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Experimental Testing of Emulative and Post-Tensioned Earthquake Damage Resistant Technologies for Accelerated Bridge Construction

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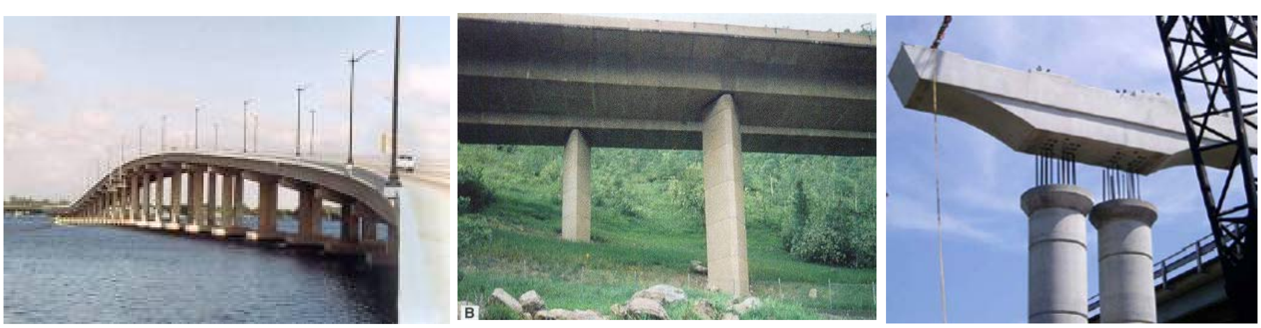
Abstract

Over the last few decades Accelerated Bridge Construction (ABC) has been developed to answer the growing number of societal needs, as well as advancing the bridge practice. There have been many applications of ABC in the United States, primarily in Texas, Utah, New Jersey, Florida, and Washington. However, application of ABC in regions with moderate-to-high seismicity requires in depth development, detailing consideration, experimental investigation, and analytical guidelines for the suitable connections between the precast members. This paper investigates the seismic performance of two types of connections through experimental testing for ABC in seismic regions. The research concludes that both connections have the potential to be used within the concept of ABC between the precast elements in a bridge substructure.

Keywords: Accelerated Bridge Construction, Low Damage Seismic Design; Precast Concrete; Unbonded Post-Tensioning

1. Introduction

There have been plenty of examples of ABC in the United States by Departments of Transportation (DOTs) in regions with low seismicity, refer to Figure 1. Recent examples from the Texas DOT include the Pierce Elevated Freeway Bridge Replacement project, Louetta Road Overpass, segmental piers of State Highway 183, and Lake Ray Hubbard Bridge on State Highway 66. Other examples are the Seven Mile Bridge, Edison Bridge, Sunshine Skyway Bridge, and John T. Collinson Rail Bridge, all in the State of Florida, Vaina-Enon Bridge in the State of Virginia, Linn Cove Viaduct "Vail Pass" in the State of Colorado, Victory Bridge in the State of New Jersey, US 6 Bridge over Keg Creek in the State of Iowa, and I-84 Bridge over Dingle Ridge Road in New York State.



(a) Edison Bridge in Florida (b) Vail Pass in Colorado (c) Lake Belton Bridge in Florida

Fig. 1– Examples of ABC in low seismicity in the United States, after FHWA [1] and Billington et al. [2]

Marsh et al. [3] presents several type of connections that can be used for ABC in high seismic regions. Some of these connections are developed to emulate the seismic performance of a monolithic connection such as formation of plastic hinges as developed by Park and Paulay [4].

A precast bridge with emulative connections may suffer extensive damage beyond repairability during a big earthquake, Marsh et al. [3]. Following the earthquake, the bridge can be left with residual displacement, and may not be immediately functional and open for traffic. Therefore, the downtime, repairing cost, residual displacement, and possible replacement are the most undesirable aspects of bridges with emulative connections. Therefore, precast bridges with this type of connection is called "ABC High Damage" here.

Two types of emulative connections, the grouted duct and member socket connections, are considered in this research. In Grouted Duct Connection (GDC), the starter bars from one precast member are extended into the ducts inside the second precast member, as visible for the connection of column to cap beam in the bridge shown in Figure 2a.The ducts are later fully grouted using high-strength mortar to secure the connection between the precast members. Past research on GDCs include Matsumoto et al. [5] Brenes et al. [6], Riva [7], Culmo [8], Pang et al. [9], and Restrepo et al. [10].

In Member Socket Connection (MSC), the connection is formed by embedding a precast element inside another element. The second element can be either precast or cast-in-place concrete. If both elements are precast, then the connection is secured using a grout or concrete closure pour in the preformed socket. The other solution is to have the second element cast around the first one (Figure 2). Past research on MSCs are Riva [7], Haraldsson et al. [11], and Mashal et al. [12].

