IMPROVING POST-TENSIONED ROCKING BRIDGE COLUMNS FOR LARGE AND MULTIPLE EARTHQUAKE EVENTS

Liu, R.; McHaffie, B.; Palermo, A.
University of Canterbury
Christchurch, New Zealand

Abstract

There is a current shift in seismic design strategy towards minimizing post-earthquake repair. This can already be achieved by implementing low damage technologies such as post-tensioned rocking systems with replaceable dissipative devices, also known as Dissipative Controlled Rocking (DCR). However, DCR as it is currently, has some limitations with regards to seismic structural redundancy for large and multiple earthquake events. In addition to this, the current seismic design limit states used for conventional RC structures do not account for the improved reparability of DCR and so forces structures using this system to be limited by displacement ductility values based on plastic hinge performance rather than metrics such as maximum dissipative device deformation or post-tensioning strain. In this paper, an alternative design philosophy addressing the aforementioned issues is given, design strains for dissipative devices are examined, and a method for improving the seismic structural robustness of DCR called Multi-performance DCR (MDCR) is presented. Two DCR connections, one using a conventional design philosophy and one using the alternative design philosophy, were designed using a range of dissipator strain limits and subjected to repeat earthquakes to compare damage levels. It was found that the dissipator fatigue life was more sensitive to Collapse Avoidance Limit State (CALS) ground motions than sequential DCLS ground motions. From the Non-Linear Time History (NLTH) analysis it was concluded that a design level strain can be increased from 5% to 6% for buckling restrained fuse type dissipater implemented in bridge piers.

Introduction

Research on the seismic design of reinforced concrete bridges has focused on improving performance in order to reduce physical damage and residual drift associated with plastic hinging. Damage-resistant technologies intend to minimize post-earthquake damage in order to provide continued functionality for the transportation network. Dissipative Controlled Rocking (DCR) is a connection type developed to be used in place of traditional plastic hinges (Priestley, 1996). It incorporates Post Tensioning (PT) to provide re-centering, mild steel dissipators to provide energy dissipation and steel armoring at the interface to prevent concrete degradation (Figure 1).

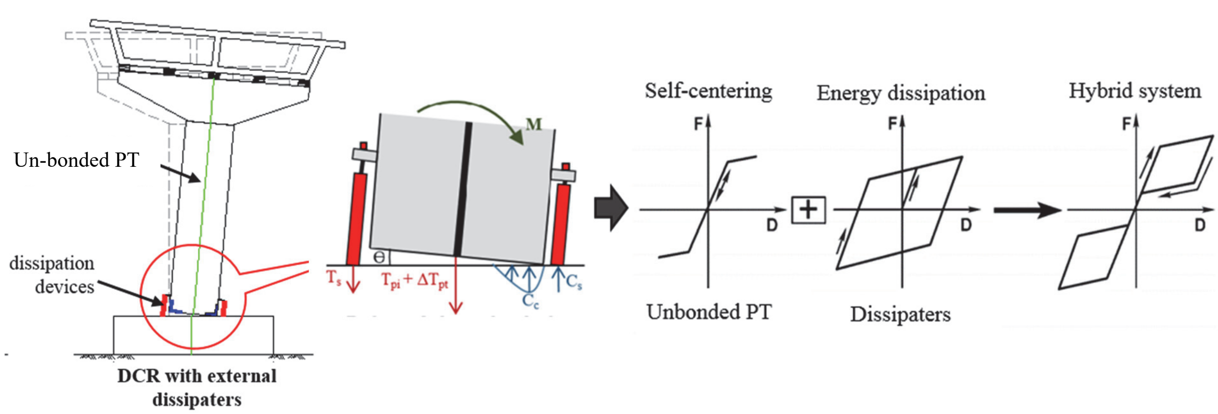


Figure 1. General layout of a pier incorporation DCR and the corresponding flag shape hysteresis

This combination of PT and dissipation leads to a flag-type hysteresis as illustrated in Figure 1. This behavior limits residual displacement after an earthquake provided the PT and axial load moment contribution (re-centering) is larger than the moment contribution of the mild steel. After a design level event the connections can be repaired to 100% of the original capacity by replacing the external dissipators.

