Development of Dissipative Controlled Rocking System for Bridge Columns Supported on Monopiles

S. Piras, A. Palermo & G. Chiaro
University of Canterbury, Christchurch.

ABSTRACT

In this research, low-damage seismic design detailing is developed for bridge columns supported by monopile foundations. The low-damage system aims to minimise, and potentially eliminate, the repair time and costs to a bridge after an earthquake. The low-damage design uses a dissipative controlled rocking (DCR) connection at the base of the column, which replaces the column plastic hinge. The DCR system combines unbonded post-tensioning and replaceable internal dissipaters to provide self-centring and energy absorption capabilities for the bridge pier, respectively. Additionally, this research validates the lateral seismic response of a DCR bridge pier with the contribution of soil-foundation-structure interaction. Specifically, this research studies how additional rotations at the head of the pile foundation delay the onset of column yielding, and how the foundation damping influences the behaviour of the DCR system. This paper includes a description of the prototype structure being investigated, an overview of the experimental testing that will occur as part of the experimental campaign, and the results of the numerical modelling that aims to predict the behaviour of the structure during testing.

1 INTRODUCTION

Dissipative controlled rocking (DCR) systems are an established engineering technology that has been successfully adopted into building design and experimentally validated for application of bridge columns. DCR systems, when applied to column joints, combine a self-centring mechanism with dissipation devises to reduce structural damage at plastic hinge zones and residual displacements in columns. The combination of recentring and dissipating components typically results in a "flag-shaped" hysteresis response. The main design parameter is the recentring ratio, lambda (λ), which dictates the overall energy dissipation and self-centring behaviour of the system.

$$\lambda = \frac{M_{PT}+M_N}{M_S} \quad (1)$$

The total moment capacity of the DCR joint is the sum of the moment contributions from the unbonded post-tensioning (M_{PT}), axial load (M_N) and the energy dissipaters (M_S). Section moment capacities are evaluated around the centroid of the total compressive force.

$$M_{TOT} = M_{PT} + M_N + M_S \quad (2)$$

The development of the DCR connection originates back to the joint United States-Japan research program called PREcast Seismic Structural System (PRESSS), which was coordinated by the University of California, San Diego (Priestly 1991, 1996; Priestly et al. 1999; Stanton et al. 1991, 1997; Stone et al. 1995). Many of the connections tested in the PRESSS program were for building structure application; one of which is called a hybrid jointed ductile connection and is referred to as a DCR connection in this paper. Research has since been extended for application to bridges (Mander and Cheng 1997; Palermo et al. 2004, 2005, 2007; Wacker et al. 2005; Palermo and Pampanin 2008; Marriott 2009; White and Palermo 2016; Guerrini et al. 2015; Mashal and Palermo 2019); however, all research to-date has assumed a rigid foundation at the base of the column.

Unlike buildings that are often time founded on rigid foundations, the lateral seismic response of bridge columns that are supported on a monopile is influenced by the soil-foundation-structure interaction. Neglecting the contribution of foundation rotations in the design of DCR columns underestimates the drift capacity of the pier. The research presented in this paper explores how foundations susceptible to rotations, like piles, affect the performance of a DCR system. Specifically, this research studies how additional rotations in the pile foundation delay the onset of column rocking. The results of a numerical analysis are presented.

2 PROTOTYPE STRUCTURE

The prototype structure chosen is representative of a typical New Zealand highway bridge (Fig. 1). The bridge consists of two spans that measure 20m in length. The pier is comprised of a single 1.5m diameter circular column on a 1.8m diameter circular pile shaft, and a hammerhead-type capping beam. The bridge deck consists of standard 1525mm deep precast Super-Tee beams with an overall width of 10.5m. The deck, beam type and dimensions are consistent with the standard designs presented in the Transport Agency's publication Standard Precast Concrete Bridge Beams: Research Report 364 (NZ Transport Agency 2008). The prototype is assumed to be of importance level 3, have a 100-year design life, located in Christchurch on non-liquefiable soil, and is not susceptible to near-fault effects.

A displacement-base design approach was used for the earthquake loading of the prototype structure. This was based on the loading criteria from the New Zealand Bridge Manual (NZ Transport Agency 2018) and NZS 1170.5 (Standards New Zealand 2004). The plastic hinge is expected to form at the bottom of the column during a design level earthquake.