(a) GDC and MSC in a bent (b) Column to footing MSC (c) Completed bridge

Fig. 2– Combination I-5 in Washington (Haraldsson et al., [11])

Non-emulative monolithic connections include "hybrid connections". The hybrid concept was initially developed for the building frames. The was done as part of a joint United States-Japan research program titled “PREcast Seismic Structural Systems” (PRESSS), coordinated by the University of California, San Diego (Stone et al. [13], Stanton et al. [14], Priestley et al. [15]).

A hybrid connection is comprised of unbonded post-tensioned tendons with mild steel reinforcement or any other type of energy dissipating devices. In a hybrid connection, the member displacement is designed to have concentrated rotation at the joint. In case of an earthquake, since the members are designed to remain elastic using a capacity design approach (Park and Paulay [4]), minimal damage to the elements can be expected. The tendons are designed to remain elastic and are able to elongate evenly along their full lengths. Therefore, they provide re-centering capacity to the system with minimum to zero residual drift following a design level earthquake. The energy dissipaters are intended to absorb the seismic energy. The final response of the system is called “flag-shaped” (Figure 3).

The concept for hybrid connection between precast members was successively extended to precast bridges by Palermo et al. [16], [17]. The concept of “Dissipative Controlled Rocking” (DCR) is an equivalent term for the hybrid connections between the precast elements of a bridge. It is called "DCR" since the rocking motion can become energy dissipative through the use of dissipative linkages (reinforcing bars, mild steel dissipaters, or mechanical dissipative devices) which are positioned at the rocking interfaces. The DCR activates when an earthquake occurs, providing restoring or self-centering capacity plus dissipation. A DCR connection reduces damage in a bridge during an earthquake. It also preserves the functionality of the bridge following the earthquake. The only sacrificial elements in this type of technology are the dissipative devices which can be easily replaced. Therefore, when DCR connections are used within the concept of ABC, it is titled "ABC Low Damage".

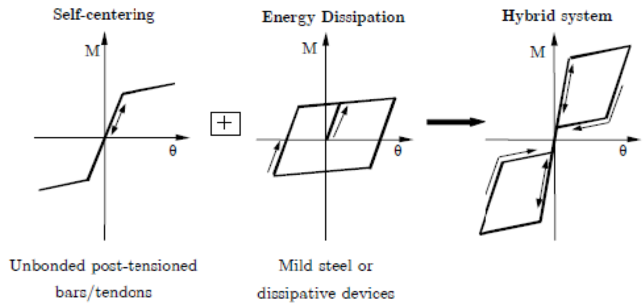


Fig. 3– Flag-shaped response (Priestley et al., [15])

2. Prototype Structure

2.1 Description

The prototype structure was developed based on a multi-column pier system (bent) for a typical high-way bridge in New Zealand, as shown in Figure 4. The bridge has six spans of equal length. Each span is 16 m long which gives a total length of 96 m for the bridge. The height from top of the footing up to the center of mass of the bridge is taken to be 5.8 m. The overall width of the bridge is taken as 10.4 m.

The superstructure is consisted of I-beam 1600 deck system in accordance with NZTA 364 Report [18]. The bridge is assumed to be located on non-liquefiable soils. The base connections are taken to be fully fixed with no soil-structure interaction taken into account. The footing system shown in Figure 4 for is only indicative.

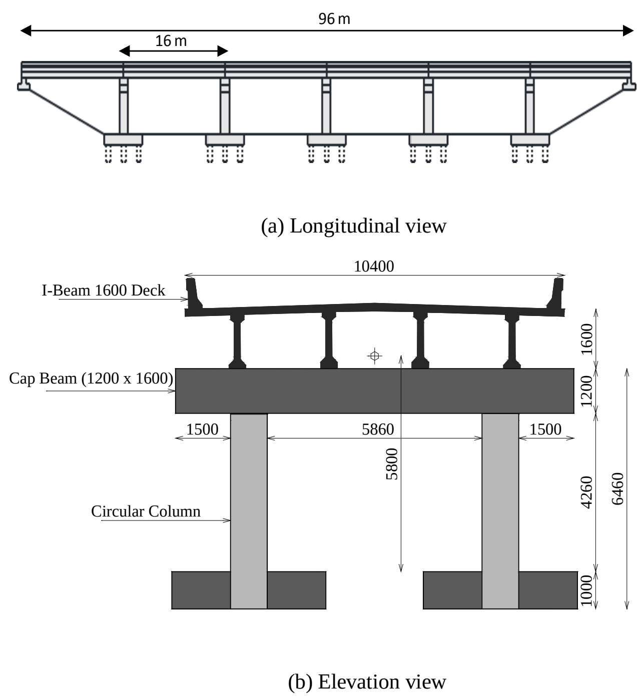


Fig. 4– Prototype structure (all dimensions are in metric)

