Concepts and Developments for Accelerated Bridge Construction and Dissipative Controlled Rocking

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SUMMARY:
The application of Accelerated Bridge Construction (ABC) in areas of moderate to high seismicity is a challenge that is being addressed by current research. An extensive research program at the University of Canterbury (UC) is investigating solutions to enhance the seismic behaviour of ABC structures through the use of Dissipative Controlled Rocking (DCR) systems. An outline of the research that is being undertaken is presented in this paper. This includes a description of the prototype structures that are being investigated, an overview of experimental testing that will occur as part of the program, and finally the results of numerical modelling that aims to predict the behaviour of the structures during testing.

Keywords: Bridges, Accelerated Bridge Construction, Dissipative Controlled Rocking, Dissipative Devices, Post-tensioning

1. INTRODUCTION

Bridge piers are typically designed with monolithic connections to the foundations and pier caps. In large earthquake events, damage is expected to occur through the formation of plastic hinges at these fixed connections. During recent years, alternative solutions have been developed which aim to reduce the damage sustained by bridge structures during earthquake events, increasing the safety of the users of the structure, reducing the costs associated with the repair of the structure and reducing the time taken for the structure to be returned to its functionality (Billington et al, 1999).

Accelerated Bridge Construction (ABC) systems have also been researched and developed in recent years which aim to increase the seismic performance of precast concrete bridge structures, while increasing the speed of construction and minimising life cycle costs (Marsh, 2011).

A promising system for low damage bridge structures is the use of Dissipative Controlled Rocking (DCR) (also known as hybrid) bridge systems which use rocking precast pier elements to minimise bridge damage and provide recentering capabilities to the bridge. The use of precast, post-tensioned elements in these systems means these systems have qualities that align with the concept of Accelerated Bridge Construction (Palermo, 2012).

Research is currently being undertaken into ABC and DCR at the University of Canterbury (UC) as part of the ABCD research program (Palermo, 2012). This research aims to investigate the use of Dissipative Controlled Rocking in an Accelerated Bridge Construction context. This research will look at the use of internal and external dissipative devices in self-centering pier systems to minimise bridge damage during earthquakes while minimising life cycle costs of the structure including construction, maintenance and repair costs and time delays associated with these activities.

This paper aims to provide an introduction and overview of ABC and DCR systems and the associated research that is occurring at the University of Canterbury. An outline of the research will be given. This includes a description of the prototype structures that are being investigated, an overview of experimental testing that will occur as part of the program, and finally the results of numerical modelling that aims to predict the behaviour of the structures during testing.

2. LITERATURE REVIEW

2.1. Accelerated Bridge Construction

Accelerated Bridge Construction techniques aim to reduce construction time, minimise traffic disruptions, reduce life cycle costs, and improve construction quality and safety. Many successful applications of ABC techniques have been recently realised, largely in regions of low seismic activity. Examples include Vail Pass in Colorado, Louetta Road Overpass, Pierce Elevated Freeway Bridge, Sunshine Skyway Bridge, Texas State Highway 183, and Dacio Marin III in Lake Belton (Fig. 2.1).

Figure 2.1. Lake Belton precast hammer head caps, Dacio Marin III, Texas DOT (2002)

The use of ABC in moderate to high seismic regions has been limited due to concern regarding the seismic performance of these structures. This concern is mainly caused by uncertainty in the performance of connections between precast elements. The connections must not only be easy to construct, but also robust enough to maintain their integrity under seismic loading. The need for improved seismic performance of precast structures was highlighted in earthquakes that occurred in 70s and 80s, such as Loma Prieta earthquake in 1989 (Buckle 1994).

Marsh et al. (2011) investigated the application of Accelerated Bridge Construction (ABC) connections in moderate-to-high seismic regions as part of the National Cooperative Highway Research Program (NCHRP) by the Transportation Research Board. In this report, a literature review of precast concrete connections and systems that are currently in use or being studied for use is given.
A number of different connection types, including hybrid connections (combined post-tensioning with mild reinforcement), are compared in terms of technological readiness, potential seismic performance and time savings potential.

This paper concludes that significant work is under way and more is needed to ensure that ABC connections can meet the required seismic performance, in addition to having the necessary non-seismic properties of constructability, cost effectiveness, durability and inspectability. Hybrid (or DCR) systems were identified as showing promise for use in ABC systems. Hybrid systems investigated offered better seismic performance than conventional cast in place (CIP) systems but on average had slightly worse construction risk, durability and inspectability than CIP systems. Further research into hybrid bridge systems is required to address these issues.