The main advantages of DCR, when detailed appropriately, are the elimination of residual drifts and the minimization of structural damage. However, there are two key areas where further improvement can be made. Firstly, the initial construction cost associated with implementing the technology in bridges is higher than that of a traditional plastic hinge. Secondly, dissipater strain limits that are required for the design of bridges is not well defined, in addition to their intended performance at the CALS. This paper intends to investigate these issues. The first, through the development of an alternative design philosophy and the second through NLTH analysis and the development of the modified DCR connection.

Alternative Design Philosophy

The main drawback of low damage technologies is the increase in construction cost associated with using novel design and construction. In reality, this can be offset by the minimized traffic disruption and safer repair methods as well as the other advantages listed previously. However, those benefits are not easily measurable, nor can they be easily accounted for at the design stage. Therefore, the advantages of this type of technology need to be considered in order to reduce the initial construction costs. To do this, the design philosophy used for traditional monolithic connections can be altered to account for the performance benefits of low damage systems.

Building on the notion that accessibility, and hence reparability, influences ductility an alternative seismic design philosophy is proposed. This is based on the premise that as long as the appropriate CALS (which ensures life safety) is satisfied for a particular importance level structure, it would be justifiable to allow higher ductilities based on the economic and social impacts of the expected damage and speed of repair. This would allow structures which have been specifically designed to achieve limited damage that can be easily repaired, to be designed to a higher ductility provided there is no compromise on life safety. For this reason DCR or similar connections can be designed directly for CALS and the Damage Control Limit State (DCLS) can be altered based on economic effects of doing so.

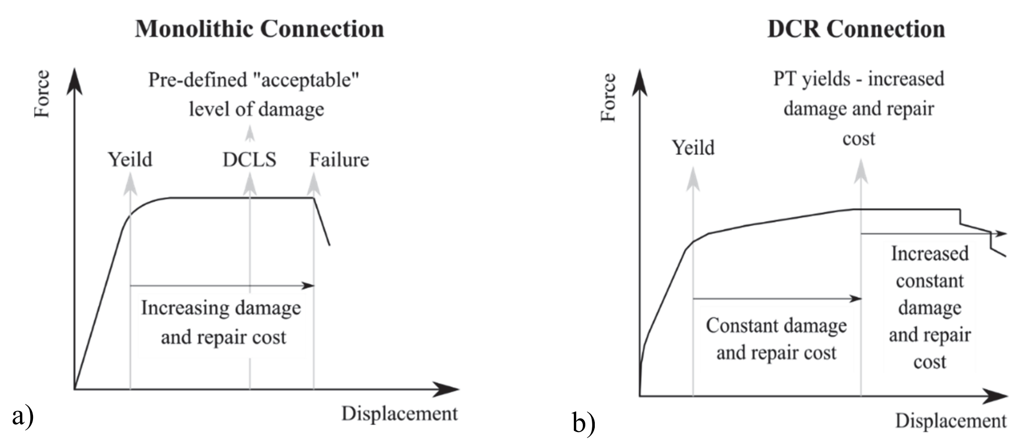


Figure 2: Idealized force displacement plot for: (a) traditional plastic hinge (b) DCR connection.

As shown in Figure 2, the monolithic connection has increasing damage beyond the yield point, this manifests itself through yielding of reinforcement, spalling of concrete, and buckling of reinforcement. Material degradation makes it difficult to predict the response at large displacements. Steel armoring in the DCR connection prevents concrete degradation so the DCR connection mainly exhibits damage in the dissipators, damage to the PT will be observed at large drifts. However, since it is recommended the connections are designed to ensure PT doesn't yield until the CALS, the damage in any design level event is limited to the replaceable dissipators. Given that the DCLS implies that there is repairable damage, this design level becomes redundant as for any level of shaking below the CALS the connections sustains only repairable damage. If, for example the DCR connection is designed for a CALS event of 1/2500 years and the connection undergoes a 1/1000 year event, the repair strategy, replacing external dissipators is exactly the same as if the connection undergoes a 1/2000 year event.

Designing at the CALS rather than the DCLS has several advantages. The first is a result of the post-yielding stiffness of the DCR connection which is caused by the increasing contribution of PT to the moment capacity of the section. As shown in Figure 3 the force demand is much larger at the CALS than the DCLS. This is a concern when designing using capacity design principles, as common practice is to take the over strength capacity at the DCLS. This is sufficient for monolithic connections as they generally have a flat or negative post yield stiffness. However, for DCR connections this process will grossly underestimate over-strength demands which will result in damage to capacity protected parts of the structure. The result is that the CALS has to be examined in order to derive the correct over-strength demands regardless of the design philosophy used. The second advantage is that the design base shear can be reduced. As shown in Figure 3, designing to the same limits as a monolithic connection results in an artificially high base shear demand due to the post yielding stiffness, particularly for piers in double bending. If the DCLS is ignored the same performance at the CALS can be achieved with much smaller sections (McHaffie, Sarkis, & Palermo, 2018).

