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CONTROLLED ROCKING, DISSIPATIVE CONTROLLED ROCKING AND MULTI-HIERARCHICAL ACTIVATION: NUMERICAL ANALYSIS AND EXPERIMENTAL TESTING

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Abstract. *The earliest modern work on rocking focussed on pure rocking structures. That is, structures that are able to uplift and where the tendency to self-centre is purely provided by self-weight. Since then, free rocking has evolved into a multitude of new design strategies due to the addition of elements such as post-tensioning (controlled rocking) or having multiple interfaces in a single element where uplift can occur (segmental rocking). Although these new design strategies evolved from free rocking, there is little clarity in current literature about the differences in dynamic behaviour which is important in seismic design. A specific example of this, is that, the PRESSS system also known as DCR (dissipative controlled rocking: the combination of post-tensioning, dissipative devices and free rocking) and free rocking are usually mistaken to reduce damage to a structure through the same mechanism of gap opening and hence that the dynamic behaviours are the same. This paper looks to give a short modern history of the evolution the rocking structure and argue that design strategies based on rocking may not have the same dynamic response as pure rocking through comparison of the results of non-linear response history analyses of a SDOF structure utilizing pure rocking, controlled rocking, and dissipative controlled rocking strategies. Following on the theme of the evolution of the rocking structure, at the University of Canterbury, unidirectional, quasi-static, cyclic, tests were conducted on a 1/3 scale two span bridge utilising a single cantilever controlled rocking pier which was designed to operate in three different configurations: without dissipative devices, with one set of hysteretic dissipative devices, and with two sets of hysteretic dissipative devices. The very last configuration is a new design strategy proposed by the authors as "hierarchical DCR" where there are two sets of dissipative devices across the rocking interface and where one set is activated at a later pier displacement to the other. The concept behind this idea is to increase structural robustness of the DCR system as a means of collapse prevention due to subsequent or unusually rare events such as the maximum credible earthquake. This paper will also present the results of this testing.*

1 INTRODUCTION

Past major earthquakes have shown significant drawbacks related to bridges using conventionally designed RC piers. These include: residual drift, which affects post-earthquake functionality and speed of reinstatement; physical damage from non-linear material behaviour, which not only affects post-earthquake functionality and the speed of reinstatement, but also, the remaining life of the bridge; and major indirect losses, from down time of the bridge caused by the aforementioned consequences of allowing non-linear material behaviour within the pier member. An alternative to conventional RC design, whose aim is to minimise and or eliminate the aforementioned performance issues related to member plastic hinging, are a family of design strategies based on rocking. These include free rocking, controlled rocking and dissipative controlled rocking (DCR) also known as hybrid PRESSS [1] and are all shown in Figure 1. Controlled rocking is free rocking with the addition of unbonded post-tensioning (Fig. 1b). Instead of wholly relying on self-weight to provide self-centering, where the tendency to self-centre reduces with displacement (Fig. 1a), controlled rocking also relies upon both the initial post-tensioning force and elongation of the tendons to provide self-centering. The name of this design strategy was coined from the fact that there is greater control over the tendency to self-centre due to the adjustable nature of the post-tensioning. This combination results in a bilinear elastic force-displacement plot with positive stiffness after uplift initiates (Fig. 1b).

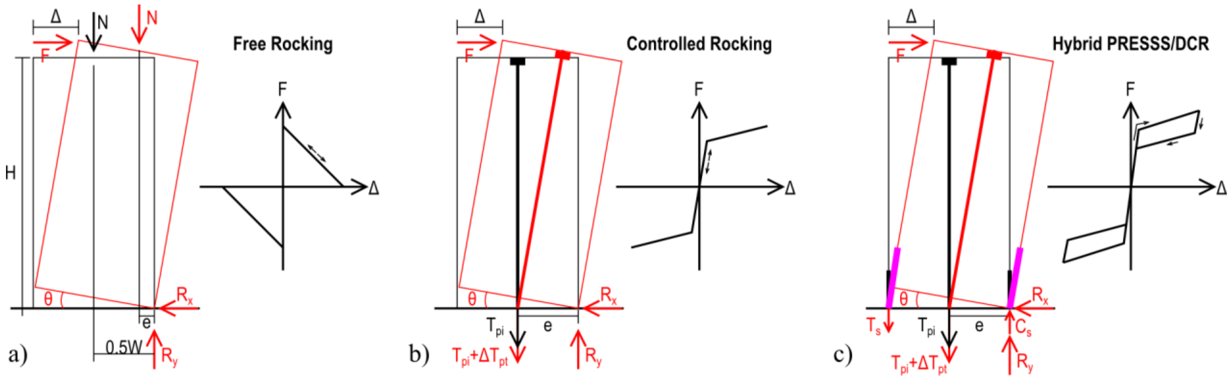

Figure 1: Free body diagrams and force displacement plots for a rigid block on rigid foundation utilising: **a)** free rocking; **b)** controlled rocking; and **c)** hybrid PRESSS/DCR.

The further addition of dissipative devices (usually metal hysteretic) across the rocking interface (internal or external to the member) results in the design strategy of dissipative controlled rocking (Fig. 1c). The dissipative devices add to the moment capacity and or damping of the structure resulting in a flag shaped hysteresis loop (Fig. 1c).

This contribution focusses on rocking bridge structures and has three main aims. The first is to elaborate more on the variety and development of rocking solutions in order to show the evolution of the rocking structure and the reasoning associated with it. The second is to argue that not all design strategies based on rocking exhibit the same dynamic behaviour which is a common misconception. And the third is to present the concepts for a new design strategy called Multi-Performance DCR (MDCR) developed by the authors, in addition to results from experimental testing as proof of concept.

2 LITERATURE REVIEW: EVOLUTION OF ROCKING APPLIED TO BRIDGES

Two main streams of design strategies for bridges based on rocking have evolved in parallel, namely, uplifting and jointed structures. Major interest in the use of rocking as a seismic design strategy stems from Housner [2] where he observed that water towers which were able to rock on their foundations during the May 1960 Chilean Earthquake survived relatively undamaged compared to their monolithic counterparts.