2.2 Rocking Systems

The Hybrid system for building structures was developed as part of the US-PRESSS (Precast Seismic Structural Systems) program co-ordinated by the University of California, San Diego (Stanton et al., 1997; Priestley et al., 1999). The Hybrid system combines unbonded post-tensioned tendons/bars with longitudinal mild steel or supplemental damping/dissipation devices. The post-tensioned tendons/bars provide self-centering capability to the system while the mild steel or dissipation devices provide additional energy dissipation. The result is a system that can undergo large deformations with little or no damage or residual displacement. The combination of self-centering and energy dissipation capabilities leads to a hysteresis behaviour typically referred to as “flag-shaped”.

Bridge piers that utilise pure rocking systems have been designed and constructed in the past. An example is the South Rangitikei Viaduct that was designed and constructed in New Zealand in 1981 (Kelly, 1972). An improved response and wider applicability can be achieved if an extension of the pure rocking behaviour of bridge piers to a hybrid or “passive controlled rocking” behaviour is implemented. Mander and Chen (1997) investigated non pure rocking response of bridge piers, while precast segmented circular piers with centrally located post tensioning tendons were studied by Hewes and Priestley (2001).

Pampanin, Calvi, and Palermo (2005) extended the concept of hybrid systems to bridge structures as a viable and efficient solution for improved seismic performance when compared with conventional monolithic systems. In bridge pier systems, the self-centering capacity is not only provided by the unbounded post-tensioned tendons/bars, but also by the effects of axial load in the pier element.

The total moment capacity of the section where rocking occurs is given by the combination of moment contributions from post-tensioning (M_{PT}), axial load (M_N) and mild steel or energy dissipators (M_S) as shown in Eqn. 2.1. The λ parameter (i.e. the ratio of self-centering contribution to energy dissipation contribution) is the fundamental parameter affecting the shape of the hysteresis loop.

$$M_{TOT} = M_{PT} + M_N + M_S \qquad \lambda = (M_{PT} + M_N) / M_S \tag{2.1}$$

In the last decade, research in the US on these systems is continuously growing as proposed in Billington (1999). Researchers at the University at Buffalo SUNY/MCEER successfully tested a half scale fully precast segmental bridge (Fig. 2.2) subjected to an earthquake of Richter magnitude 7.0. The bridge remained functional with no structural damage after going under three shake table tests in both vertical and horizontal directions (Sideris et al. 2010). The system didn’t incorporate any supplemental source of dissipation but relied on multi-rocking response and sliding friction between precast pier segments. Recently at the University of Canterbury, Marriott (2009) investigated the response of post-tensioned rocking bridge piers with internally and externally mounted mild steel bars and combined experimentally with monolithic solutions (Fig. 2.3).

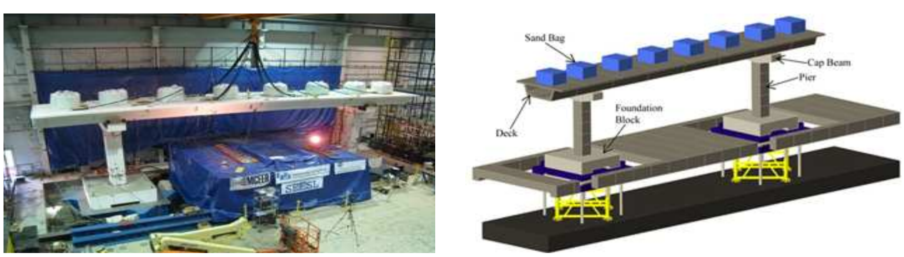


Figure 2.2. Half-scale post-tensioned segmented bridge system (Sideris et al 2010)

2.3. Methods of Energy Dissipation

Internal or external energy dissipation devices can be used in DCR systems. A typical internal dissipation system is the use of mild steel bars grouted into ducts in the precast pier element. The mild steel bars are unbounded for a certain length to prevent premature yielding of the bars under small seismic loads. The bars may also be fused by reducing the diameter of the bar over a certain length in order to concentrate inelastic deformation to a certain area of the bar. This solution is fast to construct and cost effective, but difficult to inspect and repair following an earthquake (Marsh et al., 2011). An example of internal dissipators is shown in Figure 2.3.