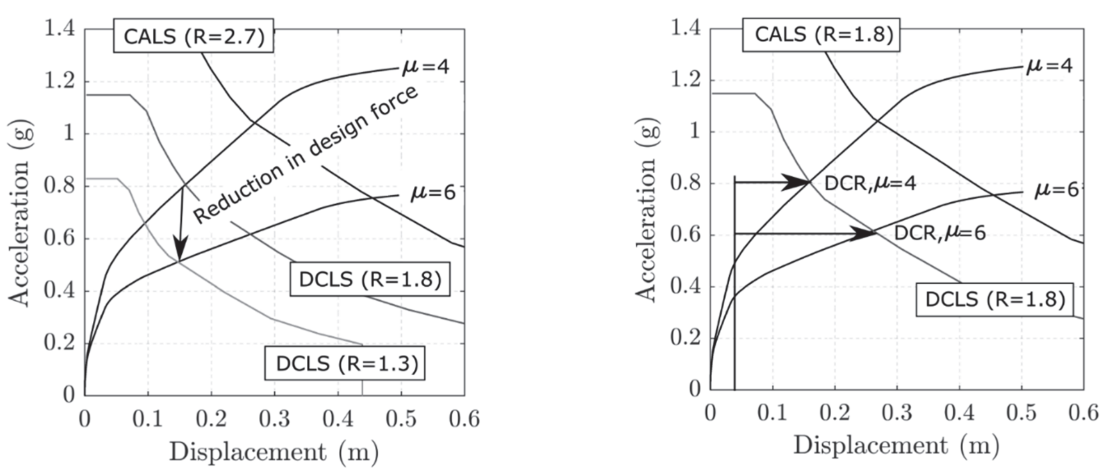


Figure 3: Left: Designing DCR connections design with more frequent return periods (DBD). Right: Allowing higher levels of ductility (FBD)

The 'catch' then is that the displacement demand is inversely related to the stiffness of the seismic resisting system. Hence, weaker pier columns reduce the stiffness and increase the displacement demand. Therefore, the 'penalty' for this economy in design is the need to achieve higher displacements (including allowing for P-delta effects and seismic gaps etc) at the CALS than would have been required otherwise.

Performance Based Strain Limits for External Dissipators

The design strain limits for buckling restrained fuse type dissipators is not currently well defined. The PRESS handbook (Pampanin, Marriott, Palermo, & New Zealand Concrete Society, 2010) specifies a design strain limit of 5%. However, this was loosely based on quasi-static cyclic experimental results which do not necessarily reflect the strain history which the dissipaters would be subjected to in a real ground motion. NLTH modelling was undertaken in OpenSEES to investigate the effect of the specified design strain on the cyclic demand of the dissipators under two scenarios: two sequential DCLS level earthquakes, and single CALS level events. Two cantilever DCR piers were designed according to Direct Displacement Based Design (DDBD). One pier was designed under the current design philosophy (DCLS first and checking the structural response at CALS) while the other was directly designed for the CALS and the DCLS response checked afterwards (Figure 4a). The DCLS elastic design spectrum was obtained from NZS1170.5:2004 (Standards New Zealand, 2004) and the spectrum at CALS obtained by amplifying the design displacement spectrum by 1.5 (New Zealand Transport Agency, 2013). Table 1 below presents the properties of the structural models and design seismic loading.

