaviour

The results are summarised as follows:

- Good benchmark performance was observed with no spalling up to drifts of 3.25%.
- Post-drilled anchorages were used for connection of dissipators rather than threaded inserts which complicated the repair process and resulted in some undesired collar slip.
- Some pull-out of dissipators occurred, partly due to prior damage to the footing and the use of post-drilled anchorages.
- The column was subjected to drifts of up to 7.8% with no failure of the dissipators themselves.
- Despite shortcomings in anchorage of the dissipators, good performance was seen in both the pre and post-repair connection with a clear flag shape visible in the hysteresis loops following repair.

4.2 Controlled Damage Coupled Bar Connection

Figure 13 shows benchmark testing of Column CDS, Figure 14 shows testing of the column following application of the repair strategy and Figure 15 gives the uniaxial force-drift behaviour observed in each test.

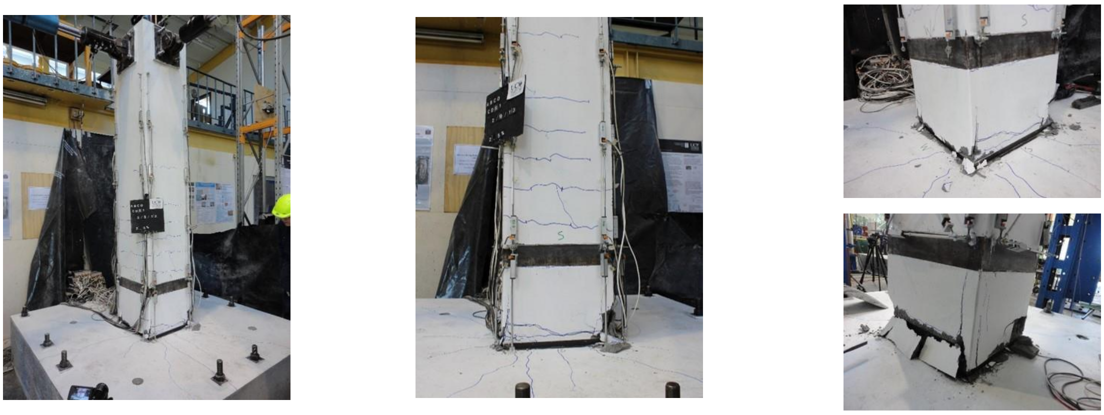

Figure 13. Column CDS benchmark testing

Figure 14. Testing of repair strategy

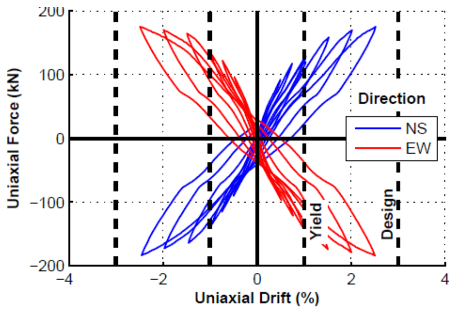

Figure 15a. Benchmark force-drift behaviour

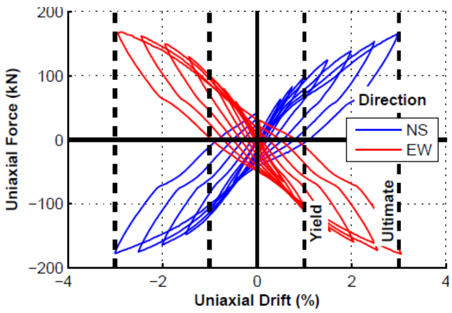

Figure 15b. Repaired force-drift behaviour

The results are summarised as follows:

- Benchmark testing of Column CDS showed good results although the flag shape was not as pronounced as in the previous CD tests. This is partly due to unintended bonding of the precast core to the footing which restrained the rocking behaviour of the joint, increasing the capacity and energy dissipation of the system. This led to increased residual drifts in the structure however they were still considerably smaller than occurs in monolithic or ABC HD structures (Mashal, White and Palermo, 2013).
- No slackness in the results was observed indicating good connection between replaceable

dissipator, coupler and threaded stud with little connection slip.

- After removal of cast-in-place fill and stirrups as part of the repair process, it was noticed that some buckling of the dissipators had occurred. The amount of buckling was limited but could be further reduced with an increase in the amount of buckling restraint in the form of stirrups, steel tubes over the dissipators or external cover confinement in the cast-in-place region.
- The damaged dissipators were removed and replacement Grooved Bar dissipators were installed. Some thread alignment challenges were faced during replacement but were overcome by swapping the location of replacement dissipators which did not offer significant delays to the repair process.
- Replacement stirrups were installed and fill material was cast, completing the repair of the connection. During casting, aggregate blockage of the fill tube was encountered and so grout was used in place of micro-concrete with no apparent effect on the performance of the column.
- During testing of the repair process, premature failure of the replacement dissipators occurred due to an identified detailing error. Previous tests have shown that with appropriate detailing, the dissipators could achieve larger strains without failure and so it is expected that the connection could have reached a higher level of ultimate drift.
- Otherwise, good performance with very similar results to the pre-repair testing indicating that the repair process was effective at reinstating both the strength and ductility capacity of the column.

5 RESULTS AND DISCUSSION

5.1 Comparison of Connections

Both connections showed promising results with flag shaped hysteresis loops occurring. Residual drifts were considerable smaller than those of the HD testing (Mashal, White & Palermo, 2013).