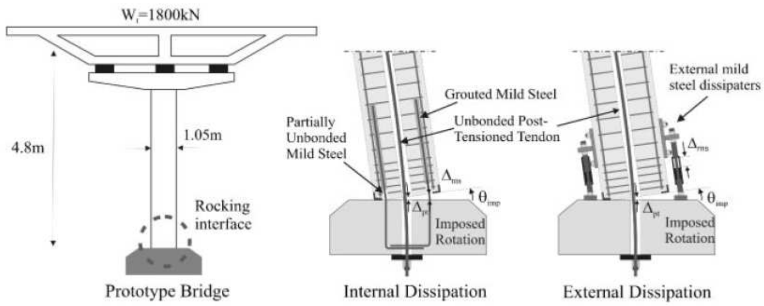
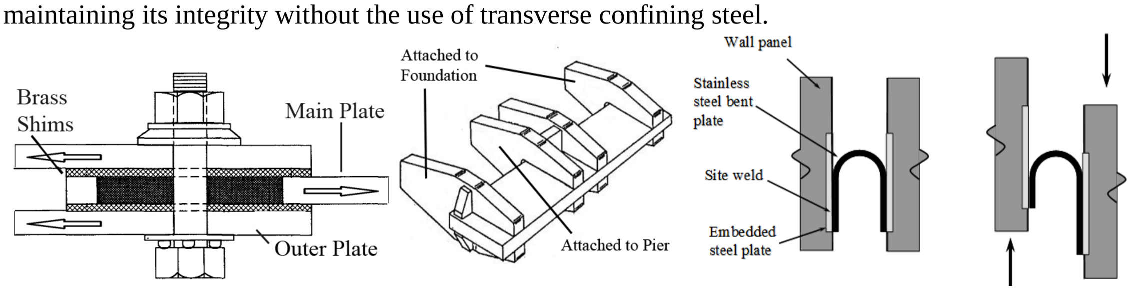


Figure 2.3. DCR concept with internal and external dissipation devices (Marriott, 2009)

External Dissipators are generally attached to the outside of the pier and fixed to the foundation. There are a wide range of devices that can be used as external dissipators. These include mild steel bars similar to Buckling Restrained Bracings (BRB) (Marriott, 2009), High Force to Volume dampers (Rodgers, 2009), viscous dampers (Palermo et al., 2005), friction dampers (Palermo et al., 2005). U-Shaped Flexural Plates have been applied to coupled rocking wall structures (Iqbal et al., 2010) but have the potential for application to bridge structures. Torsional dampers have been used in bridge structures, notably the South Rangitikei Viaduct in New Zealand (Kelly, Skinner, Hiene, 1972). External dampers have the advantage of being easily inspectable and repairable but require consideration in terms of durability since they are generally more exposed than internal dissipators. Illustrations of the friction, torsional and UFP dampers are shown in Figure 2.4.

An additional energy dissipation system investigated by Billington et al. (2004) is the use of ductile fiber-reinforced concrete in the plastic hinge zones of unbounded post-tensioned segmental precast columns. The fiber-reinforced concrete is able to dissipate energy during cyclic behaviour while maintaining its integrity without the use of transverse confining steel.



a) Bolt-slotted connection (friction) b) Torsional beam c) UFP

Figure 2.4. Examples of external dissipators

2.4. Numerical Modelling of DCR systems

Numerical modelling methods for hybrid pier systems are discussed by Palermo et al. (2005). The hybrid system can be modelled using a lumped plasticity model in which non-linear rotational springs are used at the critical interface sections to model the opening and closing of the gap during rocking motion (Fig. 2.5). The flag shaped hysteresis loop is obtained through the use of two rotational springs in parallel. The first spring is assigned a non-linear elastic rule to represent the self-centering contribution while the second spring is assigned a hysteresis rule representing the energy dissipation contribution of the system.

An alternative approach is to use a multi-spring model (Fig. 2.5). This approach uses a multi-spring element to represent the contact of the base of the pier with the foundation, (Spieth et al., 2004). Non-linear inelastic springs are used to represent the energy dissipation devices and non-linear springs are used to represent the post-tensioning steel. This modelling approach is more complex than the lumped plasticity model, but able to capture more detailed information about the behaviour of the system such as the location of the neutral axis in the concrete, and the elongation of post tensioning steel. The model can be used to analyse the behaviour of the structure when subjected to vertical acceleration.

