Impact of the post-earthquake reparability of low damage dissipative controlled rocking connections on the design framework.

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ABSTRACT: Recently, there has been a shift in the seismic design strategy toward minimizing post-earthquake repair. This can be done by implementing low damage technologies such as Dissipative Controlled Rocking (DCR). Until recently, DCR or so called PRESSS hybrid connections had been implemented in buildings only. However, the recently constructed Wigram Magdala Bridge also incorporates DCR. The technology combines post-tensioning (re-centering) and dissipative fuses that can be replaced post-earthquake. To facilitate the broader use of this technology, the way these structures are designed needs to be refined as the benefits of this technology are not captured in the New Zealand Bridge Manual. Currently, the Bridge Manual limits the ductility of a structure based on the accessibility of the plastic hinge. Since DCR connections are not only accessible but also repairable it can be argued that a higher level of ductility or lower return period could be justified for these connections. One of the major factors affecting the use of this technology is cost, accepting a higher level of ductility will offset this cost by reducing demands in other parts of the structure. Pushover and Non-Linear Time History analysis will be carried out to determine the post Damage Control Limit State performance of DCR structures designed with higher levels of ductility.

1 INTRODUCTION

Seismic resilience in bridge design within New Zealand is currently rather crudely considered based on the Importance Level (IL) determined for a particular bridge structure. The importance level is defined in the NZTA Bridge Manual based on the potential loss of human life and the economic, social and environmental consequences of failure of the bridge. The IL is then used to define the return period for Serviceability Limit State (SLS), Ultimate Limit State (ULS) and the Maximum Credible Earthquake (MCE). These limit states have recently been more appropriately renamed, for seismic design, in the latest version of the preliminary draft New Zealand Transport Agency Bridge Manual and other international displacement-based seismic design provisions, as Serviceability Limit State (SLS), Damage Control Limit State (DCLS) and Collapse Avoidance Limit State (CALS) respectively. These new terms help clarify that what used to be termed Ultimate Limit State is not in fact about life safety but rather about controlling damage and it is the CALS that is about ensuring life safety. This paper investigates the performance of DCR connections at the CALS through pushover - Acceleration Displacement Response Spectrum (ADRS) curves and Non-Linear Time History (NLTH) analysis and presents an alternative design philosophy for low damage connections where the CALS is the main design objective and the DCLS can be altered to reflect economic requirements.

2 CURRENT SHORTFALLS

In conventional forced-based seismic design, the displacement ductility factor (μ) provides a means by which, a structure can be designed for lower seismic loads on the basis of accepting more damage in a particular DCLS event. For this reason, the NZTA Bridge Manual (NZTA, 2016) places a limit on the acceptable displacement ductility factor. As shown in Figure 1 the acceptable level of ductility is largely based on the accessibility and hence reparability of the plastic hinge regions. This provision strongly influences the ease of access for inspection and repair.