Uplifting structures encompass two types of foundation rocking: uplifting shallow foundation (Fig. 2a, right) and pile cap rocking on supporting piles (Fig. 2a, left); and stepping (Fig. 2b). These types of structures are the closest to classical free rocking structures due to their reliance on self-weight for self-centering. Of the uplifting structures, the rocking shallow foundation [3–6] and stepping structures were the first to be investigated [7,8]. While the rocking pile foundation was investigated later on [9,10] but more as a solution to geotechnical constraints imposed by poor soil conditions.

Uplifting is a form of seismic isolation because seismic demands are reduced to the supported structure through period elongation [2,3,6,11–14]. However, the amount of period elongation is dependent on the amplitude of rocking displacement [2,6]. In addition to this, soil–structure interaction effects for foundation rocking structures also contribute to reducing seismic demands [15].

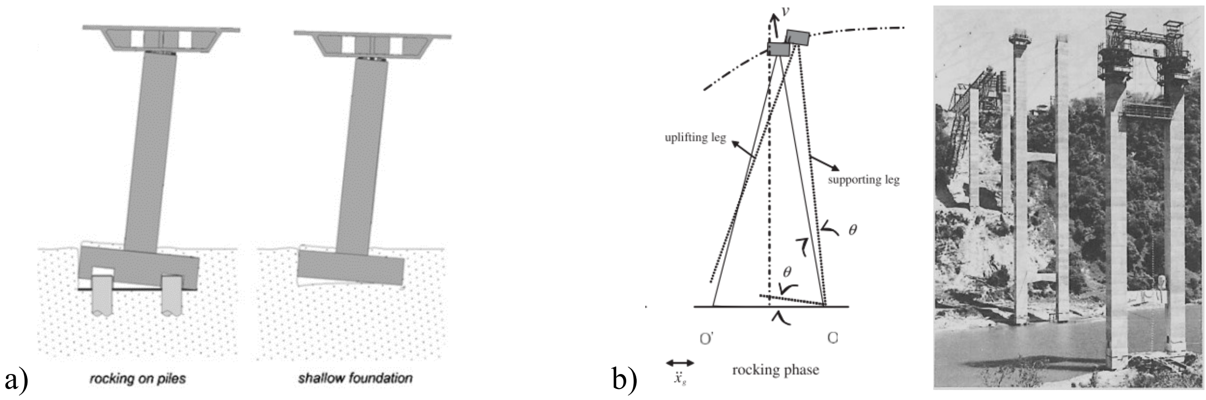

Figure 2: a) Examples of foundation rocking structures [9]. Left, rocking on piles and right, rocking shallow foundation. **b)** Examples of stepping structures. Left, displaced structure showing mode of movement [11]. Right, Rangitikei viaduct NZ a bridge using stepping piers [16].

The other stream of design strategies based on rocking are jointed structures, where, locations of plastic hinges are replaced with rocking joints as a means of reducing seismically induced damage. This type of design strategy was initially developed for precast concrete buildings under the US PRESSS program where both a crude controlled rocking solution [17] and the present day hybrid PRESSS/ dissipative controlled rocking (DCR) [1] solution were developed. The first application of a jointed rocking structure to bridges was proposed by [18]. Mander and Cheng [18] envisioned both free and controlled rocking bridge piers (cantilever and pier bent) with steel armouring at the rocking interfaces to prevent damage to the edges of the rocking sections (Fig. 3a).

The proposed application of the hybrid PRESSS system to bridges (Fig. 3b) was only made some years later by Palermo et al. [19] as a means of achieving improved seismic performance compared to monolithic construction. Initially the PRESSS system in bridges used internal dissipative devices in the form of debonded mild steel reinforcement [20] (Fig. 3c). This then changed into the use of external dissipative devices [21] to facilitate easy observation and replacement (Fig 4a). Then Kam et al. [22] proposed improvement of the response of the DCR connection to both near and far field earthquakes through combining velocity (fluid viscous dampers) and displacement dependent dissipators (metal hysteretic) to produce an advanced flag shape hysteresis curve (Figs. 4b & c).

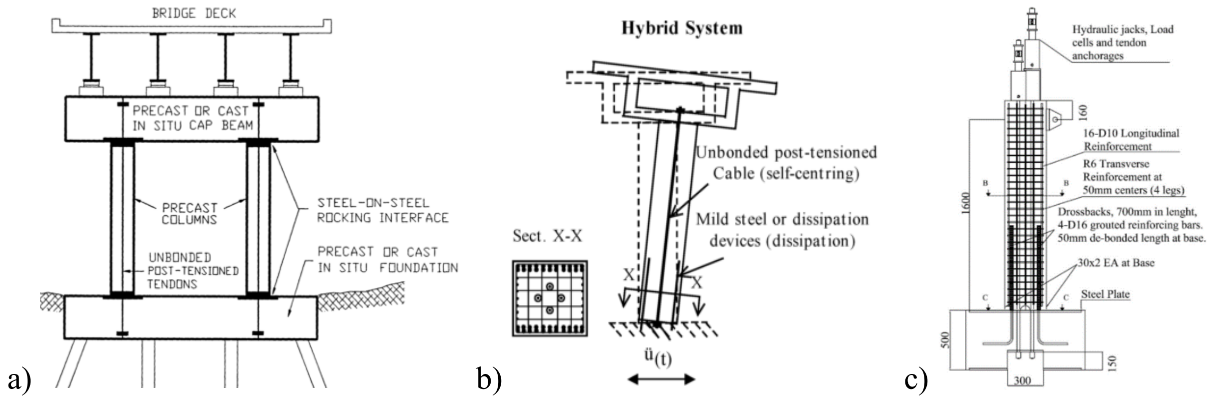

Figure 3: a) Controlled rocking pier bent [18]. **b)** Proposed application of PRESSS to bridges showing possible design [19]. **c)** Design schematic of a cantilever PRESSS column used in experimental testing [20].