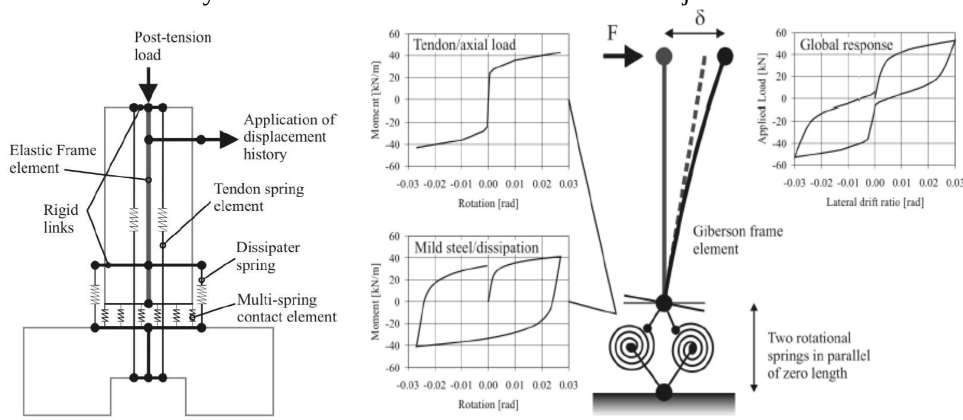


Figure 2.5. Multi-spring model (left); lumped plasticity model (right), (Marriot, 2009)

3. OVERVIEW OF CURRENT RESEARCH INTO DCR AND ABC AT THE UNIVERSITY OF CANTERBURY

Advanced Bridge Construction and Design (ABCD) is a research program funded by the Ministry of Science – Natural Hazard Platform and co-ordinated by the University of Canterbury (Palermo, 2012). It is aimed at being the starting point for the development of the next generation of bridge systems in New Zealand. As part of this program, research is currently being undertaken in the use of Dissipative Controlled Rocking systems in an Accelerated Bridge Construction context. This research will look at the use of internal and external dissipative devices in self-centering pier systems to minimise bridge damage during earthquakes while minimising life cycle costs of the structure including construction, maintenance and repair costs and time delays associated with these activities.

Two research projects are currently investigating these concepts at UC. The first is investigating the use of innovative external dissipative devices such as friction, torsional and UFP dampers in DCR systems. The second is looking at using internal dissipative devices such as mild steel bars with a focus on ease of construction, inspection, maintenance, and post earthquake repair of the system. The research work also involves a comprehensive life cycle loss assessment and investigation of the applicability of the systems to New Zealand bridge structures.

Based on the New Zealand market trend, damage resistant bridge construction should mainly target low-medium span bridges (30m maximum span) and then expand alternative construction systems for medium-long span bridges. An objective of the research program is to identify appropriate substructure systems for a variety of bridge requirements such as span length, construction limits (e.g. maximum cost-effective crane limit) and functional requirements while minimising construction times in accordance with the objectives of ABC. The substructure classification will include specification of the geometry and typology of the bridge piers for each span category as well as the type and location of dissipative devices. This information will aid in the implementation and design of DCR bridge structures in New Zealand and overseas (Palermo, 2012).

3.1. Bridge Prototypes

Two bridge prototypes were developed for investigation in this research project. These prototypes are based on typical New Zealand bridges. The prototypes were designed for small spans of 14m and 24m (medium span) in accordance with the objectives of the research program. Prototype A is a single pier structure and Prototype B is a multi pier structure as shown in Figure 3.1. The deck systems for Prototypes A and B consist of Dual Hollow Core sections and I Beam 1600 sections, respectively (NZTA, 2008). Prototypes A and B have superstructure self weights of 1000kN and 4000kN per pier, respectively. Prototype A is designed to have energy dissipation devices located at the base of the pier while Prototype B will have devices at both the Pier-Foundation and Pier-Pier Cap interfaces.