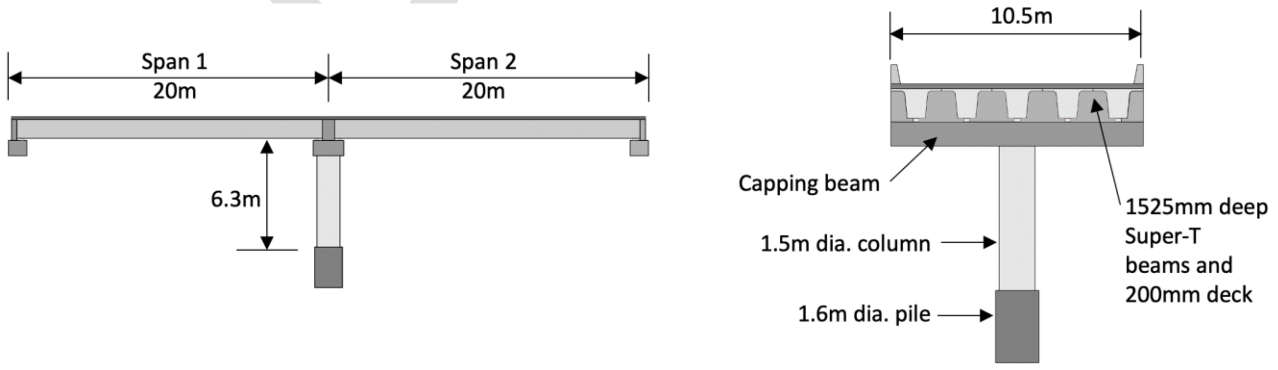


Figure 1: Prototype bridge structure: (left) longitudinal profile and (right) elevation view.

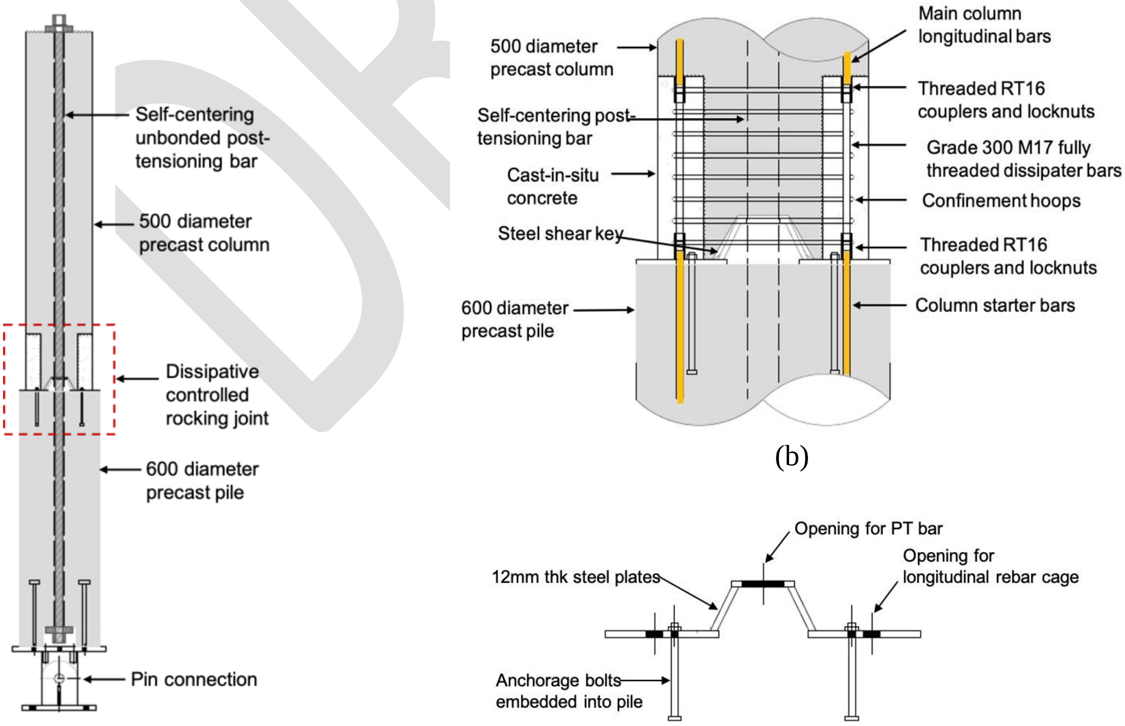
3 SPECIMEN DESIGN

The specimen in this study is a post-tensioned single cantilever pier with a replaceable DCR connection type at the base of the column, like that shown in Figure 2. The detail adopted for the DCR connection utilizes conventional construction materials and forms that will yield a similar cost as a monolithic connection. The specimen is scaled one-third of the prototype, post-tensioned for self-centring and constructed with replaceable internal dissipaters at the rocking joint. The pier consists of a 500mm diameter precast column with a design height of 2.1m and is supported on a single 600mm diameter precast pile. The pile is 1.9m tall and pinned at the base, which will allow the pile head to experience rotations. The effects of translation do not need to be considered since only relative displacements are of relevance.