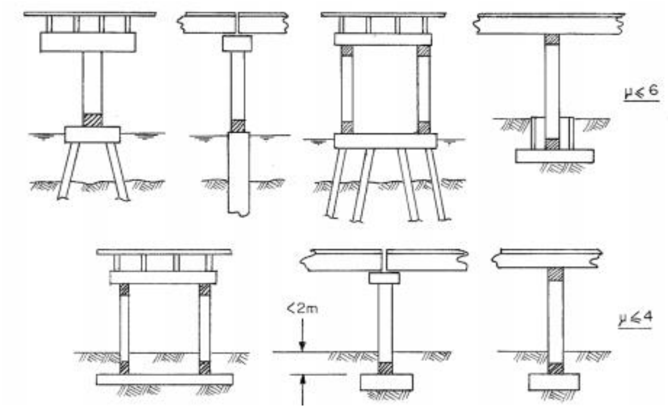


Figure 1: Ductility levels as prescribed in the NZTA Bridge Manual

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 IL 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 for CALS and the DCLS can be altered based on the economic effects of doing so. This is un-typical of traditional design methods where DCLS is designed for and CALS is checked. Reducing the DCLS demands will decrease base shear demand on the structure which, for example, could reduce the required moment capacity of the piers. The increase in cost associated with this technology can then be potentially offset by reducing over-strength demands elsewhere in the structure. Equivalently, a more frequent return period for the DCLS can be introduced which increases the probability of a DCLS event occurring over the life of the structure on the basis that the damage is limited and repair is economically viable. As shown in Figure 2, selecting a more frequent return period or a higher ductility results in reduced base shear. However, to facilitate this the CALS ductility level μ1 increases compared to the initial CALS ductility μ2.

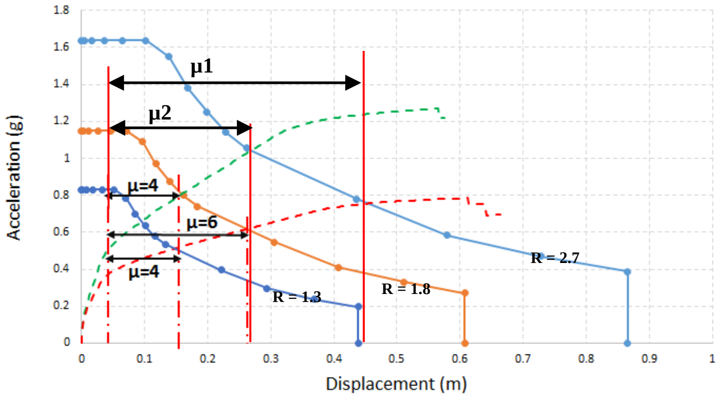


Figure 2: Effect of altering the DCLS and ductility.

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 relatively higher displacements (including allowing for P-delta effects and seismic gaps etc) at the CALS than would have been required.

The idea of higher ductilities for low damage structures lends itself well to DCR connections as these connections have very accessible mild steel dissipaters, post-yielding stiffness provided by the Post Tensioning (PT) and minimal connection degradation (Fig. 3). The dissipaters can be either internal or external both of which can be easily replaced (refer to White, 2014 for further details.) This paper refers to the low damage DCR connection which has external dissipaters because the controlled damage connections that have internal dissipaters do not, in all cases, have the same reliability at CALS.

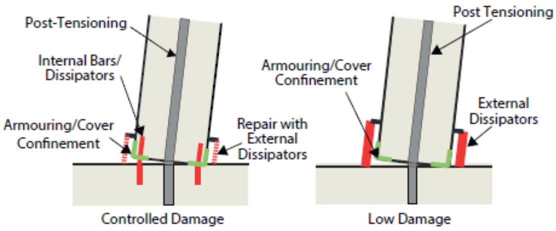


Figure 3: Schematic of example low damage connections (White, 2014)

3 STRUCTURAL SCHEME

To understand the implications of allowing a higher ductility, a typical pier bent loosely based on the Wigram-Magdala Bridge (Routledge, Cowan, and Palermo, 2016) as shown in Figure 4 was selected for a comparison. The piers are assumed to be 5.5m tall and support 7 super T beams (PT U section beams) which span 32m. The bridge supports 2 lanes of traffic over a primary lifeline route and is therefore deemed an Importance Level 3 structure which results in a DCLS return period of 1/2500 years. The structure is assumed to be situated on Class D soil.