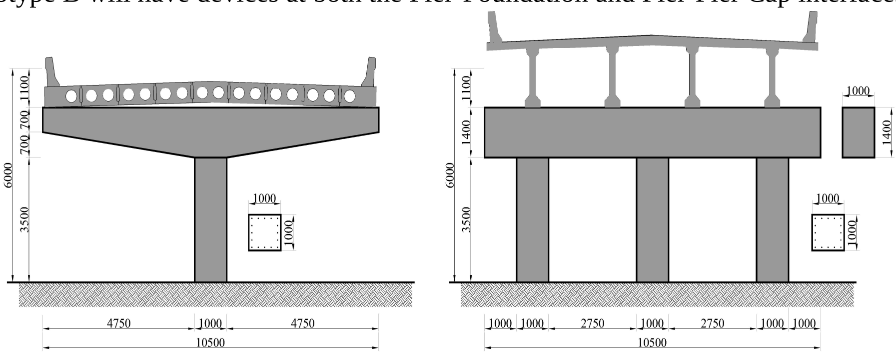


Figure 3.1. Prototype A (single pier support) (left); Prototype B (multi pier support) (right)

3.2. Experimental Testing

The experimental testing will involve uni-directional, quasi-static loading of half scale single and multi pier test specimens. The test specimens are based on the bridge geometries of the prototypes shown above (Fig. 3.1). Figure 3.2 shows the experimental test setup for the single and multi pier prototypes. The section properties for all piers are the same. Testing is expected to commence in August, 2012.

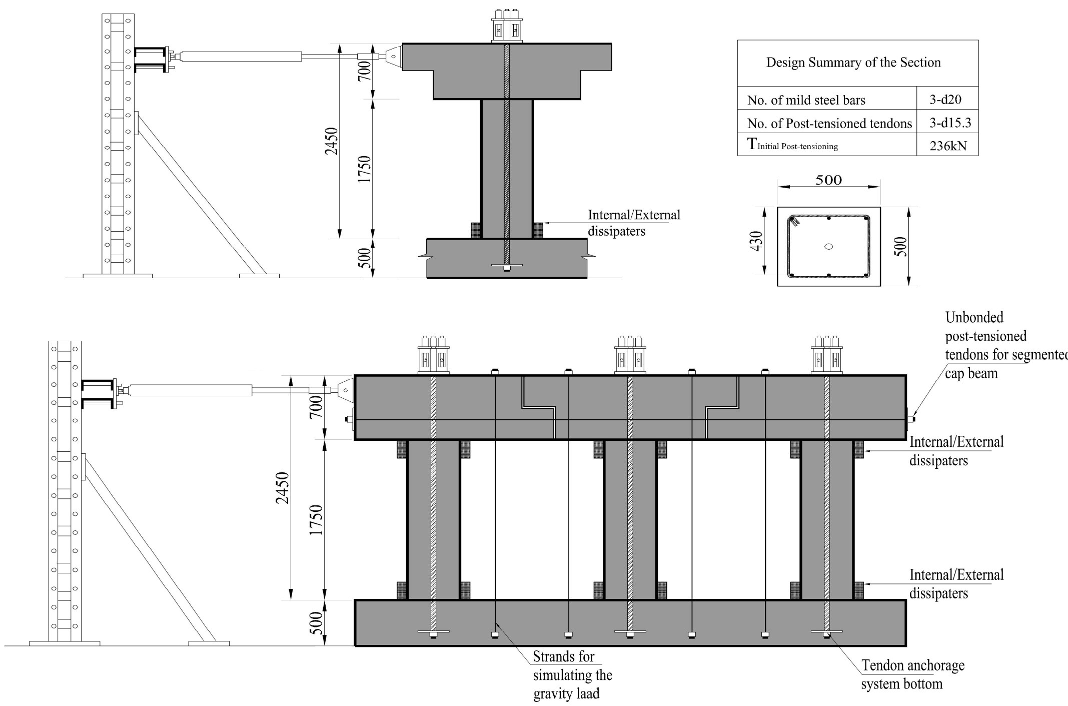


Figure 3.2. Experimental test setup, single pier (top); multi pier (bottom)

The design of the specimens was based on the design of an equivalent monolithic pier solution using NZS 1170.5 with a return period of 500 years. The pier was designed for a shallow soil type (Type C) with a seismic zone factor of 0.33(Christchurch area) and a peak ground acceleration of 0.66g. A design drift of 2.73% corresponding to a displacement of 82mm was adopted. Based on these criteria, a moment demand of 317 kNm was identified. A moment-curvature plot of the monolithic section is shown in Figure 3.3 (left).