The dimensions, design strength, and design displacement of the specimen were scaled from the designed prototype structure aforementioned. NZS3101:2006 (Standards New Zealand 2006) was used to design and detail the reinforcement cage in the column and pile. The PRESSS design handbook (Pampanin et al. 2010) was used to size the required fuse area and fuse length of the dissipaters and determine the size and initial post-tensioning force required for the central post-tensioning bar.

A single 50mm diameter fully threaded post-tensioning bar is used to simulative both the gravity and post-tensioning loads in the pier. The post-tensioning bar is debonded inside a 75mm diameter duct the full length of the column and pile.

An internal steel shear key (Figure 2) is provided at the rocking joint for shear and torsion restraint, as well as protection at the rocking surface. The shear key is fabricated from welded plates to form a rectangle with inclined edges at the centre of the column. An opening is provided at the top of the shear key to allow post-tensioning to pass through. The shear key assembly is welded on a 600mm diameter base plate, which sits on the pile. Bolts that restrain the shear key assembly are cast into the pile, which allows the shear key to be removed and reused. Additional holes were tapped into the shear key's base plate for the longitudinal reinforcement to pass through.



(a) (b) (c)

Figure 2: (a) Prototype bridge pier supported on a monopile with a DCR joint at the base of the column. (b) DCR connection detail. (c) Steel shear key.

The dissipative devices used in the specimen are eight grade 300 fully threaded M17 steel rods. The dissipaters are 16mm in diameter, 300mm in length and are wrapped in grease tape so to debond from the concrete. The dissipaters are joined to the main longitudinal column and pile reinforcement through threaded Ancon couplers. The use of fully threaded bars facilitates the installation and replacement of the dissipative bars because the couplers can be fully screwed back onto the threaded rods before being screwed to the connecting column and pile longitudinal reinforcement. After the dissipaters are installed, column hoops are distributed into place and fibre reinforced grout is cast at the joint. Refer to Figure 3 for the DCR joint installation sequence.

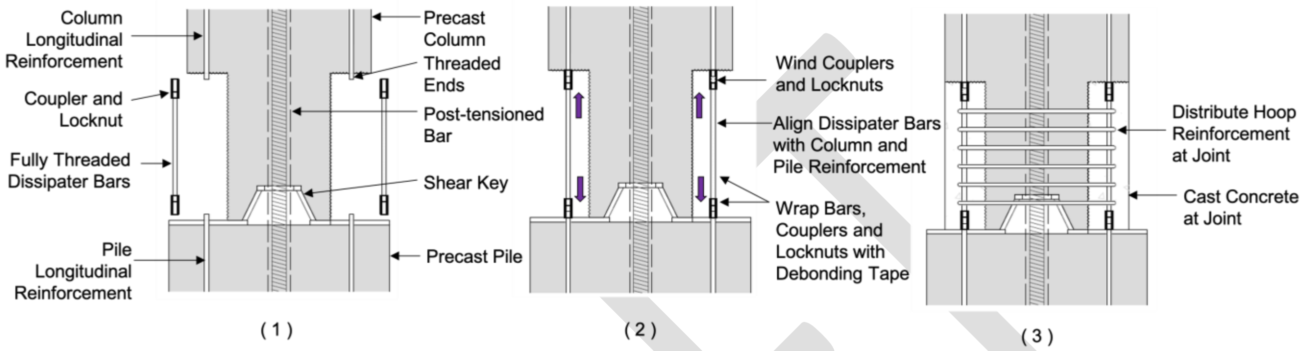


Figure 3: Installation methodology of internal dissipaters.

Tensile tests were carried out to characterise the mechanical properties of the threaded grade 300 M17 bars in tension as well as the failure mechanism between the threaded bar and coupler. Additional tensile tests were done on grade 500E 16 mm diameter deformed bars (referred to as YD16 bars herein), which are used for the column and pile longitudinal reinforcement. The results of the tensile tests are summarised in Figure 4 and Table 1. Since the yield stress for the M17 bars was not clearly represented on the graph, as it shows material yielding gradually, it was estimated using the 0.2% offset method. The ultimate tensile strength was taken as the slope of the elastic-range on the stress-strain curve.