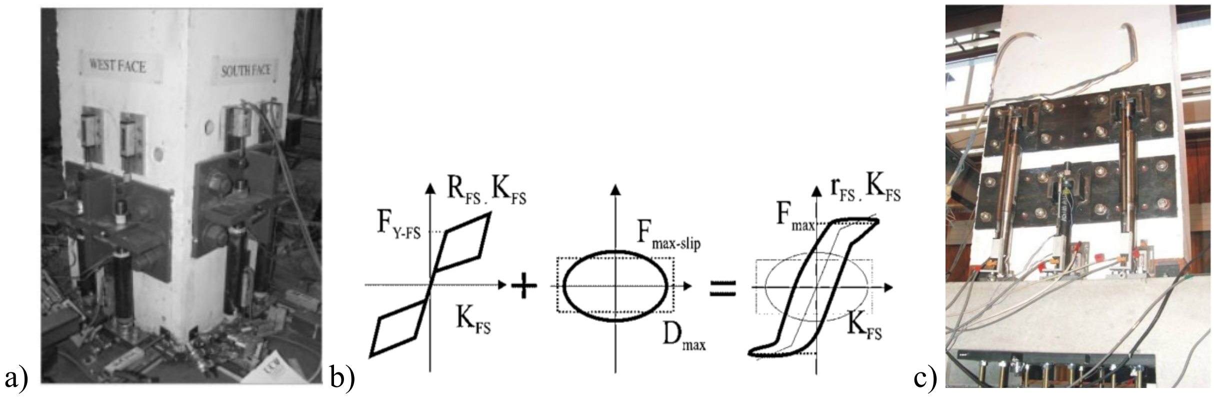

Figure 4: a) PRESSS/DCR column using external dissipators [21]. **b)** Advanced flag shape (AFS) hysteresis [22]. **c)** Experimental testing of the AFS concept showing the combination of viscous and metal hysteretic devices to achieve the advanced flag shape [23].

Most of the previously described developments on DCR applied to bridges were made at the University of Canterbury, New Zealand. Outside this institution, research has been more focussed on applying low damage technologies to accelerated bridge construction (especially in the US) and the application of DCR to tall segmental concrete bridge piers (Fig. 5) as a means of increasing the dissipative capacity of the pier [24–26].

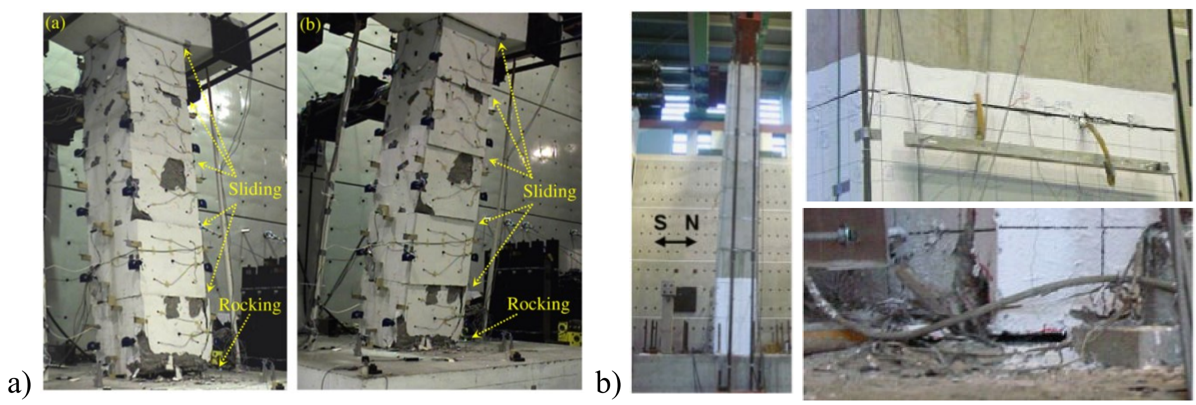

Figure 5: a) Segmental pier combining controlled rocking with frictional means of energy dissipation from sliding [27]. **b)** Segmental pier tested by Wang [24] using internal debonded reinforcement for energy dissipation.

Today, the authors of this paper see the DCR solution evolve into "Multi-Performance Dissipative Controlled Rocking" (MDCR) [28]. Further explanation of this concept is given later in this paper.

3 DISCUSSION: WHY FREE ROCKING AND HYBRID PRESSS ROCKING DO NOT WORK IN THE SAME WAY

There is a common misconception that Dissipative Controlled Rocking (DCR) and free rocking have similar dynamic behaviours and that their treatment in design can be considered similar. This misconception arises from the assumption that the addition of post tensioning, and dissipative devices to a free rocking structure does not change the dynamic behaviour of the free rocking structure. However, other than the obvious similarities, these two design strategies exhibit very different dynamic behaviours which is an extremely important consideration for design.

Consider for example the free vibration (Fig.7) and ground motion response (Fig. 8) of the HBD5/PT2 pier specimen (Fig. 6, right) taken from Marriott [29] and modelled in OpenSees using a simple 2 spring SDOF (Fig. 6, left) in three different configurations: free rocking of the pier, post-tensioning only (controlled rocking), and post-tensioning with metal hysteretic dissipators (DCR).

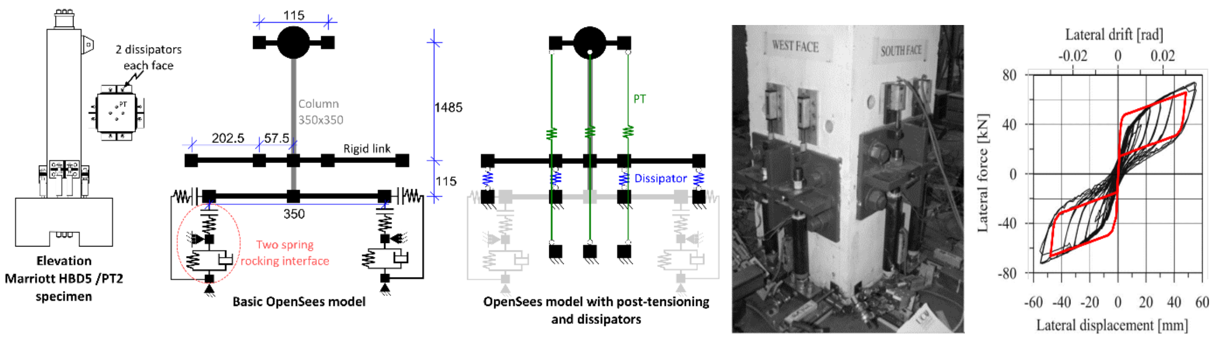

Figure 6: Left, OpenSees models of test specimens HBD5/PT2 taken from [29]. Middle, photo of HBD5 specimen from [29] with external buckling restrained fuse dissipators, and concrete to steel rocking interface. Right, comparison of the model and experimental flag shaped hysteresis curves.