The DCR section was design using the PRESSS Design Handbook (2010) guidelines in order to match the ductility and moment capacity of the monolithic solution. A λ value of 1.5 was adopted for the design in order to achieve a good level of energy dissipation and negligible residual moment at the target drift level. The design was repeated for λ values of 0.9 and 2.1 to provide comparison (Table 3.2). A summary of material properties are given in Table 3.1. A moment-rotation diagram for the section is shown in Figure 3.3 (right).

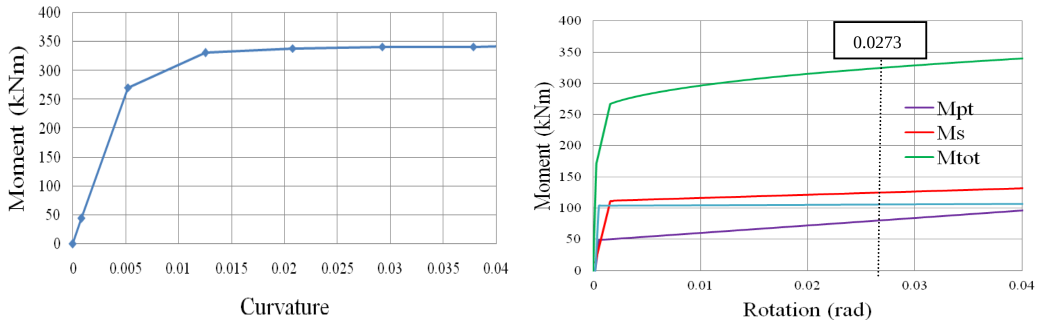


Figure 3.3. Moment-curvature, monolithic section (left); equivalent DCR section (right)

Table 3.1. Summary of Material Properties

Concrete		Post-tensioned steel (Macalloy bars)				Mild steel		
f'_c (MPa)	f'_{cc}/f_c	Type	E_{pt} (GPa)	f_{pty} (MPa)	f_{ptu} (MPa)	E_s (GPa)	f_y (MPa)	r
40	1.25	S-1030	185	835	1030	200	300	0.8%

Table 3.2. Summary of design results for the different values of λ at the design drift of 2.73%

λ	$T_{PT\ initial}$ (kN)	A_{PT} (mm^2)	A_{MS} (mm^2)	No. of mild steel bars	$\phi M_{Nominal}$ (kNm)	M_{PT} (kNm)	M_S (kNm)	M_N (kNm)
λ = 1.5	236	808	943	3-d20	324	81	125	106
λ = 0.9	51.8	808	1257	4-d20	339	43	168	107
λ = 2.1	403	1078	804	4-d16	325	126	108	106

Note: The unbonded lengths of post-tensioned and mild steel bars are 2800mm and 75mm, respectively.

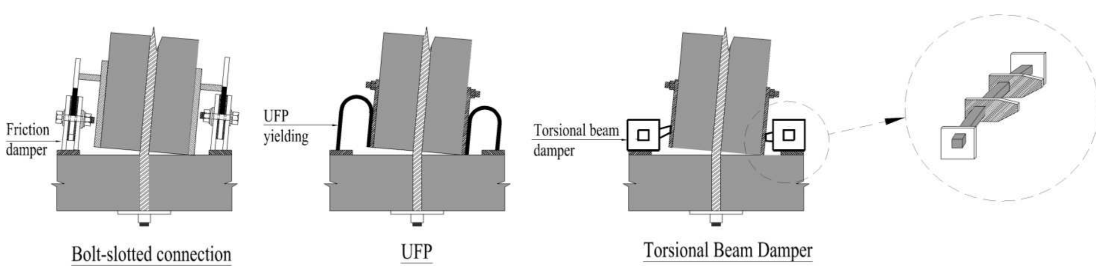


Figure 3.4. Activation mechanisms for each dissipator at the rocking interface

The devices that are to be investigated in the experimental testing are the torsional, friction and UFP dampers. Diagrams of the location and mechanism of activation of these devices is given in Figure 3.4. Internal mild steel bars will also be investigated experimentally in the single pier system. These bars will be fused and connected to the system using replaceable bar couplers allowing the yielded section of bar to be replaced following an earthquake. This system may also incorporate the use of ductile fiber-reinforced concrete or anti-buckling tubes to provide confinement to the mild steel bars. Figure 3.5 shows the construction method and activation mechanism of the internal bar system. A similar methodology would be followed for the repair of such system. The method of confinement of the bars is not shown in Figure 3.5 for clarity.