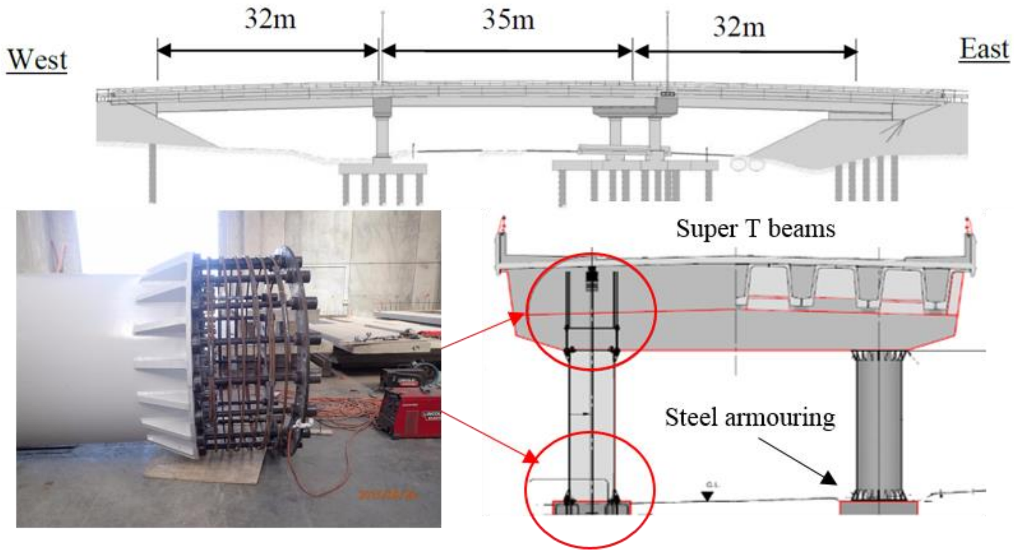


Figure 4: General arrangement of Wigram Magdala bridge: a) structural elevation; b) cross section at pier bent.

4 PUSHOVER RESPONSE

The pier bent was modelled with the three different connections shown in Figure 5, Connection 1 is monolithic with ductility 6 and Connection 2 and 3 have low damage connections with ductility 6 and 8 respectively. Displacement Based Design was used to design the piers in the transverse direction (Priestley, Calvi, and Kowalsky, 2007) and the CALS was calculated by multiplying the DCLS Return Period Factor, R, by 1.5. The design displacements and capacities are summarised in Table 1. The yield displacement is defined as the displacement at which the outermost dissipater reaches its yield strain.

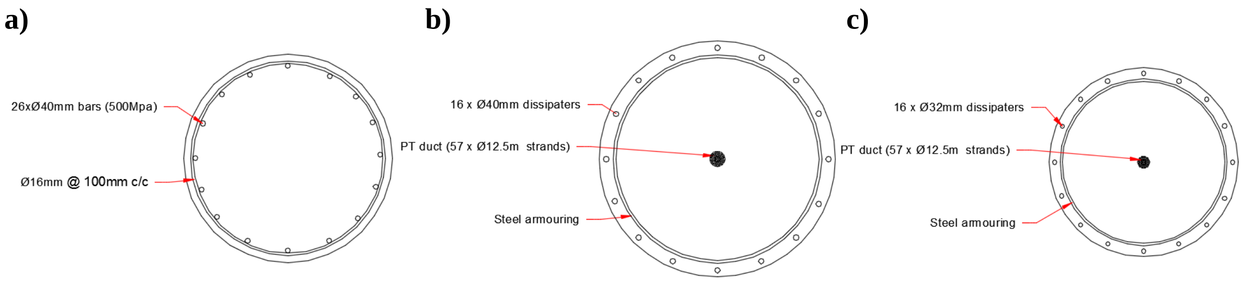
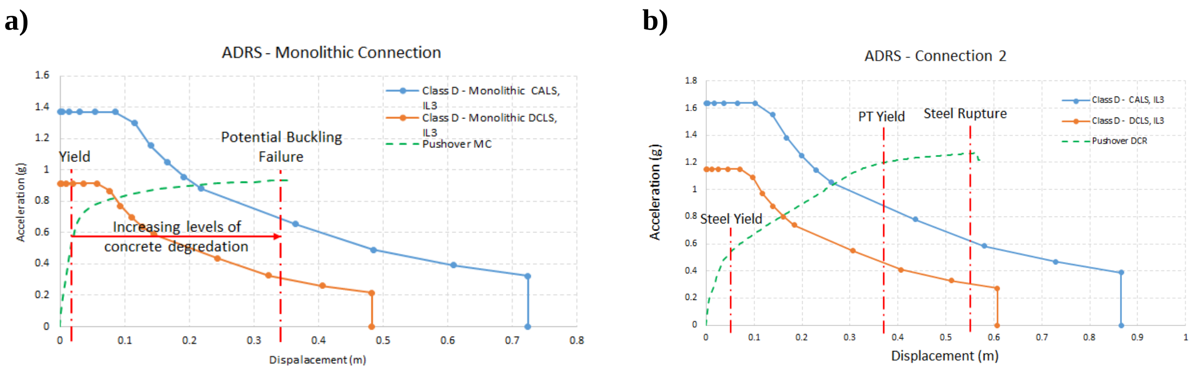