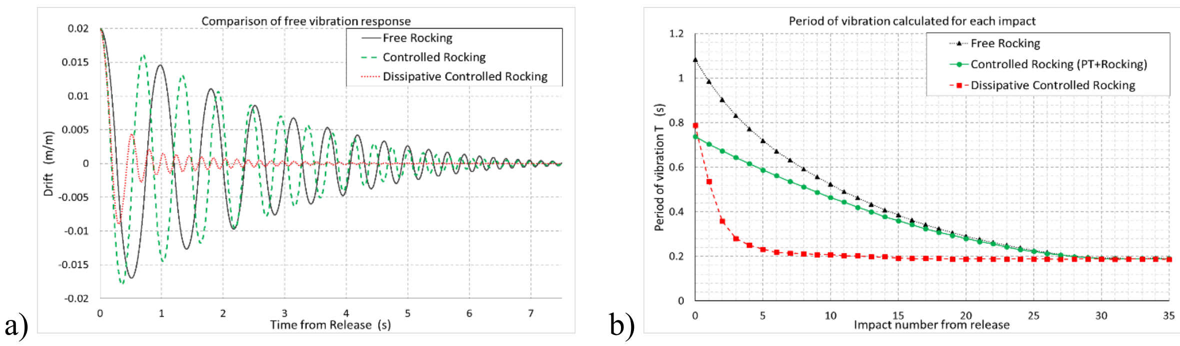

Figure 7: a) Free vibration response since release from 2% drift. **b)** Variation in the period of vibration as a function of the number of rocking impacts since release.

It can be seen in Figure 7a that the addition of post-tensioning immediately reduces the initial period of vibration due to the additional restoring force provided by tendon elongation. Figure 7b shows that the addition of post-tensioning has little effect on the damping of the system which is expected due to it behaving in the elastic range. This means that controlled rocking mainly relies on contact damping for energy dissipation. Finally, with the further addition of metal hysteretic dissipators, the pier will tend to behave as a fixed base structure. This is due to the continuous supplemental damping provided by the dissipators quickly reducing the amplitude of vibration so that the displacements of the dissipators are below yield and the pier no longer rocks due to the high elastic stiffness of the dissipators (Fig's. 7a &b).

Inspecting the response history (Fig. 8) of the same pier, in the same three configurations, subject to seven different ground motions (Fig. 8, top left) scaled to have the same PGA (0.365g) as the design spectrum, a similar trend in behaviour is apparent. The displacement response of the different configurations (Fig. 8) clearly shows the period elongation effects of free rocking which are not observed for the controlled rocking (post-tensioning plus rocking) or DCR configurations. Hence, controlled rocking and DCR do not display seismic isolation properties and should therefore be treated more like fixed base structures in terms of seismic design.

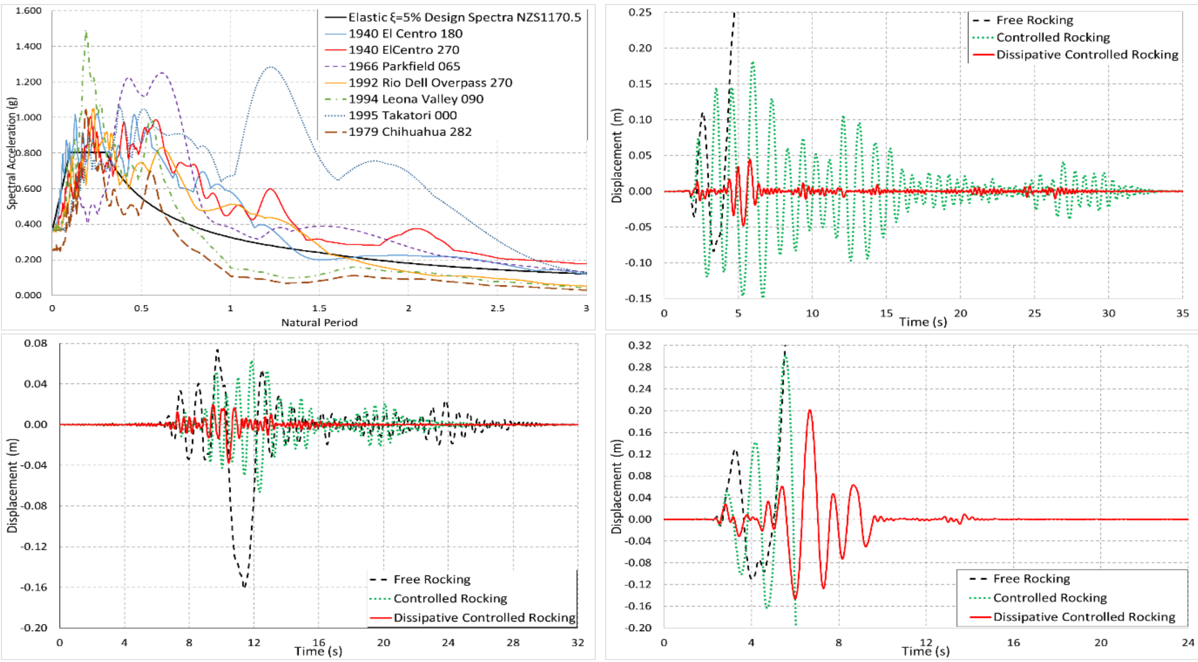

Figure 8: Top left, 5% damped elastic acceleration spectra used for nonlinear response history analysis. Top right, bottom left, and bottom right, displacement response of the three pier configurations subject to the 1940 ElCentro 180, 1994 Leona Valley 090, and 1995 Takatori 000 records respectively. The 1994 Leona Valley 090 record was the only record which did not result in overturning of the free rocking configuration.

4 IMPROVING THE STRUCTURAL REDUNDANCY OF DCR: MULTI-PERFORMANCE DISSIPATIVE CONTROLLED ROCKING (MDCR)

In the context of cantilever bridge piers, the plastic hinging mechanism is of column sway, where, collapse prevention is dependent upon the ductility capacity of the plastic hinge at the base. In DCR cantilever bridge piers the rotational ductility against overturning is dependent upon the dissipators and post-tensioning. Currently, all the dissipators are designed to activate at a set level of earthquake loading and all have the same ultimate capacities. Hence, currently the robustness of DCR is purely provided by multiplicity in the number of dissipators and post-tensioning. Once rupture of a few dissipators and yielding of the post-tensioning occurs, the pier would lose significant stiffness and would be prone to P-Δ effects which would eventuate in collapse of the structure (Fig. 9a).