Two half-scale bent specimens were developed based on the prototype bent of Figure 4b. A force based design approach was used for the earthquake loading. This was based on the equivalent static seismic loading criteria from New Zealand Bridge Manual [19] and New Zealand Standards 1170.5 [20]. There was no consideration given for the service loads on the bridge in combination with earthquake loads, except the gravity loads from the dead load of the superstructure and self-weight of the substructure (cap beam and columns). Table 1 presents a summary of the seismic parameters for the specimens from NZS 1170.5 [20].

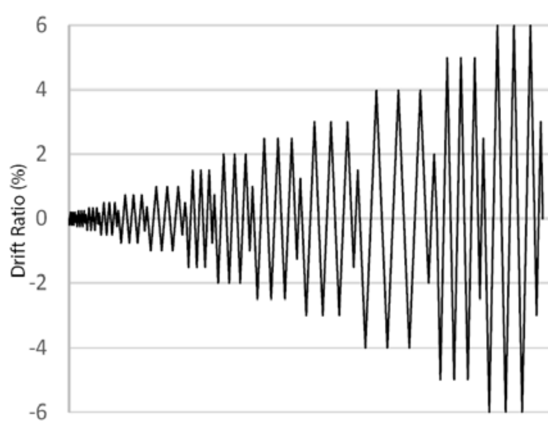
Table 1 – Summary of seismic loading parameters according to NZS 1170.5 [20]

No	Parameter	Value
1	Seismic hazard factor (Z)	0.29
2	Soil class	E (Soft Soil)
3	Return period factor (R)	1.8 (2500 years)
4	Near fault factor (N)	1
5	Assumed design ductility (μ)	3 at Ultimate Limit State (ULS)
6	Structural performance factor (Sp)	0.7
7	Fundamental natural period in seconds (T)	0.23
8	Self weight of bent in kN (Wsw)	80
9	Superstructure weight in kN (Wsp)	390
10	Design gravity load in kN (W)	470
11	Design lateral load in kN (V)	305
12	Seismic coefficient (Cd T)	0.65
13	Design drift in % (Δ)	2.2

2.2 Loading protocol and testing setup

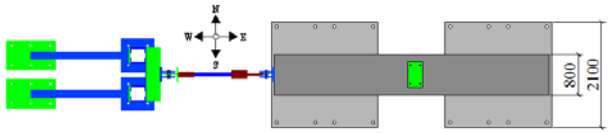
Loading protocol was adopted from the ACI recommendations [21]. The uniaxial loading consisted of quasi-static cyclic loading with increasing displacements (Figure 5a).

Testing setup is illustrated in Figure 5c and 5d. Lateral load on the bent was represented by using a horizontally placed ram with 1,000 kN capacity. The superstructure dead weight was simulated by using a vertical ram with a capacity of 1,000 kN which was placed between the cap beam and the strong floor, as shown in Figure 5c. The ram was pulling the cap beam downwards to a force level of 390 kN. In order to keep the load constant, a manual controller for the vertical ram was used during testing. The gravity load was being held constant (to within approximately ±3%) and monitored throughout testing.

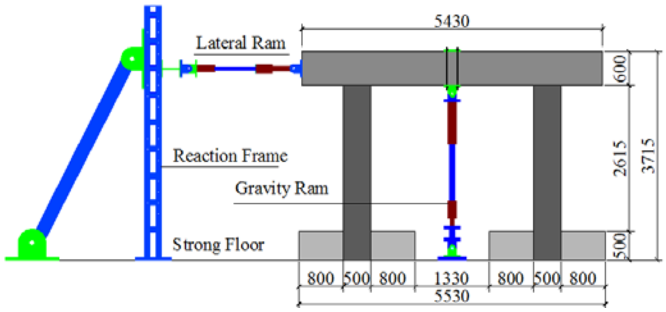


(a) Loading protocol from ACI ITG 1 [21]