Figure 5: Cross sections of connection modelled; a) monolithic, b) DCR with μ=6, b) DCR with μ=8.

Table 1: Summary of significant design properties.

	Diameter (m)	DCLS Displacement (m)	DCLS Moment Demand (kNm)	CALS Displacement (m)	Yield Displacement (m)
Connection 1	1.5	0.09	9300	0.21	0.015
Connection 2	1.5	0.18	8300	0.26	0.030
Connection 3	1.2	0.25	4800	0.43	0.030

ADRS curves were compared to pushover curves for the pier bent. From Figure 6d it is apparent that Connection 2 and 3 have significantly more displacement capacity than Connection 1 with drifts of up to 7% at the CALS. However, the Monolithic Connection (MC) still has significant displacement capacity beyond CALS, safely achieving drifts of 4%. To reach this drift, the connection undergoes significant damage which is difficult to predict due to the concrete degradation in the Plastic Hinge Zone (PHZ). DCR connections have much more reliable performance at CALS due steel encased concrete which prevents concrete degradation at the interface between the column and foundation footing. In addition, the connections have the redundancy of the post-tensioning cables centrally located in the column which has the added benefit of increasing the stiffness of the connection after the steel dissipaters yield. This effect prevents the CALS displacement capacity from being exceptionally large. This is shown in Figure 6b with a DCLS displacement of 180mm and a CALS displacement of 250mm which represents a 44% increase in displacement demand. This contrasts with the MC which has a very low post yielding stiffness that results in a 130% increase in displacement demand during the transition from DCLS to CALS. The post-yielding stiffness is only prominent in piers that have a significant moment contribution from PT and further investigation on the PT/axial load ratio limits should be carried out to limit CALS displacement demands. The downfall of this stiffness increase is the resulting over-strength demands at CALS will be larger. So, the percentage base shear reduction at DCLS will not necessarily be realised at the CALS. This is illustrated in Figure 6d which shows the difference in base shear between Connection 1 and Connection 3 at the CALS is smaller than at the DCLS.



c) d)

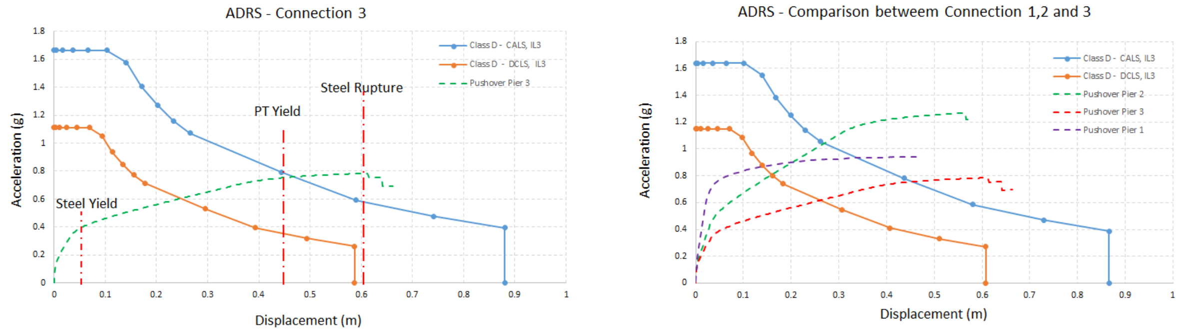


Figure 6: ADRS pushover response for the three connections: a) monolithic connection; b) and c) are DCR connections designed with ductility 6 and 8; d) shows a comparison between the three connections.

