PRECAST CONCRETE CONNECTIONS FOR ACCELERATED BRIDGE CONSTRUCTION IN REGIONS OF HIGH SEISMICITY

SAM WHITE¹, MUSTAFA MASHAL², ALESSANDRO PALERMO²

¹ Opus International Consultants, formerly College of Engineering, University of Canterbury
² College of Engineering, University of Canterbury

SUMMARY

This paper presents findings from half-scale experimental testing of ABC precast connections in single and multi-column bridge piers at the University of Canterbury as part of the research programme titled Advanced Bridge Construction and Design (ABCD). The research investigated three categories of precast connection labelled High Damage, Controlled Damage and Low Damage connections. This paper summarises testing of Controlled and Low Damage connection types.

INTRODUCTION

Cast-in-place monolithic construction is typically used for concrete bridge substructures. Although this method has proven itself to be cost effective, cast-in-place construction is time consuming, requires a significant amount on-site labour and can lead to quality and maintenance issues (Marsh, Wenli et al. 2011). Additionally, a high level of damage is often observed in monolithic structures during earthquake events, including spalling of concrete and yielding of reinforcement. In extreme cases, fracture or buckling of reinforcement may occur, often requiring replacement of the bridge structure (Priestley, Seible et al. 1996).

An alternative approach is the use of precast concrete components for the construction of bridge substructures in a method known as Accelerated Bridge Construction (ABC). ABC offers a number of advantages over cast-in-place construction including increased construction speed and quality, improved on-site safety and reduced construction labour (Billington, Barnes et al. 1999, Marsh, Wenli et al. 2011). ABC has had wide use in regions of low seismicity, but limited use in regions of high seismicity due to concerns in the performance of connections between precast components (Texas DOT 2008, Utah DOT 2008).

Three connection types were developed as part of the University of Canterbury research programme titled Advanced Bridge Construction and Design (ABCD). Funding for this research is provided by Natural Hazards Research Platform (NHRP).

High Damage (HD) connections are precast connections that emulate the behaviour of conventional monolithic construction for use in regions of high seismicity. This involves formation of plastic hinges in the columns with associated damage including spalling of concrete and yielding of internal reinforcing bars. HD connections address the need for rapid construction with minimal disruption but don’t necessarily improve on the seismic performance of conventional systems. A summary of High Damage connection types was presented at the 2013 New Zealand Concrete Industry Conference (Mashal, White et al. 2013).
Dissipative Controlled Rocking (DCR) or hybrid connections are an option for improving the seismic performance of precast concrete connections (Priestley 1991, Palermo 2004, Marriott 2009, Pampanin, Marriott et al. 2010). Post-tensioning provides self-centering capability for the piers, while energy dissipation components absorb seismic energy. A flag shaped hysteresis loop results and is illustrated in Figure 1b. The rocking connections used in this research were designed according to the procedure outlined in the NZCS PRESSS Design Handbook (Pampanin, Marriott et al. 2010).

![Figure 1. (a) Rocking Mechanism for ABC Low and Controlled Damage Connections; (b) Idealized Flag-Shaped Hysteresis Behaviour (Palermo, Pampanin et al. 2007)](image)

Low Damage (LD) connections (Figure 1a) use Dissipative Controlled Rocking (DCR) to offer very good seismic performance with little damage or residual drift, along with the benefits of ABC. Low damage connections avoid any damage to precast components and replaceable external dissipators allow for rapid repair, minimising repair costs and downtime.

Controlled Damage (CD) connections (Figure 1a) also use DCR concepts and offer a compromise between High and Low Damage by allowing some damage to occur, but ensuring this damage is localised and easily repairable (White 2014). Conventional materials and components are used to minimise initial construction costs. Predetermined repair strategies are developed and detailed for during design of controlled damage connections, allowing for rapid and cost effective repair.

The choice of connection type depends on the construction and maintenance budgets, importance of the structure, implications of disruptions associated with construction and repair, level of seismicity, soil conditions, structure type and span length.

PROTOTYPE STRUCTURE AND TESTING ARRANGEMENT

The prototypes are representative of typical highway bridge with short to medium span in New Zealand (Figures 2a, 3a). The superstructure systems were selected from NZTA Research Report 364 (NZ Transport Agency 2008). The footings shown are for indicative purposes. The seismic design loading for the specimen was according to New Zealand design codes (NZ Transport Agency 2003, New Zealand Standards 2004) for soil class A and B, a return period of 1000-2500 years and a zone factor of 0.3. An assumed ductility of 3.0 at Ultimate Limit State (ULS) was adopted when determining design actions.