(b) Typical testing setup for the bent



(c) Testing setup plan view



(d) Testing setup elevation view

Fig. 5– Loading protocol and testing setup

3. ABC High Damage

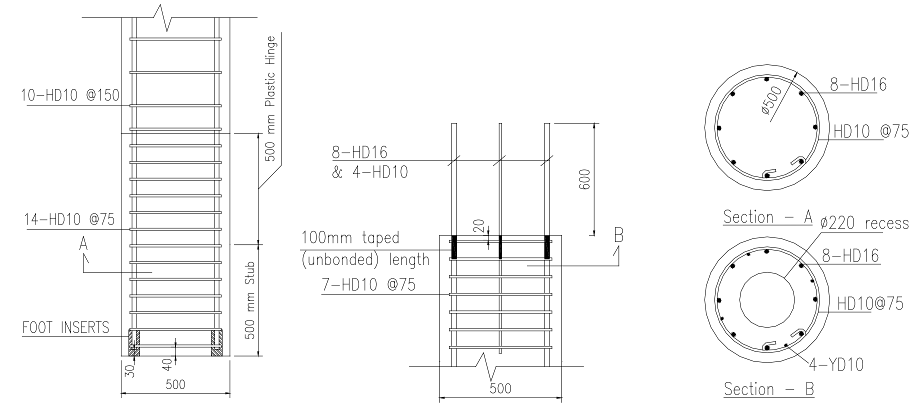
3.1 Description, design, and detailing

The High Damage Bent (HDB) incorporated MSCs for the column to footing connections and GDCs for column to cap beam connections. This was similar to the concept proposed by Marsh et al. [3] for a precast bent in seismic regions. The cap beam and footings were designed to remain elastic (capacity protected elements) in accordance with NZS 3101 [22]. Plastic hinges were intended to form near the ends of the columns (total of four hinges). Materials properties were selected to be 40 MPa for the concrete compressive strength (after 28 days) and 500 MPa for the reinforcing (longitudinal and lateral) yield strength. The grout compressive strength was specified to be 45 MPa after 7 days.

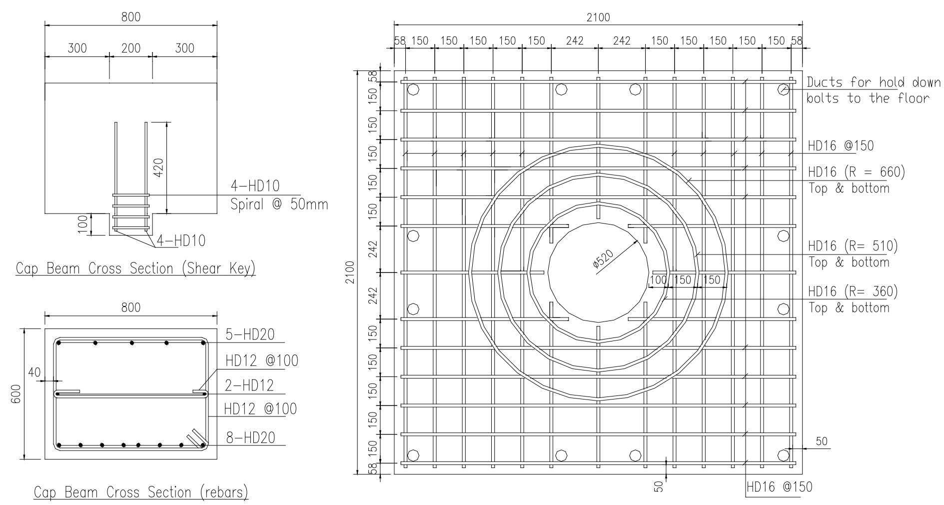
The columns were designed using NZS 3101 [22]. Confinement reinforcing was spaced closely near the ends where the plastic hinges are expected to form. Figure 6 shows reinforcing details of HDB elements. For GDCs, circular shear keys were cast in the cap beam to provide shear resistance for the connection (Fig. 6d). In this case, the dowel action of starter bars in transferring shear forces was neglected. Sockets were left at the top of the column to accommodate the shear keys. The gap around the shear keys inside the socket would be filled with grout during assembly of the bent. Therefore, making the connection very similar to a monolithic one. At the same time, in order to enhance the ductility of GDCs, a 100 mm unbonded (taped) length of the starter bars were left before casting the columns (Fig. 6b). Majority of nonlinear deformation in the starter bars during an earthquake is expected to occur over this length. This can provide a better distribution of nonlinear strains in the rebars under cyclic loading. Mashal et al. [12] showed that leaving unbonded length in the rebars can enhance the ductility and ultimate displacement capacity of columns with GDC.

Corrugated steel ducts were placed in the cap beam before casting to house the starter bars during the assembly process. A 34 mm construction tolerance in the ducts diameter was thought to be appropriate to prevent from any misalignment of the starter bars in the ducts during assembly process. The ducts were running up height of the cap beam section with a length similar to what specified in NZS 3101 [22] for normal reinforcing bars development length in a monolithic construction.

For MSCs, there was 20 mm tolerance between the column diameter and the socket in the precast footings. Circular rebars were placed around the socket to minimize radial cracking due to hoop stresses (Figure 6e). The depth of socket (footing thickness) was chosen to be equal to the diameter of column (500 mm). The concrete surface of the column stub and the footing socket was roughened using a retarding agent during precasting. This is intended for a better bond with the filling grout during assembly process.