Figures 6c shows the pushover for Connection 3 which has been designed with a ductility of 8, larger than BM currently allows. However, the only damage observed for this connection is yielding of the dissipaters. In this case the PT was designed to yield after CALS although it would be acceptable for this to happen between the DCLS and CALS. However, the acceptable DCLS limit state for PT may be different as the cost of repair could be significant unless the PT is replaceable. As shown in Figure 6d, Connection 3 has a force demand 30% lower than Connection 2 and still sufficiently satisfies the CALS demand. The PT yields at a drift of 7% which is very close to the CALS displacement but there is significant displacement capacity for the connection beyond this as the mild steel does not rupture until a drift of 10% and the PT and axial load still provide re-centering and moment capacity. Therefore, designing to CALS is viable as not only are the DCR connections predictable at this level but they also have significant capacity beyond this.

5 TIME HISTORY ANALYSIS

To further investigate the post-DCLS performance, NLTH was used. As shown in the Figure 7, lumped plasticity models were adopted for the simplified model which have been shown to accurately predict the behaviour of the DCR connection (Palermo, Pampanin, and Carr, 2005). For the DCR connections this was done busing two rotational springs in parallel. One rotational spring was assigned a Non Linear Elastic rule to represent the self-centering contribution from the PT and axial load. The other rotational spring was assigned Ramberg-Osgood hysteresis rule to represent the mild steel dissipaters (Carr, 2004). The springs were then calibrated to represent the moment-rotation behaviour provided by each contribution. The monolithic connection was modelled with one spring using a modified Takeda hysteresis rule.

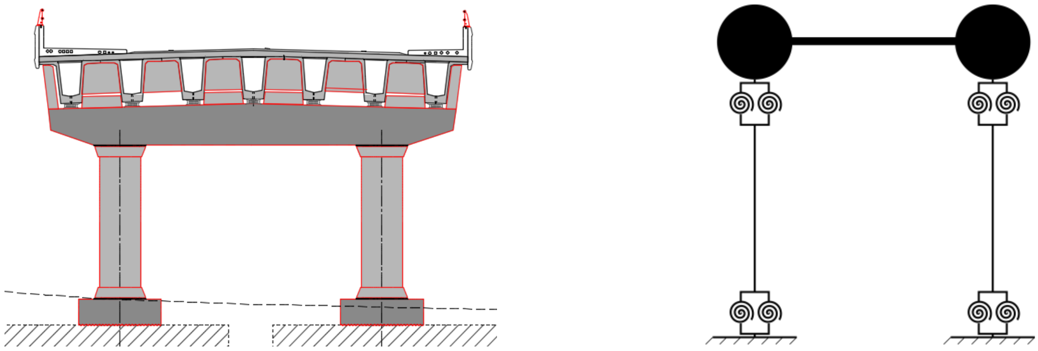


Figure 7: Schematic lumped plasticity model of the pier bent

Ground motions were scaled in accordance with NZS1170.5. The scaled ground motions are plotted against elastic design spectrum in Figure 8 and the key characteristic tabulated in Table 2.