To mitigate this issue, research is being conducted by the authors on a new design strategy based on dissipative controlled rocking called "Multi-Performance Dissipative Controlled

Rocking" (MDCR). The concept is to delay the onset of collapse through discretizing the capacity of the structure provided by dissipative devices and or mechanisms (rocking), such that, the devices and or mechanisms are activated in a hierarchical manner under increasing levels of shaking. The authors have proposed three methods of achieving this [28], however, only one is explained in detail here due to its relation to the experimental results being presented

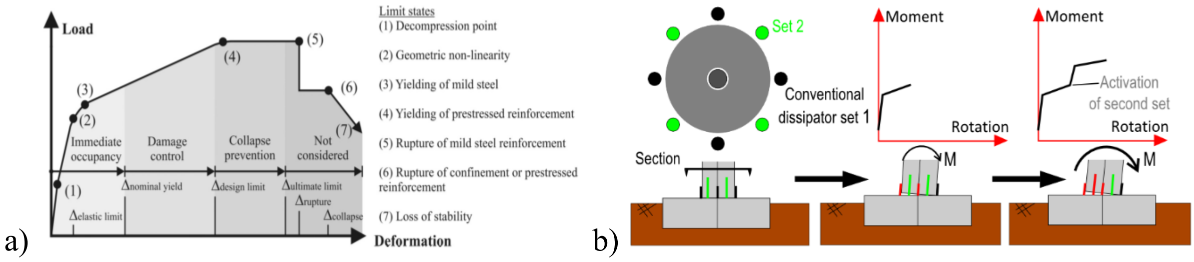

Figure 9: a) Performance objectives and limits for a DCR pier [29]. **b)** Example of hierarchical activation used.

The method of achieving hierarchical activation focussed on in this paper, is to have two sets of dissipators across one rocking interface (Fig. 9b). One set, is directly attached to the members either side of the rocking interface, while, the other is attached in such a way that it is only engaged when uplift at the rocking interface exceeds a specified value. The purpose of this arrangement, is that under frequent seismic loading (return period less than ULS) only one set of dissipative devices is relied upon and if the intensity of the ground motion exceeds that of the ULS ground motion then the second set of dissipative devices is activated in addition to the first set. In this way, after a ULS ground motion, even though one set of dissipators may be spent, the vulnerability of a DCR pier to a sequential significant ground motion (if the first set is not immediately replaced) is lessened due to the presence of the second unused set on standby. In addition to this, in extreme events where both sets contribute to resisting the ground motion, the onset of yielding of the post-tensioning and major P-Δ effects are delayed due to the activation of the second set reducing overall displacements.

5 EXPERIMENTAL INVESTIGATION INTO MDCR

Experimental testing was carried out on a 1/3 scale precast concrete bridge with single cantilever, post-tensioned, rocking pier designed to operate in controlled rocking, DCR, and MDCR configurations. The same pier was also tested in isolation after removal of the decks in DCR and MDCR configurations. The aim of the testing was to physically test the MDCR concept and compare it to a conventional DCR benchmark.

5.1 Specimen overview

The specimen is based on a prototype structure (Fig. 10) typical of a two lane, short-span, reinforced concrete, New Zealand Highway Bridge. The prototype consists of two, 13m simple spans; a single, 1.5m diameter circular pier; and hammer head type cap beam, supporting, a precast superstructure made of standard design double hollow core units. The test specimen, is a fully precast concrete structure (design f'c = 40MPa) and is 1:3 scale. Like the prototype, it is a two span simply supported bridge (Fig. 11). The decks are hollow core slabs each nominally 4222mm long by 2400mm wide and rest on rectangular UHMWPE bearings.

The pier is 500mm in diameter, and has a clear length of 2140mm. The armouring at the base of the pier is a custom made, 500 x 10 CHS with an annular steel ring welded to the base (Fig. 12c).Shear studs welded to the inside of the CHS ensure composite action with the pier. Shear and torsion restraint of the pier base is provided by external shear and torsion keys (Fig.

12b). Pier post-tensioning is provided by a single 26.5mm diameter Macalloy bar of 3182mm unbonded length. Grooved type dissipators were used. The dissipators had 4 grooves, are 16mm in diameter, have a design fuse length of 185mm, a design fuse area of 135mm^2 and are made from mild steel (Fig. 12e) The pier base accommodates a maximum of 8 dissipators (Fig. 12a) which are evenly distributed around the pier (Fig. 9b): 4 for conventional PRESSS hybrid configuration and 4 for hierarchical activation ($\theta_{engagement}$ =2.5% so that yielding would occur prior to θ_{MCE} =2.75%). The dissipator to dissipator circle diameter is 570mm.

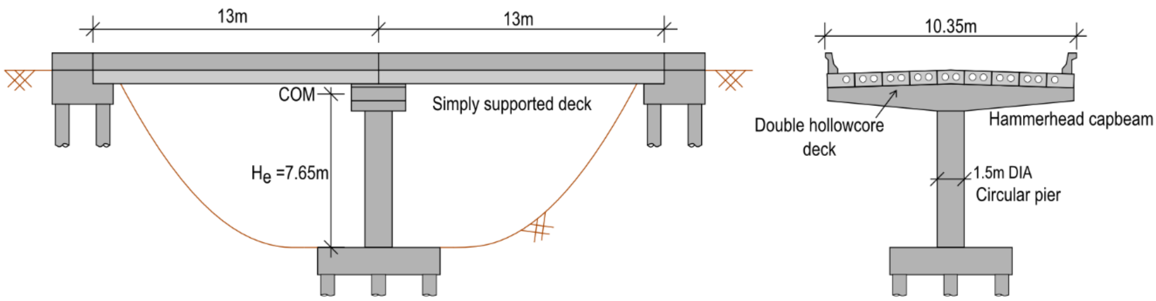

Figure 10: Prototype bridge.