(a) Column base detail (MSC) (b) Column top detail (GDC) (c) Column sections



(d) Cap beam section details (e) Footing reinforcing details

Fig. 6– Reinforcing details of precast elements for HDB

3.2 Experimental observation and results

Table 2 presents a summary of observed cracks sizes during testing for each type of connection in HDB.

Table 2 – Summary of the maximum crack size in (mm) for HDB

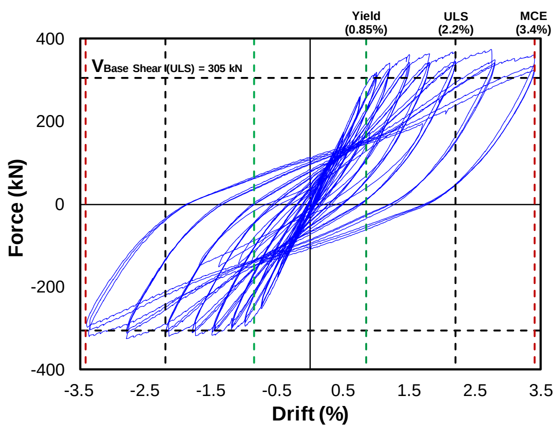
	Drift Ratio (%)							
	0.35	**0.5**	**1.0**	**1.5**	**1.8**	**2.2**	**2.8**	**3.4**
Crack size for bottom MSC (mm)	<0.4	0.4	2	3	8	Spall	Spall	Spall
Crack size for top GDC (mm)	<0.4	0.4	0.5	1.5	4	6	7	Spall

As expected, there were 4 plastic hinges formed in the bent (Fig. 7). The extent of damage and spalling was more severe for the bottom MSCs (Fig. 7c) compared to the top GDCs (Fig. 7d). At the end of testing, the spalling height (taken as the plastic hinge length) was measured to be 500 mm (equal to diameter of column) for MSCs and 250 mm (half diameter of column) for GDCs. The observed plastic hinge length for MSCs corresponded to that of a ductile monolithic column in accordance with NZS 3101 [22]. There was no damage to capacity protected elements (cap beam and footings) throughout testing (Fig. 7a).

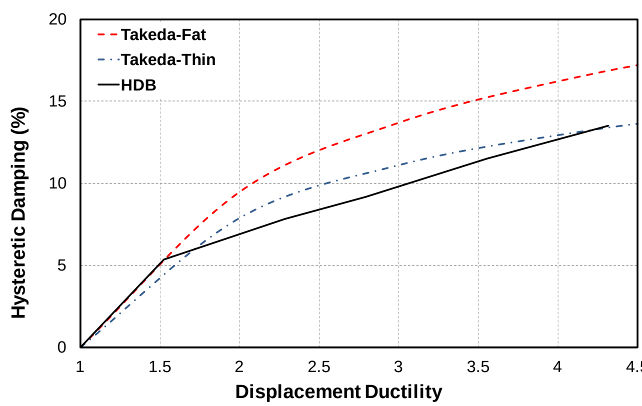
(a) Plastic hinges in the columns of HDB following uniaxial cyclic testing (b) Typical bottom MSC (c) Typical top GDC

Fig. 7– Extent of damage and plastic hinges in HDB

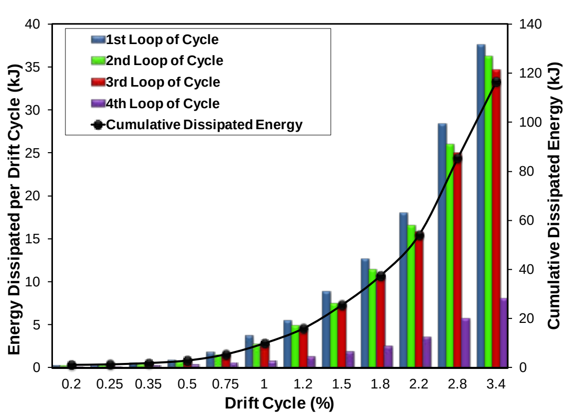
The force-drift cyclic response of HDB is shown in Fig. 8a. The bent showed a very stable hysteresis. The hysteretic damping was calculated from Dwairi et al. [23], see Fig. 8b. For comparison, theoretical damping plots for other hysteresis rules are also shown. The energy dissipation and Acceleration-Displacement Response Spectrum (ADRS) plots are shown in Fig. 8c and Fig. 8d, respectively. The plots in Fig. 8 show that HDB achieved its predicted ductility at the Ultimate Limit State (ULS).