The two connection types demonstrate different approaches in the development and application of repair strategy. For the CD MSC, damaged energy dissipation components were severed and new components were installed on the exterior of the pier, offering an alternative energy dissipation system. This approach requires design for both internal and external dissipation systems but offers a much simpler repair process with no repair or replacement of concrete or grout required. For the CBC, the repair approach involved replacement of the components of the energy dissipation system rather than installation of an alternative system. This approach offers a simpler design process where only one dissipation system needs to be considered and offers aesthetic advantages but requires a more involved repair process with removal and replacement of cast-in-place fill and stirrups. The repair process, however, is still significantly simpler than that of HD or conventional monolithic systems where repair or replacement of reinforcing bars and cast-in-place concrete may be required, along with correction of residual drifts of the structure.

It should be noted that in current NZ design codes, the use of couplers in the plastic hinge region is not permitted and the use of bar couplers in general is discouraged by the NZTA. In this case, however, it should be appreciated that couplers are being used with Grade 300 bars of reduced cross section, significantly reducing the probability of coupler failure.

6 CONCLUSIONS

The experimental testing of the Controlled Damage (CD) Member Socket Connection (MSC) and Coupled Bar Connection (CBC) through biaxial loading was presented in this paper. A repair strategy was applied to each connection type and the columns were re-tested to demonstrate the repair process and effectiveness. Assembly and repair of both connections was relatively straightforward and demonstrates the advantages of precast substructures in terms of speed and ease of assembly.

Despite some shortcomings in the construction and testing of the columns, both connection types showed promising results both in increasing construction speed and quality, and significantly reducing post-earthquake repair cost and downtime.

CD connections will generally have a higher initial construction cost than HD connections due to the inclusion of post-tensioning, armouring and replaceable energy dissipation components. This additional cost, however, may be balanced by the reduced repair cost should a significant earthquake event occur. Consideration of the full life cycle costs of the structure with appropriate discount factors is required when comparing CD and conventional construction in order to account for all benefits associated with the system, rather than focusing only on initial construction cost.

Application of the repair strategy removes all uncertainty into the residual strength and ductility capacities of the connection, as all energy dissipation components of the connection are replaced. The relatively low cost of the repair strategies mean they can be implemented in any case where there is uncertainty in the level of damage of components and capacity of the substructure as a whole, avoiding the need for costly investigative procedures to be implemented.

Both connection types show good potential for use in bridge substructures offering the advantages of precast construction, notably increased speed and quality of construction, along with simple and cost effective repair. Further investigation into durability of the connections is being carried out at the University of Canterbury. Although Controlled Damage connections have higher initial construction costs, with further research and development and appropriate consideration of life cycle costs, it is expected that they will offer a competitive alternative to conventional construction approaches while improving post-earthquake serviceability and repair options of bridge structures.

REFERENCES

Billington, S. L., Barnes, R. W., & Breen, J. E. (1999). *A Precast Segmental Substructure System for Standard Bridges*. J. Precast/Prestressed Concrete Inst., 44(4), 56-73.

Billington, S. L., & Yoon, J. K. (2004). *Cyclic Response of Unbonded Posttensioned Precast Columns with Ductile Fiber-Reinforced Concrete*. Journal of Bridge Engineering, 9(4), 353-363.

Mander, J., Priestley, M. J. N., Park, R. (1988). *Theoretical Stress-Strain Model for Confined Concrete*. Journal of Structural Engineering, 114(8):1804-1826.

Marriott, D. (2009). *The Development of High-Performance Post-Tensioned Rocking Systems for the Seismic Design of Structures*. (PhD), University of Canterbury.

Marsh, M. L., Wenli, M., Garrett, B. E., Stanton, J. F., Eberhard, M. O., Weinert, M. D. (2011). *NCHRP Report 698 - Application of Accelerated Bridge Construction Connections in Moderate-to-High Seismic Regions.*

Mashal, M., White, S., Palermo, A. (2013). *Quasi-static cyclic tests of Emulative Precast Segmental Bridge Piers (E-PSBP)*. 2013 NZSEE Conference, Wellington, New Zealand.

Palermo, A. (2004). *The Use of Controlled Rocking In the Seismic Design of Bridges*. (Doctor of Philosophy), Politecnico Di Milano, Milan, Italy.

Pampanin, S., Marriott, D., Palermo, A., Bolognini, D. (2010). *PRESSS Design Handbook.*

Priestley, M. J. N. (1991). *Overview of PRESSS Research Program*. PCI Journal, 36(4), 50-57.

Priestley, M. J. N. (1996). *PRESSS Program - Current Status and Proposed Plans for Phase III*. PCI Journal, 41(2), 22-40.

Ralls, M. L., Hyzak, M. D., Medlock, R. D., & Wolf, L. M. (2004). *Prefabricated Bridges - Current U.S. Practice and Issues.* FHWA/AASHTO Second National Prefabricated Bridge Elements & Systems Workshop. New Brunswick, New Jersey.

Sarti, F., Palermo, A., Pampanin, S., Carradine, D.M. and Smith, T.J. (2013). *Experimental and Analytical Study of Replaceable Buckling-Restrained Fused-Type (BRF) Mild Steel Dissipaters*. 2013 NZSEE Conference, Wellington, New Zealand.

Stanton, J. F., Wacker, J. M., Hieber, D. G., & Eberhard, M. O. (2005). *Design of Precast Concrete Piers for Rapid Bridge Construction in Seismic Regions*: Washington State Transportation Center.