Table 1: Design Properties of the Two Cantilever Piers Modelled in OpenSEES

Parameter	*Units*	*DCLS first*	*CALS first*
Design gravity load, W	kN	1067	1067
DCLS lateral load, V_b	kN	405.7	310.8
CALS lateral load, V_b	kN	521.6	401.7
Effective height of equivalent SDOF, H_e	mm	4000	4000
Pier diameter, D	mm	1000	1000
Unbonded post-tensioning length	mm	4455	5842
Post-tensioning area	mm^2	5280	1962
Dissipator fuse area	mm^2	345	204
Initial post-tensioning force	kN	430	430
Design displacement, Δ_{DCLS}	mm	80	108.5
CALS displacement, Δ_{CALS}	mm	126	191

In OpenSEES the DCR piers were modelled as 2D structures using the multi-spring element method and the dissipative devices were modelled explicitly as truss members. Each pier used 8 dissipators which were modelled using 5 layers in the 2D elevation. Low cycle fatigue was included in the model using the "Fatigue" material (Uriz & Mahin, 2008), where the coefficients used, were calibrated off experiments conducted previously at UC on the grooved dissipator. In addition to cyclic fatigue life, a tensile rupture strain of 20% was also specified.

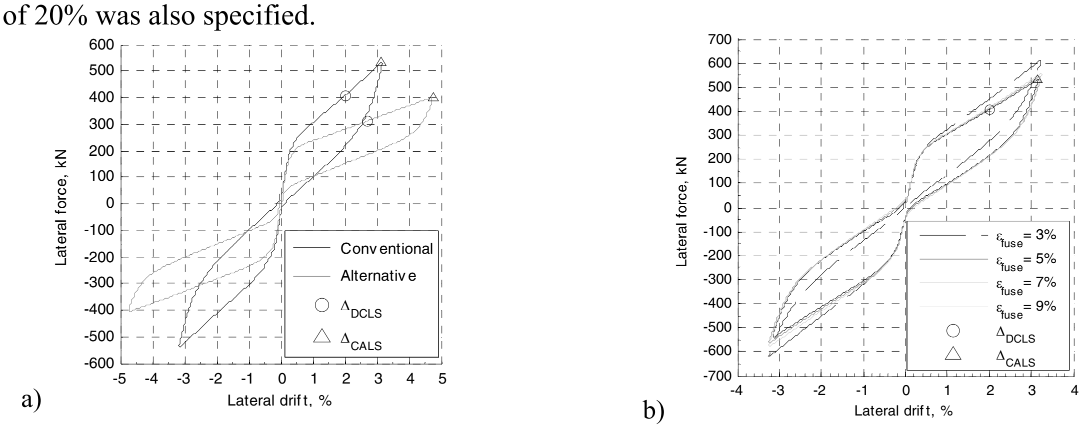


Figure 4: a) Force-displacement response of the conventional and alternative designs; b) Effect of different design fuse strains on the force-displacement response of the conventional DCR model.

The DCLS and CALS strain levels that were investigated are shown in Table 2. The effect, on the force-displacement response, of varying these strain levels is illustrated in Figure 4b. Each connection was subjected to a host of ground motions scaled in accordance with NZS 1170.5:2004.

Table 2: Summary of dissipater strains levels used for design.

	Conventional Design Philosophy (Design to DCLS)				*Alternative Design Philosophy (Design to CALS)*			
Dissipater Strains at DCLS (%)	3	5	7	9	4	6	7	9
Dissipater Strain at CALS (%)	5	9	15	15	8	10	13	17
Lfuse (mm)	450	258	200	160	550	420	320	240

Figures 5 shows the NLTH analysis results for the connection designed using a conventional design approach under CALS level ground motions. In general, the design strains did not have a significant effect on the key performance parameters. However, damage to the dissipater located at the extreme fibers increased with an increase in the design strain. Figure 6 which shows the results for the connection using the alternative design philosophy indicates the same trends. Therefore, altering the design strain does not adversely affect any components other than the dissipators (i.e the peak drifts are insensitive to the design strains of the dissipators).