Half scale bi-directional testing with a clover shaped displacement path was used to test the Controlled Damage columns. Hydraulic actuators were used to apply lateral load. A post-tensioned bar with axial hydraulic actuator was used to represent both axial and post-tensioning loads in the column (Figure 2b, 2c).
The half scale Low Damage specimens were tested uni-directionally in a multi-column arrangement (Figure 3b). Gravity loads were applied to the cap beam using a hydraulic actuator. Post-tensioned bars were used in the precast columns to provide re-centering effects.

All of the test columns were designed using NZS 3101 (New Zealand Standards 2006) using conventional design methods. Concrete compressive strength of 40MPa, steel yielding strength of 500MPa, and grout compressive strength 50MPa was specified for construction. Grade 300 steel was used for yielding components in the Controlled Damage and Low Damage components due to increased ductility capacity.

CONTROLLED DAMAGE CONNECTIONS

Controlled Damage Member Socket Connection

The Controlled Damage Member Socket Connection (MSC) (Figure 5) builds upon the High Damage MSC where one precast element in placed into a socket which is formed in another precast element. The connection is completed with a grout closure pour (Mashal, White et al. 2013, White 2014). For the CD MSC, pre-tensioned or post-tensioned bars or tendons are included to limit residual drifts in the structure (Stanton 2010, Marsh, Wenli et al. 2011). Cover confinement is used to limit spalling damage which is otherwise induced at lower levels of drift in this type of connection due to the increased levels of axial load. Glass Fibre Reinforced Polymer (FRP) wrap was used for confinement of the test column. To facilitate repair of the connection, mechanical anchorages are cast into the connection during construction. This allows for rapid repair of the structure following an earthquake event through installation of external dissipation devices.
During a seismic event, the column forms a natural rocking interface through opening of a major crack at the base of the column between the armouring and footing (Figure 5b). Energy is dissipated through yielding of the longitudinal reinforcement in the column, which is debonded over a length at the connection interface to localise yielding, and further encourage formation of a rocking interface. Unbonded post-tensioning recenters the connection, minimising residual drift in the structure. Steel angles may be used as a supplementary shear transfer mechanism.

Following a severe seismic event, the internal bars are cut using a concrete saw, removing their contribution to strength of the connection, and external dissipators are installed which offer connection performance that is equivalent to the pre-repair connection (Figure 5c). Innovative grooved buckling-restrained dissipators were used for repair of the test column (Figure 4) (White 2014). These dissipators are an evolution of an existing dissipator type known as the Buckling Restrained Fused (BRF) dissipator (Marriott 2009, Sarti et al. 2013) which provides buckling resistance using a confining tube and a filling material such as grout or epoxy. Grooved dissipators offer the advantage of dry fabrication, meaning no epoxy or grout filling material is required.

The connection performed well in both the pre and post-repair cases (Figures 6a, 6b). There was very little damage to the column with no spalling of concrete. Some cracking occurred in the column with the cracks extending through the FRP wrap. Hairline cracks also formed up the height of the column, but all cracks closed upon unloading.

Figure 6c and 6d show the hysteretic behaviour of the connection for the benchmark and repaired cases. Both cases showed small residual drifts and moderate energy dissipation. A flag shape is more evident in the hysteresis loop of the repaired case due to the column being subjected to larger drifts in this case.
Figure 6. (a) Benchmark Column Following Testing; (b) Repaired Column Following Testing; (c) Benchmark Force-Drift Plot; (d) Repaired Force-Drift Plot

Controlled Damage Coupled Bar Connection

The Controlled Damage Coupled Bar Connection (Figure 7) uses replaceable segments of longitudinal bar connected to threaded studs formed in the ends of permanent reinforcement using threaded bar couplers. The bar segments, couplers and threaded studs are located in a recess in the base of the column (Figure 7b). Steel angles are used to armour the corners of precast components and help align the threaded studs. Conventional mild steel stirrups are placed around the bar segments and the recess is filled with cast-in-place concrete or grout, enclosing the components of the energy dissipation system. Figure 8 illustrates the construction sequence.

Figure 7. (a) CD CBC Test Column; (b) Connection Detail; (c) Connection Components

During a seismic event, spalling of the fill material is expected, along with yielding of the replaceable segments of bar. No damage to threads, couplers or precast components will occur. To repair the connection, the cast-in-place material and stirrups are removed, allowing access to the bar segments for replacement. Following replacement, new stirrups are installed and fill material is cast.
Good performance was also exhibited by the CD CBC. As intended, damage was constrained to the cast-in-place material, with little damage to precast components (Figure 9a). The repair process was straightforward and significantly simpler than repair of a conventional monolithic connection (Figures 9b, 9c). Grooved dissipators were used for the repair of the connection (Figure 4). There were some minor thread alignment issues while installing replacement dissipators, however this was overcome by swapping dissipator locations and did not lead to significant delays in repair.