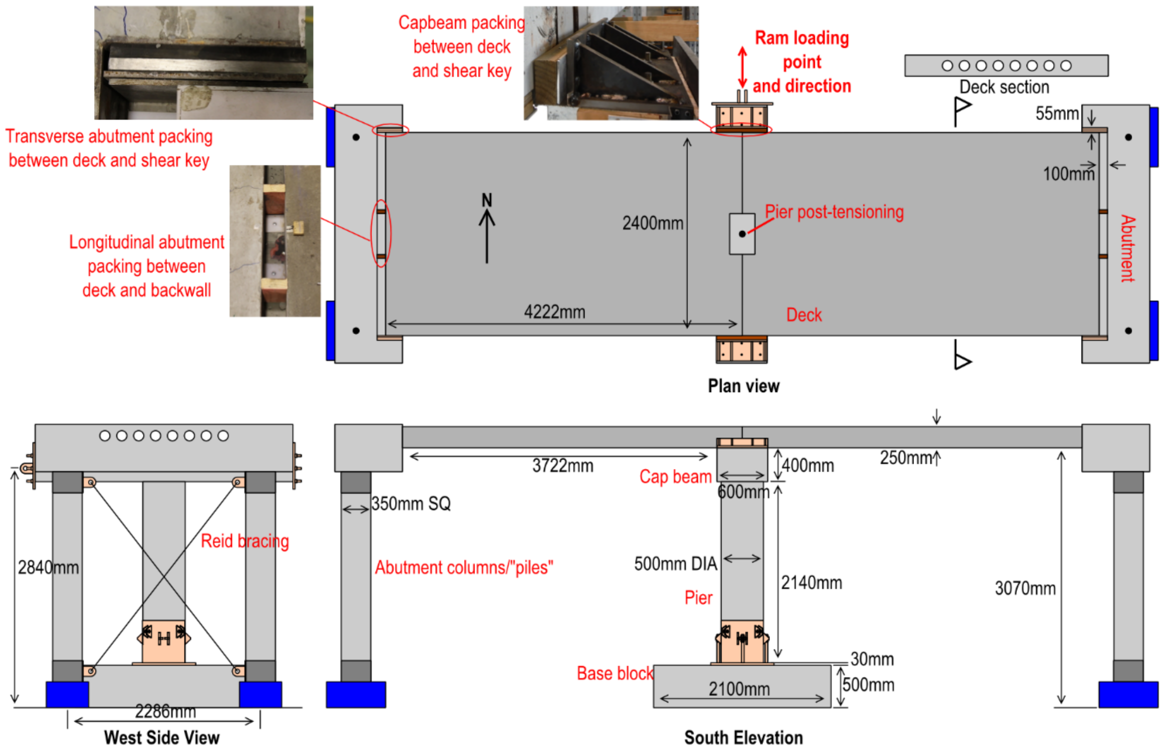

Figure 11: Overall specimen dimensions and detail regarding the boundary conditions around the decks.

5.2 Pier details: hierarchical activation of two sets of dissipators

In the experimental testing shown here, hierarchical activation, involved two sets of dissipators, where, one set is engaged at a later pier displacement to the other. Many options for achieving this were investigated, however, most were either infeasible or impractical. The final option chosen, consists of dissipators being connected by pins to the foundation and pier (Fig. 12a), but where, the pinned bracket connecting the dissipator to the pier has a slotted hole (Fig. 12d).

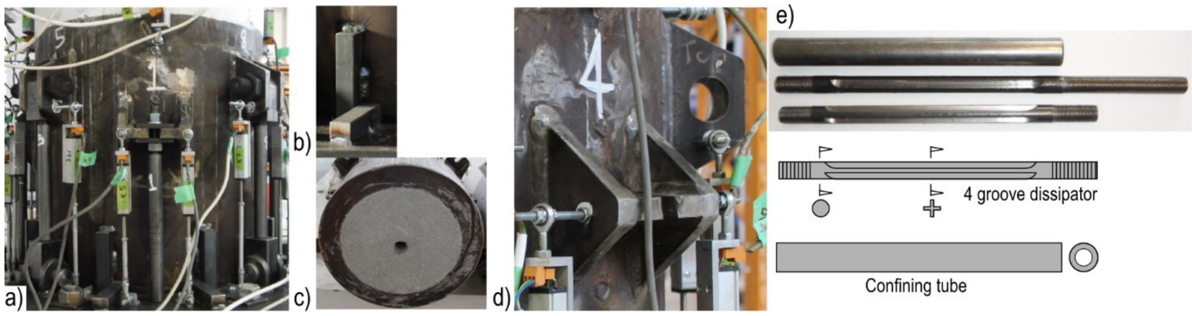

Figure 12: a) Pier with all dissipators attached; **b)** Shear and torsion keys; **c)** Pier base rocking interface; **d)** Dissipator bracket detail, pinned dissipator bracket in background; **e)** Groove type dissipator and confining tube.

At zero lateral pier displacement, the pin in the slotted hole is designed to sit at the top of the slot. Then as the pier uplifts, the dissipator bracket with slotted hole moves upwards and relative to this the pin approaches the bottom of the slot. Only when the uplift is sufficient for the pin to engage with the bottom of the slot, is the dissipator pulled upon. This option for producing hierarchical activation was chosen for three reasons: the pins allow the dissipator to be pulled on axially, despite, the arced uplift movement of the pier; the slotted hole allows the dissipator to undergo compression once it has been extended, whilst, also providing vertical and horizontal restraint of the dissipator ends; and this option was reasonably practical to implement, along with the spent dissipators being accessible for replacement.

5.3 Specimen design

In terms of seismic action design parameters, the prototype was assumed to be of importance level 2; sited in Christchurch, with a hazard factor of 0.3; constructed on non-liquefiable soil of class C; and not subject to near fault effects. Seismic design was only conducted in the transverse direction due to this direction of loading being the governing load case for the pier. Displacement based design was used to determine the seismic design parameters for the prototype pier which were then scaled for specimen design. Table 1 below summarizes the salient pier seismic design parameters calculated.

Table 1: Summary of specimen seismic design parameters from displacement based design.