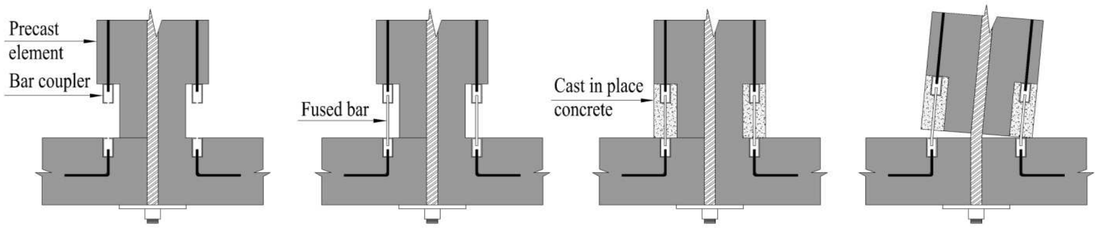


Figure 3.5. Construction sequence and activation mechanism of the internal bar system

3.3. Numerical Prediction of Experimental Behaviour

Numerical models were developed using Ruaumoko2D (Carr, 2004) to predict the behaviour of the test specimens during testing. The results of the experiments will be used to validate and refine the models for use in more general applications such as application to a case study bridge or prediction of the behaviour of other DCR systems.

3.3.1. Description of Models

Four models were developed for the prediction of experimental outcomes. These models were a single pier model and a multi spring model with the use of two different hysteresis rules for each model. The models were based on the centreline dimensions of the half scale experimental test specimen.
The pier elements were expected to remain elastic during testing and so were modelled as elastic beam elements. The pier cap and deck elements were assumed to be very stiff in comparison to the piers and so were modelled as rigid members.

A lumped plasticity model was used with two rotational springs representing the energy dissipation and self-centering components of the system. The lumped plasticity model was chosen for simplicity since vertical acceleration is not being considered during experimental testing. A multi-spring model will be developed following the experimental testing for further analytical investigation.

A bi-linear elastic hysteresis rule was used to represent the self-centering component of the system. Two energy dissipation systems were investigated using the model. A Ramberg-Osgood inelastic hysteresis rule (Osgood, 1949) was used to represent systems in which yielding is the primary form of energy dissipation (such as the mild steel bar, torsional damper and UFP systems). An elasto-plastic hysteresis rule with a very high initial stiffness was used to represent friction based energy dissipation devices. The initial and post-yield stiffnesses and yield capacity of the springs was determined based on the output of the Hybrid design program that was developed by Palermo, Pampanin, Marriot (344) as part of the PRESSS Design Handbook.

The models were subjected to a cyclic displacement series in which the drift of the structure is increased gradually to a drift of 4% in 1% increments to show the behaviour of the structure at a number of drift levels corresponding to the displacement demand at different levels of earthquake excitation.

3.3.2. Results of Analysis

Figures 3.6 and 3.7 show the moment-rotation hysteresis loops obtained from the single pier model using Yielding and Friction based energy dissipation devices. It can be seen that the design moment demand of 317 kNm is obtained at approximately the design drift of 2.7%. These diagrams illustrate the contribution of self-centering and energy dissipation to the overall shape of the hysteresis loop.
Figures 3.8 and 3.9 show the moment-rotation hysteresis loops obtained from the multi pier models using the two types of hysteresis devices, the vertical axis represents total moment. The piers in the

multi pier model underwent a larger level of rotation for a given drift level when compared to the single pier model resulting in a larger moment for a given drift than the single pier model. This is due to the fact that the pier cap and deck cannot rotate in the multi-pier system meaning the relative lateral displacement in the system occurs only in the pier elements.

Figure 3.10 shows a comparison of the moment-rotation hysteresis loops of the single pier model with yielding based dissipators designed using three different values of λ as discussed previously. A single hysteresis loop is shown for each value of λ corresponding to a pier drift of 3%. The figure shows that the pier with a λ =0.9 exhibits a high level of energy dissipation as seen by the large area of the hysteresis loop but also exhibits significant residual drift of about 2%. The pier with a λ = 2.1 exhibits very good self-centering behaviour but a reduced level of energy dissipation. A λ = 1.5 as used in the design of the pier gives a good balance between energy dissipation and self-centering with no residual displacement.