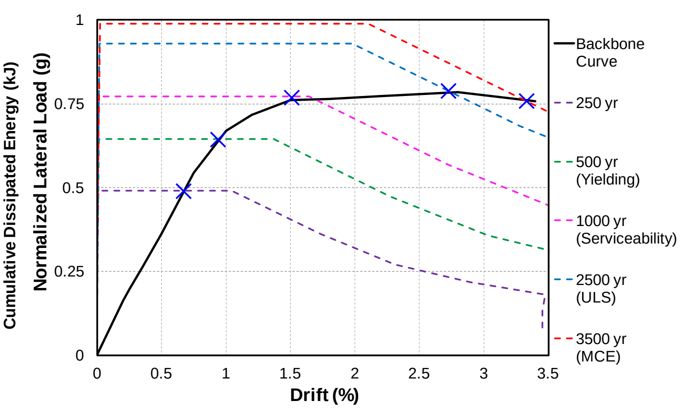
(a) Force-Drift hysteresis



(b) Hysteretic damping plots from Dwairi et al. (2007)



(c) Energy dissipation plot



(d) ADRS plot for a variety of demands from NZS 1170.5

Fig. 8– Experimental results for HDB

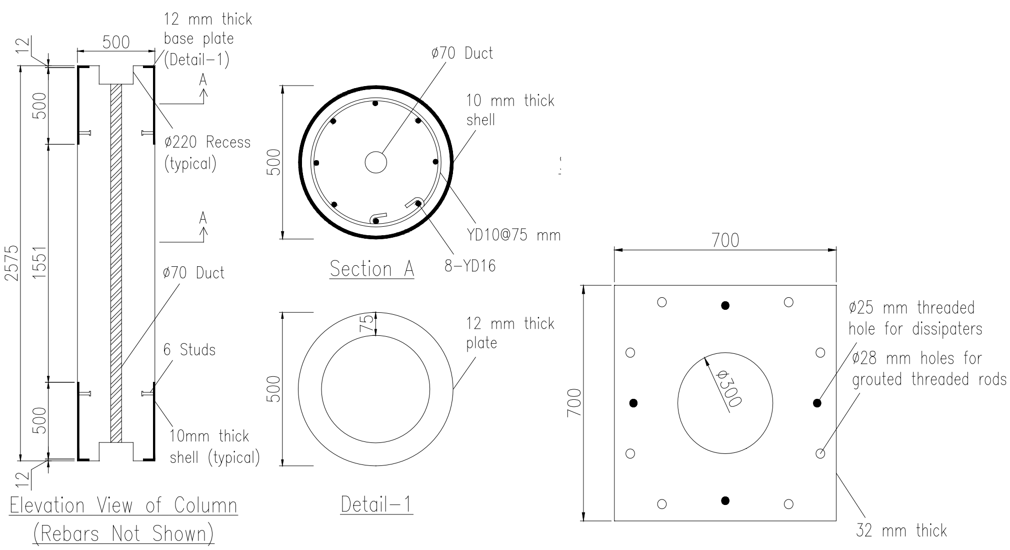
4. ABC Low Damage

4.1 Description, design, and detailing

The Low Damage Bent (LDB) incorporated Dissipative Controlled Rocking (DCR) connections to replace the plastic hinges in HDB. The design of DCR connections were in accordance with PRESSS Design Handbook [24]. LDB was designed to match the capacity of HDB at ULS level (2.2% drift ratio).

The cap beam was re-used from HDB. New columns were constructed which were designed in accordance with NZS 3101 (Fig. 9a) with similar reinforcing to those of HDB. Steel armoring shoes were left in the columns before casting. The armoring shoes intended to prevent from crushing of the concrete under high compressive stresses when rocking initiates during lateral loading. Similarly, steel base plates (Fig. 9b) were provided at the rocking connections (top of the footings and under the cap beam). Macalloy bars (40 mm diameter) were used for post-tensioning of the columns. There was a 70 mm diameter duct left at the center of each column to house the post-tensioning. The bars were extending up height of the columns and were clamped at the bottom of footing and top of the cap beam.

DCR connections require tighter construction tolerances for assembly, however, using match casting of the elements and providing bigger brackets for the dissipaters, could lower the construction risks.