For application in a DCR connection, the M17 bars are expected to yield before the connected YD16 bars; however, it is predicted the M17 bar will be susceptible to brittle failure under fatigue loading.

The tensile strength of the threaded ends of the YD16 bars was not tested. However, the stress-strain relationship is predicted in Figure 4, which shows an increase in tensile strength. This is ideal for application in a DCR system, where the grade 300 M17 bars are expected to be the sacrificial fuse.

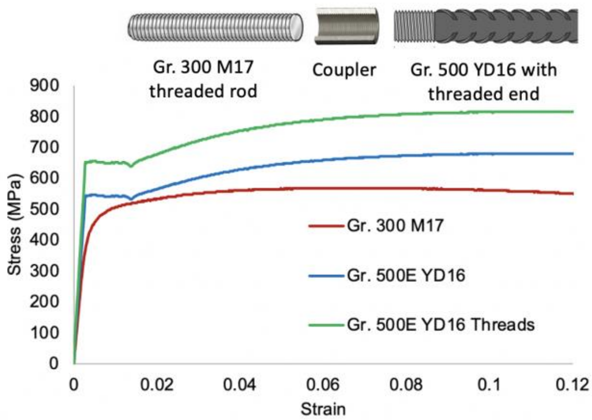


Figure 4: Stress-strain curve

Table 1: Summary of average tensile strength properties.

Bar	**Young's Modulus (GPa)**	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**
Grade 500E YD16	200.5	536	682
Grade 300 M17	148	307	563

4 TESTING ARRANGEMENT

The proposed experimental campaign is being conducted as a means of obtaining experimental evidence to validate the theoretical predictions used to model and design the structure and to validate numerical modelling for future parametric analysis.

The test setup will consist of two hydraulic rams that load the pier transversely at the column and pile. The position of the ram and magnitude of loading at the column was chosen to simulate transverse inertial loading of the specimen from the superstructure. The position of the ram and magnitude of loading at the pile was chosen to simulate the soil-pile interaction. A third ram will be attached at the mid-height of the column to prevent out-of-plane movement; however, this ram will not be loaded.

Lateral loading of the bridge pier will be cyclic, displacement controlled and quasi-static. Gravity loads on the column will be simulated using the unbonded post-tensioning, which run through a duct at the centre of the column and fixed mechanically at the bottom of the pile and top of the column. The bar will be stressed to the force level corresponding to the scaled gravity load as well as the load required for self-centring for the DCR configuration. Refer to Figure 5 for an illustration of the test setup.

The loading protocol used for testing is derived from ACI T1.1-01 (ACI Innovation Task Group 1 2001) in which three fully reversed cycles are applied at each drift ratio to the top of the column. The initial drift ratio is within the essential linear elastic response range for the module, and the subsequent drift ratios are 1.25 to 1.5 times the previous drift ratio. The loading protocol at the pile will be scaled to reflect the approximate soil pressure reaction at the pile. The lateral drifts and corresponding displacements are plotted in Figure 6. As column rocking is initiated, it is evident that the ratio between the column and pile displacement increases.

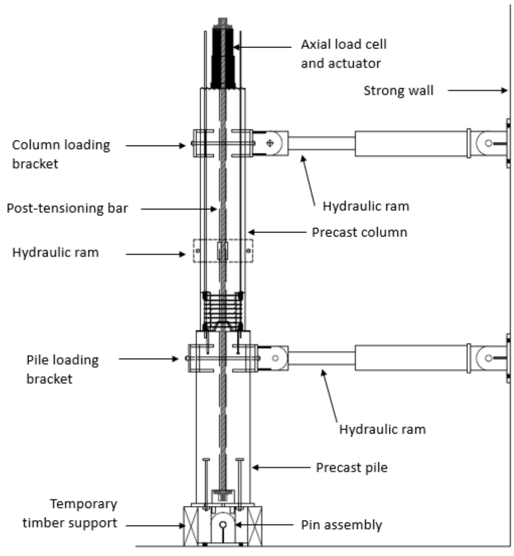


Figure 5: Test set up.