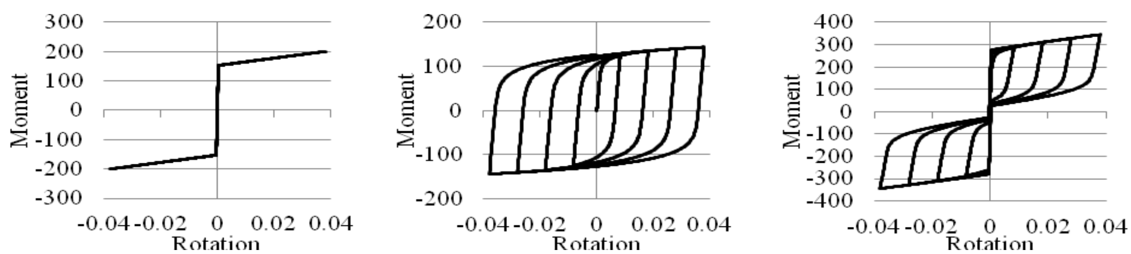


Figure 3.6. Single pier with yielding dissipators; self-centering (left); dissipator (middle); total hysteresis (right)

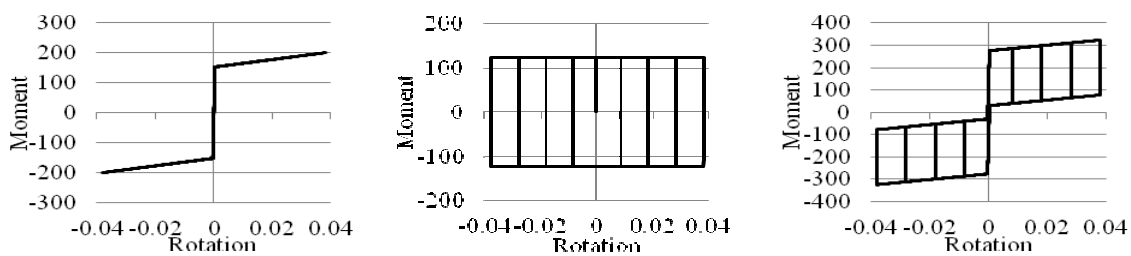


Figure 3.7. Single pier with friction dissipators; self-centering (left); dissipator (middle); total hysteresis (right)

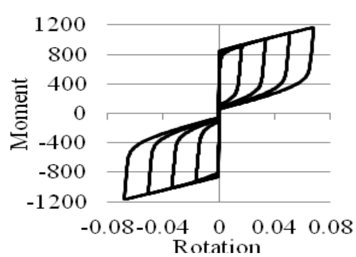


Figure 3.8. Multi pier model with yielding dissipators

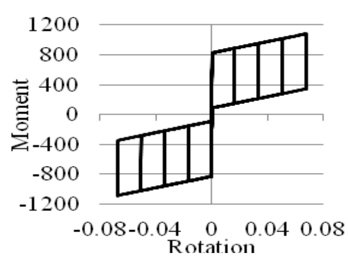


Figure 3.9. Multi pier model with friction dissipators

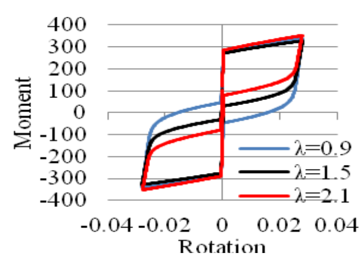


Figure 3.10. Comparison of different values of λ

4. CONCLUSION

This paper has provided an introduction and overview of ABC and DCR systems and methods of energy dissipation. Research that is currently being undertaken at the University of Canterbury has been discussed including description of the prototype structures, energy dissipation devices and experimental test setup. Numerical modelling showed that the DCR structures behaved as anticipated with no residual drift while achieving the target moment capacity. The differences in behaviour between friction and yielding based devices were also illustrated. Overall, the application of DCR concepts in an ABC context has shown promise for the design and construction of low damage bridge structures. Further research is required into the development of low cost, high performance dissipation systems and methods of minimising life cycle costs including construction, maintenance and repair costs and time delays associated with these activities.

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