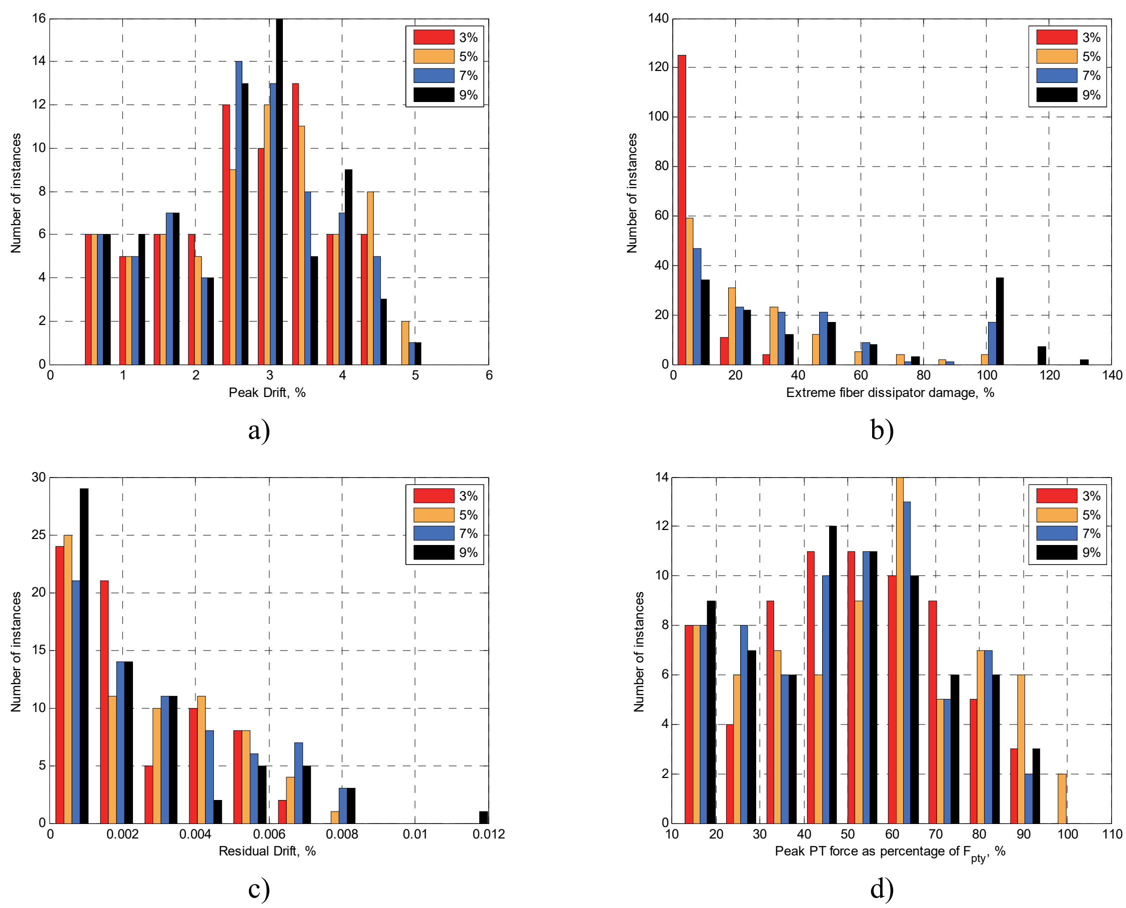


Figure 5: Summary of results from NLTH under CALS level events of connections designed using conventional design philosophy. a) Peak drifts recorded, b) cumulative damage to dissipator at extreme fibers, c) residual drift post-EQ, d) Peak force demand in PT.