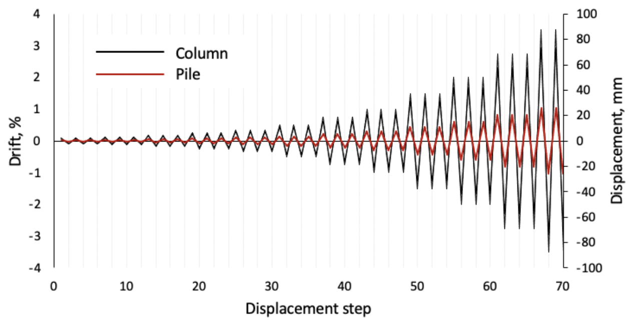


Figure 6: Loading protocol displacement history.

The precast column specimen will be constructed so that it can be utilised in two configurations. One end of the column will be detailed with a DCR connection, like that shown in Figure 2. The other end of the column will be fabricated with the longitudinal bars protruding from the joint. To emulate a monolithic connection, the column will be inverted, and the protruded bars will be grouted into cast-in drossbach tubes in the pile.

5 NUMERICAL PREDICTIONS

5.1 Numerical model

The modelling of the DCR pier is based on the use of a multi-spring macro model (Fig. 7), which is the adopted modelling scheme as recommended by Marriott (2009) as it has the greatest potential in terms of accuracy versus computational effort. Compression-only non-linear link elements in SAP2000® were used to define the rocking interface at the base of the column. Spring elements were used to define the self-centring post-tensioned bar and dissipative steel bars. Since the column and pile are designed to remain elastic in a DCR pier, they are modelled as elastic frame elements. Linear elastic soil springs were defined along the length of the pile. Soil spring stiffness was defined assuming non-liquefiable medium-dense sand. It is also assumed that soil springs remain elastic under the design earthquake load.

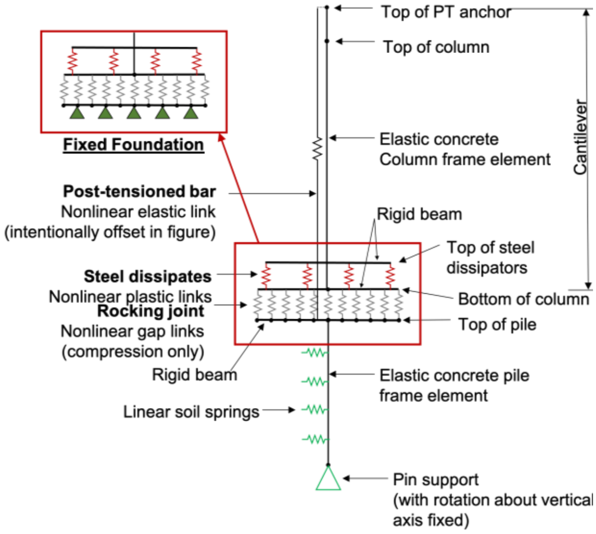


Figure 7: Multi-spring model adopted for cantilever bridge pier with DCR joint at the column-pile joint. Figure is not drawn to scale.

5.2 Numerical analysis

The results of the hysteresis response of the prototype DCR column on a monopile ('pile foundation') and fixed foundation ('fixed foundation') are plotted in Figure 8. The drift of the pile foundation is based on the relative displacement between the top of the column and pile. A symmetric force-displacement response is observed and resembles a flag-shape response that pinches at the origin indicating self-centring, as expected in a DCR system. Both columns (fixed and pile) were designed with a self-centring ratio (lambda) of 1.75; however, the hysteretic response of the pile foundation does not approach the origin as much as the fixed foundation. This indicates that the DCR column supported on a pile foundation has a smaller self-centring capacity. It is evident that the additional rotations in the monopile and increase in unbonded post-tensioning length delay the onset of the rocking mechanism in the DCR column, which results in a delayed engagement of the post-tensioning. Additionally, the flexibility of the monopile reduces the DCR pier's stiffness and results in a reduced base shear and moment.

The results of the predictive numerical analysis have raised the following questions, which will be validated through experimental work:

- How sensitive is the DCR system to the soil spring stiffness?
- What passive resistance in the pile must be achieved to initiate gap opening at the rocking joint?
- How should the moment contributions from the axial load, steel dissipaters and post-tensioning be adjusted in Equation 1 and Equation 2 to account for foundation flexibility?