(a) Details of low damage columns for LDB

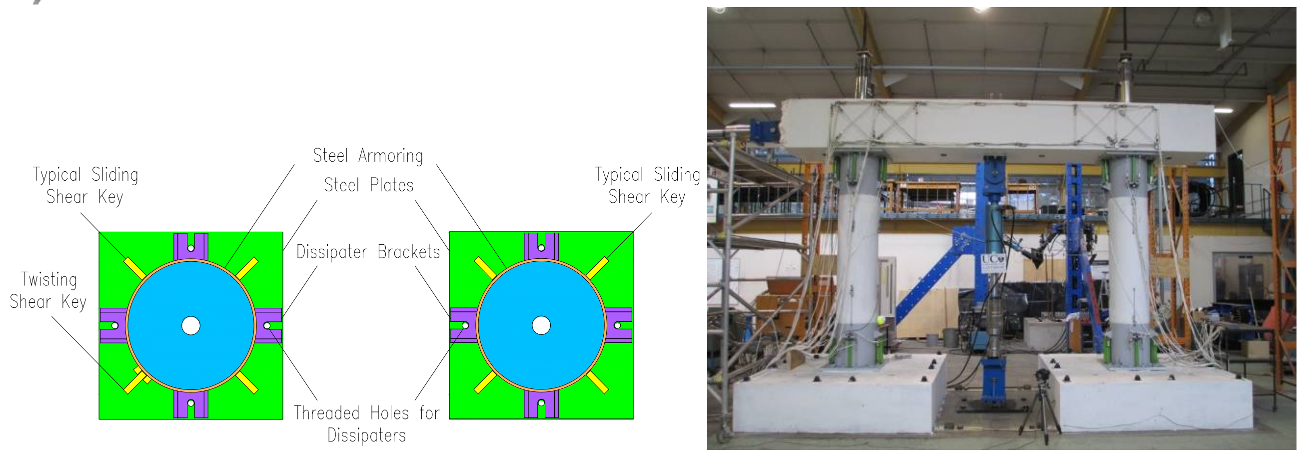
(b) Typical steel armoring base plate

Fig. 9– Reinforcing details of precast columns for LDB

In order to prevent from sliding and twisting at the DCR connections during rocking of the columns, external shear keys were welded to the armoring shoes and base plates (Fig. 10a). Steel brackets were provided at the face of armoring shoes to make anchorage points (Fig. 10f) for the dissipaters. The other end of the dissipater is tightened inside the threaded holes of base plates.

Two types of external metallic dissipaters (Fig. 10d and Fig. 10e) were used for an enhanced performance of the bent. The dissipaters shown in Fig. 10e incorporated novel aspects such as easy fabrication, cost-effectiveness, high capacity, compactness, resistance against low-cycle fatigue failure, and minimal strength degradation. The dissipaters were part of a group of damping devices invented by Dr. Mustafa Mashal, Dr. Alessandro Palermo, and Gavin Keats at the University of Canterbury in 2014. Patent applications have been filed by the University of Canterbury to protect the technology given its valuable commercial viability [25]. The assembled LDB with two types of dissipaters is shown in Fig. 10c.

The axial load (390 kN) was applied using similar configuration to that shown for HDB. Each connection incorporated four dissipaters (two of each type). Each Macalloy bar was post-tensioned to 125 kN which corresponds to 11.4% of its yield strength.



(a) Bottom DCR connection (b) Top DCR connection (c) Assembled LDB with DCR connections using two types of dissipaters

(d) Metallic Dissipater Type 1 (e) Metallic Dissipater Type 2 [25] (f) Typical DCR connection

Fig. 10– Details of LDB

4.2 Experimental observation and results

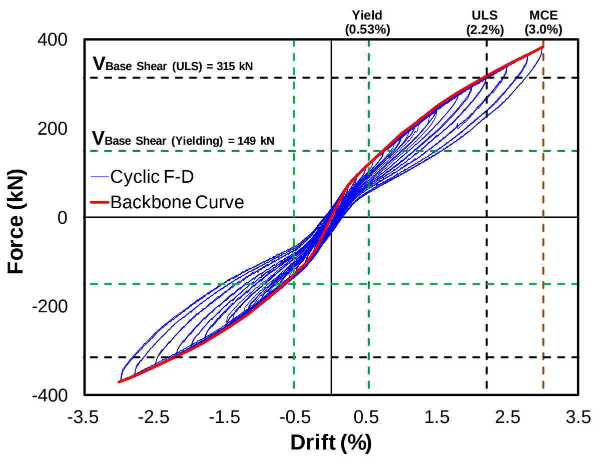
Table 3 presents a summary of observed gap opening (Fig. 11) for a typical DCR connection in LDB.