Specimen ULS design actions and dimensions	Units	Value
Design gravity load, W_{scaled}	kN	195
Design lateral load, V_{scaled}	kN	42.9
Effective height of equivalent SDOF, $H_{e, scaled}$	mm	2550
Pier diameter, D_{scaled}	mm	500
Design base moment, M_{scaled}	kNm	109.4
Design displacement, Δds	mm	52
MCE displacement, ΔMCEs (ADRS assuming EPP F-Δ)	mm	81.4

5.4 Test setup and loading regime

The test set up consisted of a single 300kN ram, loading the bridge transversely at the cap beam level 2310mm above the base of the pier (Fig. 13). The position and direction of loading were chosen to simulate transverse seismic loading of the bridge and to allow later pier only tests to be conducted. Loading of the bridge was cyclic, displacement controlled, and quasi-static. The loading protocol used for testing was derived from ACI T1.1-01 [30]: three fully reversed cycles are applied at each drift ratio; the first drift ratio is within the linear elastic response range; subsequent drift ratios are between 1.25 and 1.5 times the previous value. Lateral drifts of 0.1%, 0.125%, 0.175%, 0.25%, 0.35%, 0.5%, 0.75%, 1.0%, 1.5%, 2.0% 2.75% 3.5%, and 4.5% were imposed. However, only during testing of the pier in isolation were all of the drift ratios imposed. During bridge testing, the maximum applied drift ratio was 2.75% due to safety reasons and the load capacity of the ram to cap beam loading attachment.

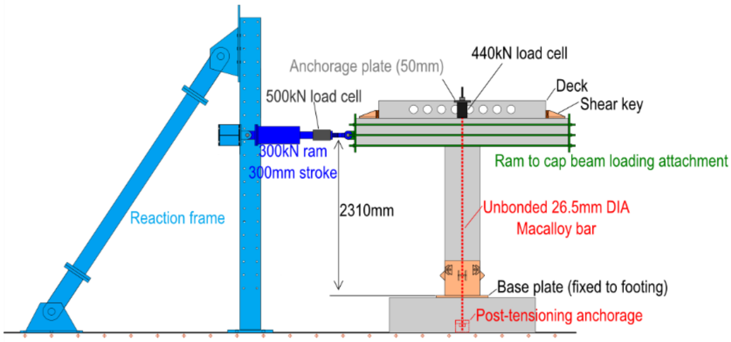

Figure 13: Experimental test set up showing that the bridge was loaded by a single ram at the cap beam level

5.5 Testing schedule

The bridge and pier only test configurations relevant for comparing the performance of DCR and MDCR are summarized in Table 2 below.

Table 2: Selected bridge and pier test schedules. No deck post-tensioning or deck dissipators were used in tests 1,3 and 4.

Test	Pier post-tensioning kN	Conventional pier dissipators	Pinned dissipators
1: Bridge, no pier dissipators	89.2	-	-
3: Bridge, 8 pier dissipators (MDCR)	91.37	4	4
4: Bridge, 4 pier dissipators (PRESSS)	92.3	4	0
12: Pier only (decks removed), $\lambda(\theta=2\%)$ =1.33	154.7	4	0
13: Pier only (decks removed), $\lambda(\theta=2\%)$ =0.75	155.3	4	4

5.6 Experimental results and analysis

In the very first test of the bridge system (Test 1), energy dissipation was found to be significant despite the source only being from friction (Fig. 14a). The self-centering characteristic of the pier combined with the frictional hysteresis produced a flag shaped response. The addition of 4 dissipators in Test 4 so the pier would be in a conventional PRESSS hybrid configuration increased both the stiffness and damping of the entire system (Fig. 14a). In Test 3, the bridge was tested with the pier utilising hierarchical activation. However, due to the activation drift being just over 2% and the maximum drift applied being 2.75% the contribution made was small (Fig. 14a). In tests 3 and 4 no failure of the dissipators occurred.

Testing of the pier in isolation, allowed the full effect of hierarchical activation (Test 13) to be observed (Fig. 14b). Compared to the conventional PRESSS arrangement (Test 12), the activation of the second set of dissipators increased the amount of energy able to dissipated (Fig. 15) in addition to the pier stiffness. In test 12, during unloading from the peak positive displacement of the second cycle at 3.5% drift, failure of one dissipator on the extreme tension side of the pier occurred. The dissipator failed due to shear failure of the dissipator threads engaged with the nut below the dissipator bracket. This caused that particular dissipator to work in tension only for the following load cycles resulting in pinching of the hysteresis loops.

Further evaluation of the changes in damping between tests 12 and 13 was undertaken through evaluation and comparison of the area based hysteretic damping from these two tests (Fig. 16a).The area based hysteretic damping was computed using equation 1. Where: ED is the area enclosed in one cycle of a hysteresis loop; F_{pp} and F_{pn} are the signed peak positive and negative forces measured during that cycle; U_{pp} and U_{pn} are the signed peak positive and negative displacements for the same cycle; K_{eff}, is the effective secant stiffness; and U_o is the average peak displacement.

$$\xi_A = \frac{ED}{2\pi K_{eff} U_o^2} \quad where, \quad K_{eff} = \frac{F_{PP}-F_{PN}}{U_{PP}-U_{pn}} \; and \; U_o = \frac{U_{pp}-U_{pn}}{2} \tag{1}$$

Figure 16a compares the area based damping averaged over the repeated cycles for each drift level for tests 12 (conventional PRESSS) and 13 (MDCR). It can be seen that past a drift of 1.5% for test 13, that the hysteretic damping is less than that for test 12 until failure of the thread on one dissipator occurred. This reduced hysteretic damping can be explained as follows: because the experiment was displacement controlled U_o is very much the same for both tests 12 and 13, therefore, comparing the difference between the two tests in terms of the area based damping is effectively the average ratio of the energy dissipated per cycle (ED) to the effective stiffness K_{eff}. Although, ED for test 13 is larger than the corresponding cycle in test 12 once activation occurs (Fig. 15), this increase in ED is not as large as the increase in Keff therefore resulting in a reduced value of area based damping when compared to test 12. The implications of this reduced area based hysteretic damping combined with increased secant stiffness with respect to transient seismic response is currently unknown and further work will be conducted to numerically assess such impacts.