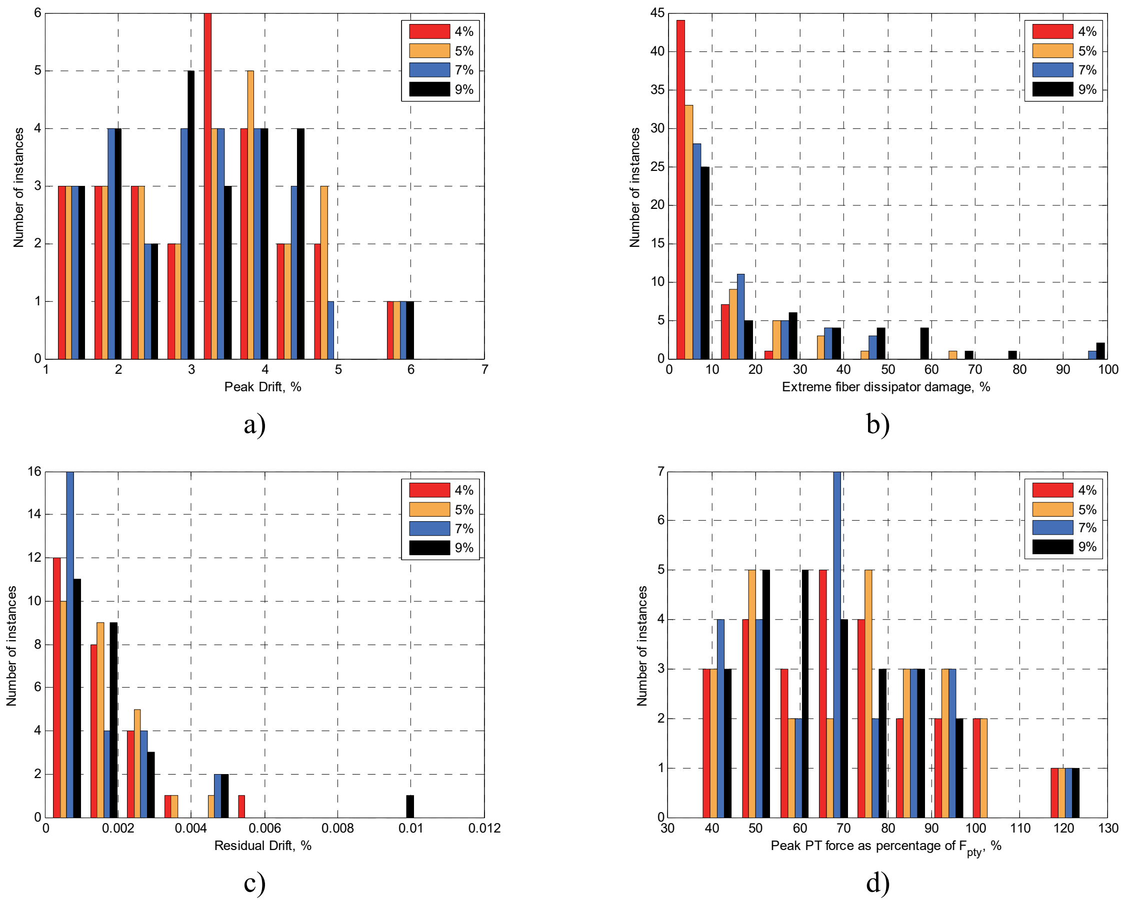


Figure 6: Summary of results from NLTH under CALS level events of connections designed using an alternative design philosophy. a) Peak drifts recorded, b) cumulative damage to dissipator at extreme fiber, c) residual drift post-EQ, d) Peak force demand in PT.

In the simulations dissipator rupture occurred and the number of instance and average number of layer of dissipators fractured are tabulated below. The results show that for connections designed with a DCLS strain of less than 6%, there is a 2% probability of fracturing dissipators. For a DCLS strain larger than 6% there is a 10% and 25% probability of fracturing dissipators for DCLS strains of 7% and 9% respectively. Based on this sample (72 ground motions) it is recommended that a DCLS strain limit of 6% be used to ensure adequate performance at the CALS. When designing directly for the CALS a strain limit of 10% is recommend as the probability of rupture was 0 (for the 36 ground motions used in this analysis). These strain limits are deemed the most suitable given the low probability of rupturing dissipators. At or near the CALS it is quite reasonable to have fracture of a small percentage of dissipators as these: a) can be replaced and b) only account for approximately 40% of the total moment capacity so loss of a single dissipater results in a small loss in section capacity.

Table 3: Number of ground motions that caused rupture, conventional philosophy.

DCLS design strain	*3% Strain*	*5% Strain*	*7% Strain*	*9% Strain*
CALS design strain	*5% Strain*	*9% Strain*	*12% Strain*	*15% Strain*
Number of GM's that caused rupture*	0	3	10	25
Average no. of dissipator layers which ruptured	0	1.3	1.7	2.2

*Connection was subjected to 72 ground motions

Table 4: Number of ground motions that caused rupture, alternative philosophy.

DCLS design strain	*4% Strain*	*6% Strain*	*7% Strain*	*9% Strain*
CALS design strain	*8% Strain*	*10% Strain*	*13% Strain*	*17% Strain*
Number of GM's that caused rupture*	0	0	1	1
Average no. of dissipator layers which ruptured	0	0	1	3

*Connections was subjected to 36 ground motions

Designing for Large and Multiple Earthquake Events

The amount of dissipator cyclic life consumed in a seismic event (DCLS, CALS) is relatively difficult to predict. Accurate prediction of the fatigue life consumed in a seismic event corresponding to a particular limit state is important, as knowledge of this is required in order to specify strain limit requirements for that limit state (DCLS and CALS). However, these strain limits do not account for multiple seismic events. Multi-performance Dissipative Controlled Rocking (MDCR) adds an additional layer of conservatism through modifying the DCR system by inserting extra rocking interfaces and or extra dissipative devices which are activated in such a way as to protect the post-tensioning and or minimize loss of damping capacity under CALS and multiple seismic events (Liu & Palermo, 2015).