The hysteresis loops show good energy dissipation (Figures 9d, 9e), but with less re-centering effect than the CD MSC due to unintended bonding of the precast core and footing. Debonding of the column and footing using a bond breaking agent is therefore required. Similar performance was observed in the benchmark and repaired cases, indicating that the repair process was effective at reinstating the strength and ductility of the connection.
LOW DAMAGE CONNECTIONS

The Low Damage specimen is a multi-column bent with the dimensions and testing arrangement shown in Figure 3. The cap beam from a previous testing phase (ABC High Damage) was reused. Two new columns were reinforced with 8-HD16 longitudinal rebars and mild steel shell armouring at the rocking zones for additional confinement and to prevent concrete spalling (Figure 10). Grooved dissipators were used as the energy dissipating components of the system (White 2014) (Figure 4).

![Figure 10. (a) Precast Columns with Steel Shell (b) Typical Column with Recess for Shear Key and Central Duct for the Unbonded Post-Tensioned Bar](image1)

The rocking interfaces on the footings and under the cap beam were armoured with steel plates (Figure 11). Internal shear keys were used at the rocking interface on the footing and cap beam to prevent excessive sliding (Figure 11b). A post-tensioning Macalloy bar of 40mm diameter was located in the central duct in the column and anchored at the footing and cap beam.

![Figure 11. Armouring Details at the Rocking Interfaces: (a) Footing; (b) Footing Shear Key Close-up View; (c) Cap Beam with Similar Shear Key Detail](image2)

Once the bent was assembled, the mild steel dissipators were connected to the footing by winding the dissipators into tapped holes in the base plate. Steel brackets were welded to the column shell for attachment of the dissipators (Figure 12b, 12c). Figure 12a shows the assembled ABC Low Damage bent.
In the initial phase, three quasi-static uni-directional tests were undertaken with different levels of initial post-tensioning to investigate the response of the structure with un-bonded post-tensioning only. The axial force (gravity ram) was released and the nuts were removed from end of the dissipators, making the dissipators free to slide through the brackets without any loading. The levels of initial post-tensioning were selected to be 15%, 30%, and 45% of the yielding strength of the Macalloy bar. The capacity of the connection, size of gap-opening at the rocking interface, and re-centering ratio are directly related to the initial post-tensioning force in the Macalloy bar. In all three tests, the bent was taken up to 2.2% drift (slightly higher than its ULS design level) and did not suffer any damage.
The columns remained intact with not even hairline cracking. There was sliding at the rocking interfaces with lower levels of initial post-tensioning (15% and 30%). This was mainly due to presence of a gap (10mm) which was left for construction tolerance purposes between the internal shear key and the column recess.

There was also some twisting of columns which showed that internal round shear keys are insufficient for prevention of twisting of columns. Therefore, external steel shear keys were provided to solve the issue of twisting and sliding. All three testing with post-tensioning were repeated again using external shear keys.

Figure 13 presents a comparison of the force-displacement plots with internal and external shear keys. With external shear keys, it is evident that the behaviour can be improved significantly.

Further work is required to evaluate the performance of the Low Damage connections with energy dissipation and the results of the research will be published at a later date.

CONCLUSIONS

Although monolithic cast-in-place construction has proven itself to be cost effective, it is time consuming, requires a significant amount on-site labour and can suffer from quality and maintenance issues. Additionally, these structures often suffer major damage during earthquake events leading to costly repair or replacement.

Precast components used as part of an ABC system offer advantages over conventional construction techniques including increased construction speed and quality, improved on-site safety and reduced construction labour. High Damage connection types offer the advantages of precast construction but do not necessarily improve upon the seismic performance.

Controlled and Low Damage precast connections use DCR or Hybrid connections to improve the performance of precast systems while also offering the advantages associated with ABC. Improvements include minimal damage to the structure with little or no residual drifts, as shown by the experimental results of this research. The experimental testing also demonstrated the ease of construction and repair of these precast connection types.

Further research into these connection types is underway looking into improvements in the ease of construction and repair, seismic performance and durability. It is expected that with further research and development, High, Low and Controlled Damage connection types will offer a strong alternative to conventional methods of bridge construction.
REFERENCES


Utah DOT (2008). "Utah Department of Transportation Accelerated Bridge Construction Standards Workshop."