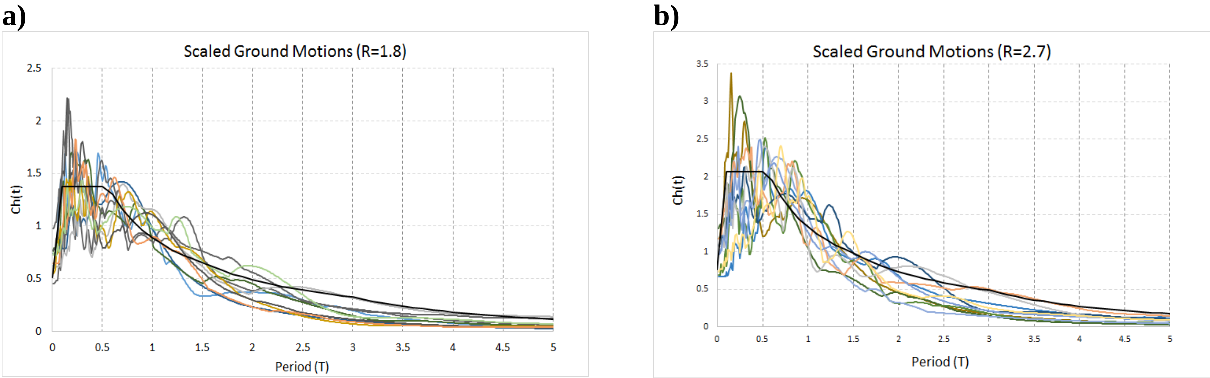


Figure 8: Scaled ground-motions compared to the elastic design response spectrum: a) motions scaled for a return period factor, R, of 1.8 (DCLS); b) shows motions scaled for a return period factor, R, of 2.7 (CALS).

Table 2: Characteristics of considered earthquake records.

	DCLS, R = 1.8					**CALS, R = 2.7**				
	Name	Year	Mw	Scale factor	Scaled PGA	Name	Year	Mw	Scale factor	Scale PGA
EQ1	Imperial Valley-02	1940	7.0	2.0	0.52	N. Palm Springs	1986	6.1	1.97	1.16
EQ2	Coyote Lake	1979	5.7	1.7	0.69	San Salvador	1986	5.8	1.49	0.97
EQ3	Imperial Valley-06	1979	6.5	2.1	0.46	Loma Prieta	1989	6.9	1.80	0.50
EQ4	Imperial Valley-06	1979	6.5	1.6	0.59	Northridge-01	1994	6.7	1.63	0.75
EQ5	Imperial Valley-06	1979	6.5	1.8	0.74	Northridge-01	1994	6.7	1.29	1.04
EQ6	West-morland	1981	5.9	1.5	0.62	Northridge-01	1994	6.7	2.09	0.95
EQ7	N. Palm Springs	1986	6.1	1.3	0.76	Northridge-01	1994	6.7	1.41	0.91
EQ8	Loma Prieta	1989	6.9	1.9	0.73	Northridge-01	1994	6.7	1.77	1.24
EQ9	Cape Mendocino	1992	7.0	1.7	0.71	Kobe, Japan	1995	6.9	1.40	0.99
EQ10	Northridge-01	1994	6.7	1.4	0.63	Chi-Chi, Taiwan	1999	7.6	1.22	0.55

The simplified models, illustrated in Figure 7, were subjected to the scaled ground motions tabulated above. All three connections were subjected to the ground-motions associated with DCLS (Return Period Factor, R=1.8) and CALS (R=2.7) events. Figures 9-11 show the response of the models to the ground motion which resulted in the largest demands for the connection. The response of Connection 1, the monolithic connection, is shown in Figure 9. The moment-rotation behaviour, which is approximately equal to drift neglecting a small elastic contribution from the pier, illustrates that there is some residual displacement and degradation as expected.