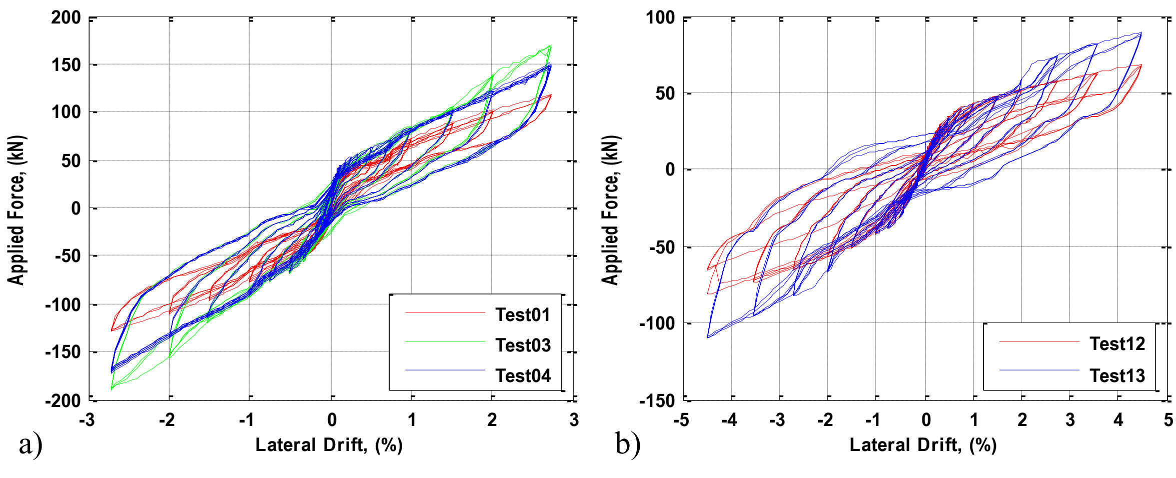

Figure 14: a) Comparison of the force displacements of tests 1, 3 and 4; **b)** Comparison of force-displacement behaviour of tests 12 and 13 showing effect of hierarchical activation during a pier only test.

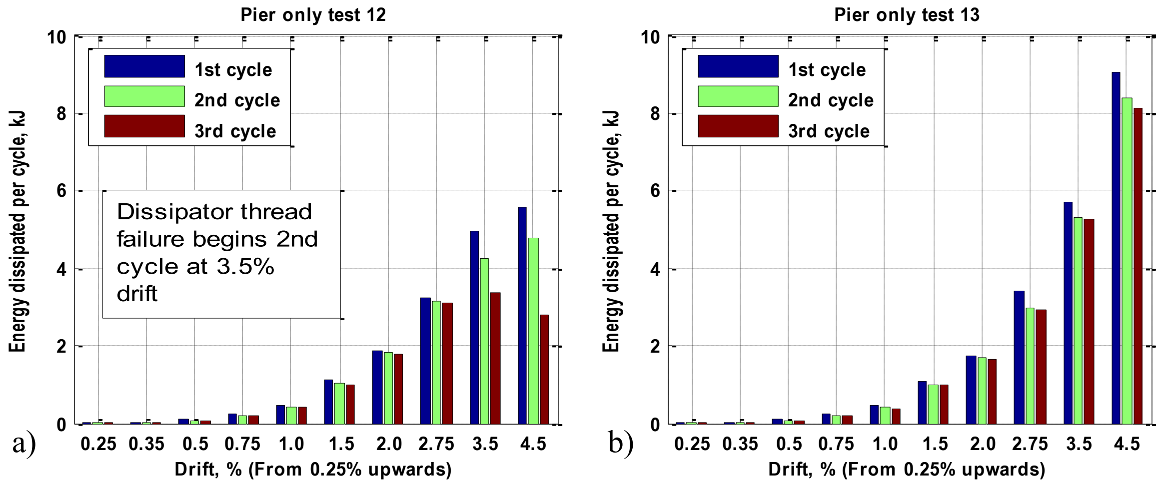

Figure 15: a) Energy dissipated per cycle for pier only test 12 – PRESSS configuration. **b)** Energy dissipated per cycle for pier only test 13 – MDCR configuration.

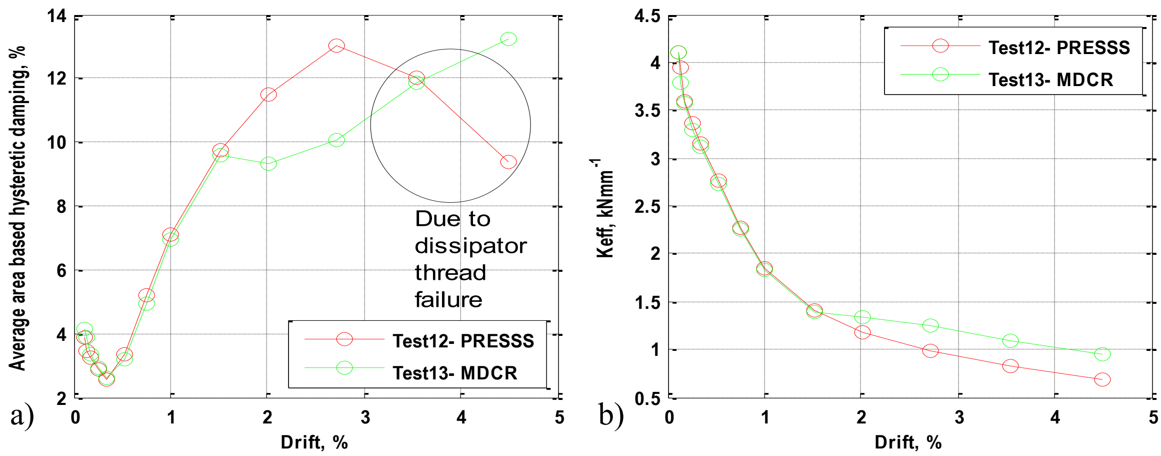

Figure 16: a) Comparison of the average corrected hysteretic damping for tests 12 and 13 as a function of ductility. **b)** Average effective stiffness for each drift level of tests 12 and 13. Activation of the second set of dissipators increases the effective stiffness.

6 CONCLUSION

In conclusion, a brief literature review was given outlining the family of rocking structures and their relation to one another. The literature review showed the progressive development and changes of rocking structures with time. The distinction in dynamic behaviour between free rocking, controlled rocking, and DCR was shown through the results of preliminary numerical analysis in OpenSees. A possible future evolution of PRESSS hybrid rocking was suggested in the form of hierarchical activation (MDCR) and description of this new design strategy given. Finally, results from experimental testing, focussing, on the comparison of DCR against MDCR were given. The results prove the concept of MDCR, however, the unexpected effect on area based hysteretic damping will require further investigation to ascertain whether this is detrimental to transient response.

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