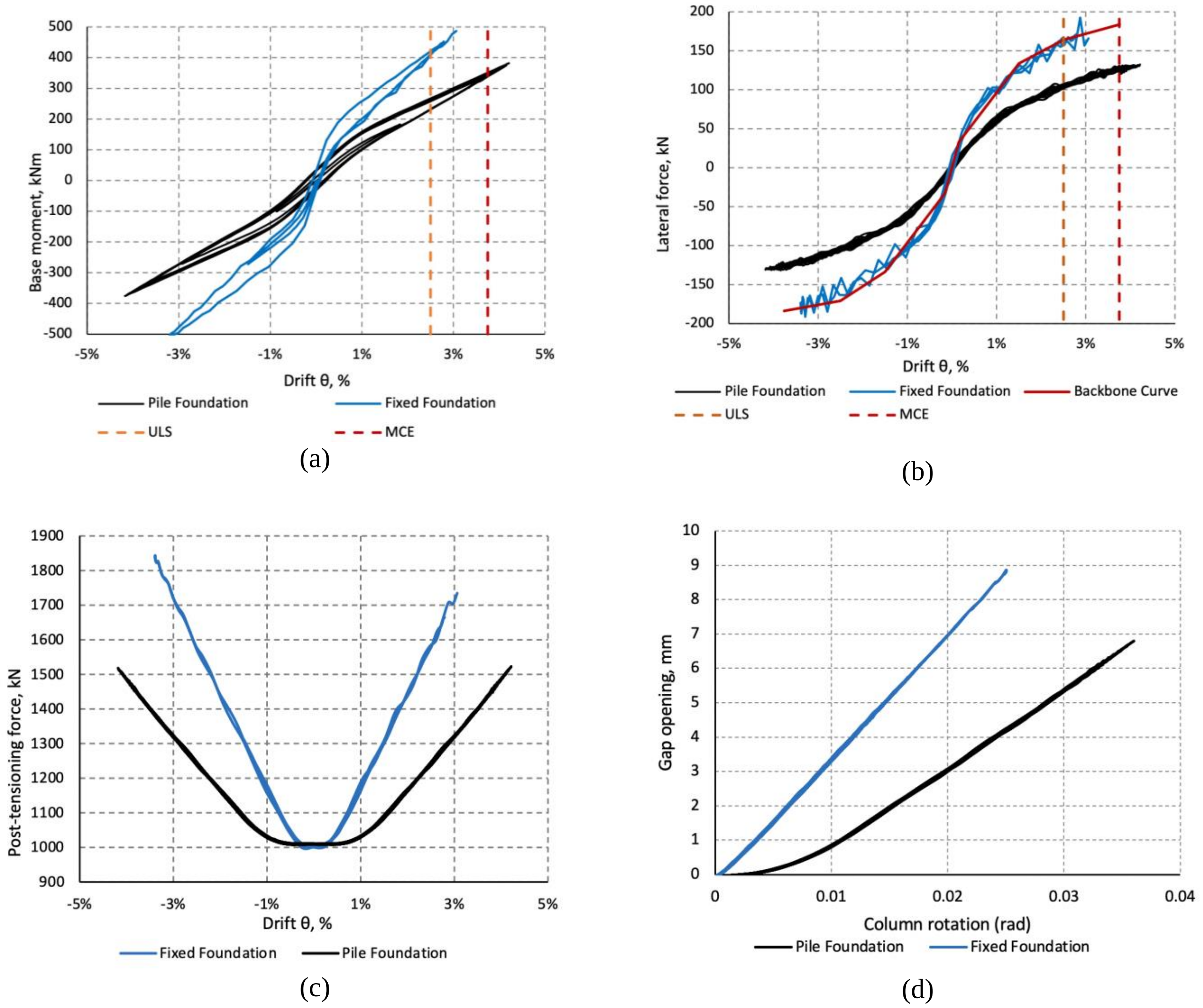


Figure 8: (a) Base moment, (b) lateral load, (c) post-tensioning and (d) gap opening response of DCR pier with fixed and pile foundation.

6 CONCLUSIONS

In this research, the use of a dissipative controlled rocking connection at the potential plastic hinge zone of a bridge column founded on a monopile is investigated. In the proposed connection, a combination of unbonded post-tensioning and internal dissipaters are used to provide self-centring and energy dissipation for the bridge substructure during an earthquake, respectively. A description of the experimental work being undertaken at the University of Canterbury on a 1/3 scale bridge pier is presented in this paper. In addition, the results of a numerical analysis are described which compares the predicted response of the DCR bridge column founded on a monopile with a one founded on a fixed base.

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