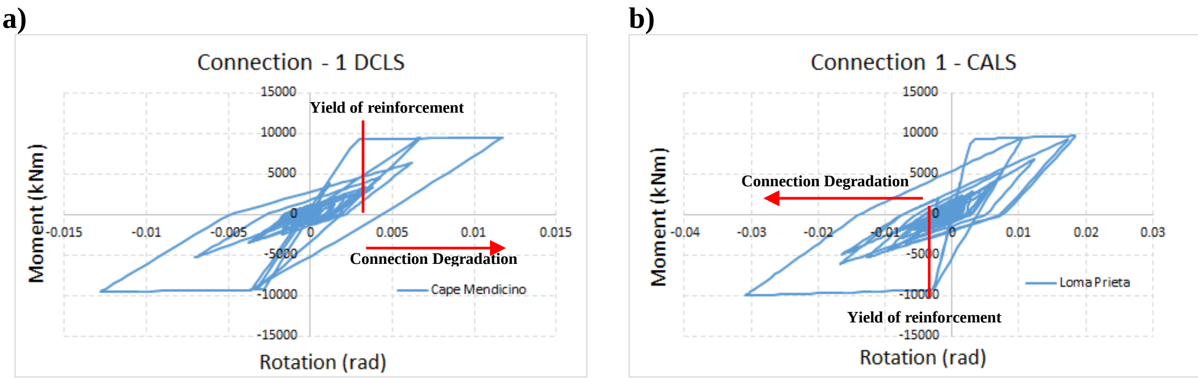


Figure 9: Moment-Rotation response of Monolithic Connection.

As illustrated in Figure 9, for the MC, after the steel yields the concrete begins to crack and spall and the level of damage occurring at the plastic hinge zone is hard to quantify making the level of repair required difficult to assess. Moreover, after a DCLS event the performance of the connection becomes more uncertain as the concrete core can begin to degrade which can result in bar buckling and failure of reinforcement. Essentially, what this indicates is that the performance of a plastic hinge is uncertain beyond DCLS regardless of the ductility level. In contrast, with a DCR connection the steel armouring prevents concrete degradation and as illustrated in Figures 10 and 11 below the damage is limited to the dissipaters with no other degradation observed.

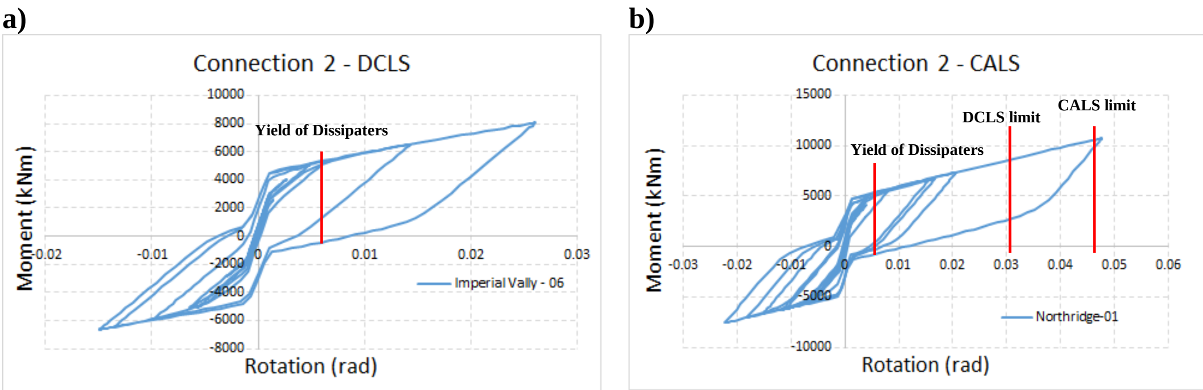


Figure 10: Moment-Rotation responses of DCR connection with ductility 6.

Connection 3 satisfies the overarching goal of life safety in a CALS event. Connection 3 undergoes larger displacements and as with all other connections the dissipaters yield. The yielding occurs at 0.6% drift and no damage to other elements occurs in the connection until beyond a CALS. At the maximum drift of 7% the PT is very close to yielding. However, even if in the worst case the PT did yield the connection still has significant additional capacity, as dissipaters do not rupture until 10% drift and following that residual capacity from PT and axial load exists.