Table 3 – Summary of gap opening in (mm) for LDB

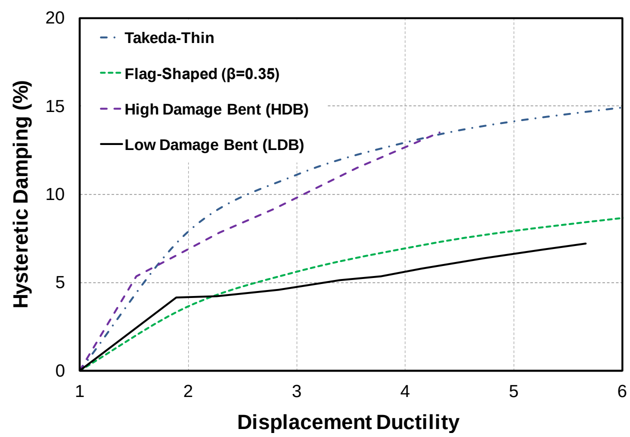
	Drift Ratio (%)							
	0.35	**0.5**	**1.0**	**1.5**	**1.8**	**2.2**	**2.5**	**3.0**
Typical DCR Connection gap opening in (mm)	0	1.0	5	7	9	10	11	15

Fig. 11– Gap opening of a typical DCR connection

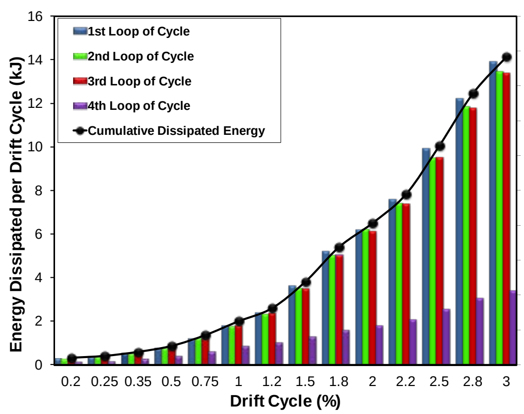
During testing, the rocking motion of four DCR connections were very obvious. There was no damage to the columns including hairline cracking. Similarly, the cap beam and footings remained intact throughout testing. The specimen capacity at ULS level (2.2% drift) was slightly higher (315 kN) than the design base shear of 305 kN. There was no signs of degradation or fatigue in the dissipaters. Following testing, there was no residual drift in LDB. The specimen achieved good levels of ductility and energy dissipation which is shown in Fig. 12 plots.



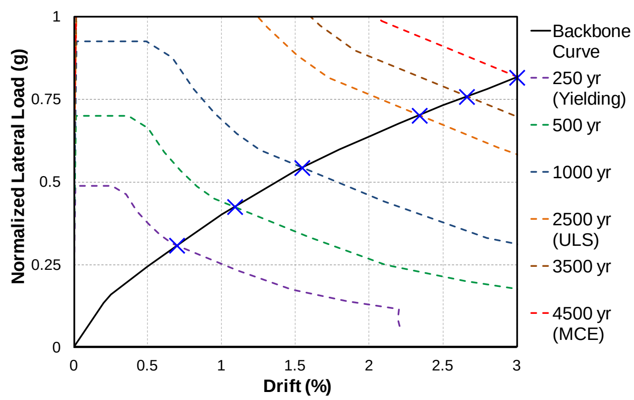
(a) Force-Drift hysteresis



(b) Hysteretic damping plots from Dwairi et al. (2007)



(c) Energy dissipation plot



(d) ADRS plot for a variety of demands from NZS 1170.5

Fig. 12– Experimental results for LDB

5. Comparison and Discussion: ABC High Damage Vs. ABC Low Damage

Testing of HDB showed extensive cracking to the column. There was extensive damage to plastic hinges (Figs. 13a and 13c). Experimental observations and results showed strength degradation, spalling of cover concrete, yielding and buckling of longitudinal rebars, and residual displacement of the bent. HDB achieved good levels of strength, ductility, and energy dissipation. However, for a real life bridge incorporating this technology, it means that the bridge would not collapse during a design level earthquake, and may remain open for traffic with delayed or limited functionality. However, extensive repair work and possible replacement of the bridge would be necessary for long term resilience.

Testing of LDB showed no damage to the columns or other precast elements (Figs. 13b and 13d). The bent achieved good levels of strength, ductility, and energy dissipation. There was no visible signs of strength degradation or fatigue failure in the dissipaters. Following testing, there was zero residual drift in the bent. For a real life bridge incorporating this technology, it would mean that the bridge remains functional with minor to no repair work needed following a design level earthquake.

(a) HDB after testing (b) LDB after testing (c) Typical plastic hinge in HDB (d) Typical DCR connection in LDB

Fig. 13– Damage to HDB and LDB following testing

6. Conclusions

The research concludes that ABC Low Damage offers better seismic performance compared to ABC High Damage and cast-in-place solutions. Although life-cycle cost analysis and seismic loss assessment for the above solutions are outside the scope this study, however, past research works on similar topics have shown that if the life-cycle cost of a bridge is considered, then the traditional cast-in-place, ABC High Damage, and ABC Low Damage solutions may result in similar total cost.

7. Acknowledgements

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