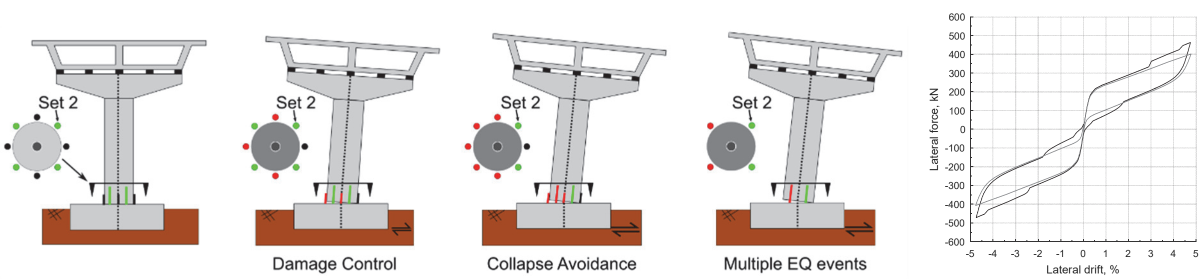
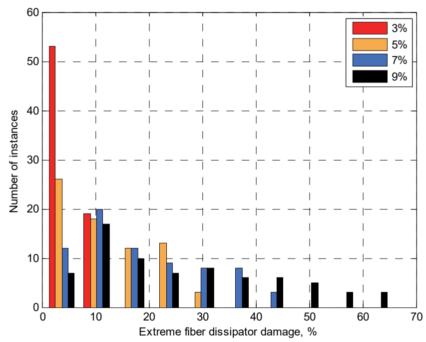


Figure 7. Left: example of Multi-Performance DCR using two sets of dissipators. Right, force-displacement of such a system compared with conventional DCR

Figure 7 depicts an example of this. Here, the structure employs an additional set of dissipators (green) which are not activated until the structure exceeds the DCLS drift. Under frequent seismic events (return period less than DCLS) only one set of dissipative devices is relied upon and if the intensity of the ground motion exceeds the DCLS then the second set of dissipative devices is activated in addition to the first set. In this way, after a DCLS or CALS 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/partially used 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.

Following on previous analysis the effect of sequential earthquake motions was investigated. NLTH analysis was carried out on the two previously designed DCR connections to examine the cumulative damage resulting from multiple DCLS events and whether this would be enough to cause dissipator rupture. Figure 8 shows that for both design philosophies no dissipators ruptured, even when designed with a DCLS strain of 9%. This indicates that the specification of DCLS strain limits is to ensure adequate performance at the CALS and that cyclic demands arising from multiple DCLS level events do not appear to be critical.



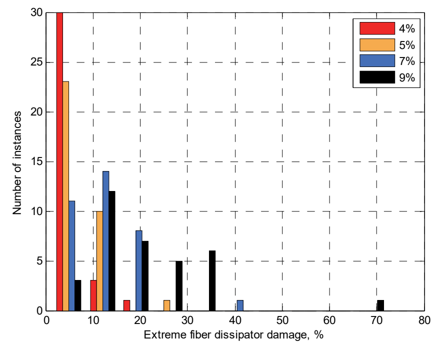


Figure 8: Damage to extreme fiber dissipators – Left: Conventional philosophy, Right: Alternative philosophy.

Conclusions

This paper has introduced an alternative design philosophy for DCR connections which ensures they are designed correctly for over-strength and improves the efficiency of the connection by reducing the DCLS design restriction. Comparison of the design philosophies through NLTH analysis has indicated satisfactory performance for both connections types. In addition, strain limits for DCLS and CALS have been proposed at 6% and 10% respectively. These limits allow for low cycle fatigue and minimize the probability of dissipator fracture at the extreme fibers. Finally, the MDCR connection was introduced as an improvement to DCR which is particularly suitable to high importance level structures in high seismic zones. MDCR will likely be able to sustain a CALS event followed by a DCLS event without collapsing. Further research on the strain limits is recommended. This research should aim to investigate near field, far field, short duration and long duration events as well as utilize a larger sample size of ground motions and connection detailing.

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