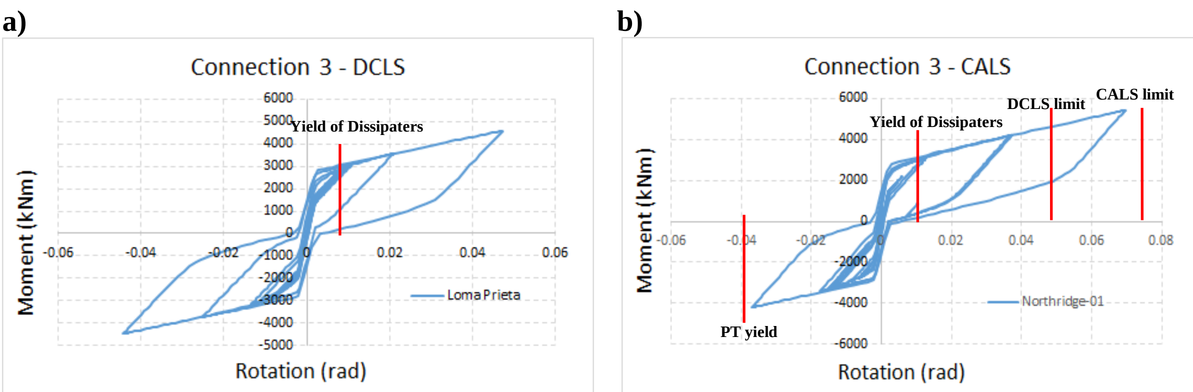


Figure 11: Moment-Rotation response of DCR connection with ductility 8.

The results of this analysis show that designers can design the connections at CALS with the comfort that not only is the connection going to behave reliably but also have significant post CALS capacity. Non-Linear Time History (NLTH) analysis showed that the pushover accurately predicts the response of the DCR connections. Currently, the DCLS demands are governed by the IL of the structure which is related life-safety, economic and social impacts. Provided life safety is satisfied at CALS, then the DCLS is not directly related to life safety and the DCLS becomes an economic decision regarding the cost and speed of repair. Therefore, the DCLS level can be designed on a case by case basis making the CALS the fundamental design level.

6 CONCLUSION

This paper has briefly discussed the shortfalls of the current Bridge Manual when it comes to implementing low damage technologies and has compared the performance of monolithic and DCR connections. It outlined that DCR connections have more reliable performance at the CALS by having extra layers of robustness from the PT and steel armouring of the connection. This was shown initially through pushover and ADRS curves and verified through NLTH analysis. This develops the idea that for DCR connections the designer should think about designing for a CALS level and then about what ductility or return period is allowable for DCLS based on client requirements and the cost of repair. The effect of this is that design level earthquakes will be smaller, potentially helping to offset some of the additional costs associated with the DCR connection. The combined effect of a lower design level along with other whole of life benefits will lead to more economic bridge designs that are more resilient, reliable and predictable in large earthquakes. This will improve the overall resilience of the road network and more importantly allow repair costs to be estimated before a quake rather than reacting to the damage after.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Carr, A.J. (2004). RUAUMOKO Program for Inelastic Dynamic Analysis - Users Manual.

NZTA. (2016). Earthquake Resistant Design of Structures, Bridge Manual 3rd Edition Amendment 2.

Palermo, A., Pampanin, S. & Carr, A. (2005). Efficiency Of Simplified Alternative Modelling Approaches To Predict The Seismic Response Of Precast Concrete Hybrid Systems,

Priestley, M., Calvi, G.M. & Kowalsky, M.J. (2007). Displacement-based seismic design of structures.

Routledge, P.J., Cowan, M.J. & Palermo, A. (2016). Low-damage detailing for bridges – A case study of Wigram-Magdala Bridge

White, S. (2014). Controlled damage rocking systems for accelerated bridge construction.