Low Damage Design and Seismic Isolation: What's the difference?

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ABSTRACT: Low damage design and seismic isolation are alternative philosophies to conventional capacity design, both with the goal of reducing physical damage to the structure they are applied to. However, the distinction between these two alternative seismic design philosophies is unclear in current literature along with the design strategies used to achieve them. An example of this is the misconception that the design strategies of rocking and dissipative controlled rocking (DCR) reduce damage to a structure through the same mechanism of gap opening and hence, that both strategies belong to the philosophy of low damage design.

This paper looks to clarify the definitions of low damage design and seismic isolation; argue that the two philosophies are in fact different; and that these differences can most easily be seen in the results of non-linear response history analyses of a SDOF structure utilizing the different design strategies belonging to each philosophy. In addition, two new design strategies called "hierarchical DCR" and "hierarchical foundation rocking-DCR" proposed by the author are introduced and explained; along with the concept of "collapse limit states" as a measure of the robustness of a particular design strategy.

1 INTRODUCTION

Seismic engineering evolved from the need to design structures to resist seismic actions. The need being driven by several motivations, but, the main motivation being the prevention of loss of life from structural collapse. This has resulted in a diverse range of philosophies in which to design a structure and different strategies in order to implement each philosophy. This introduction will examine the current design philosophies and strategies with a focus on clarifying the definitions of low damage design and seismic isolation in addition to the strategies used to achieve them.

1.1 Design philosophy

A design philosophy is a way of thinking used to constrain how an engineered product is designed. In seismic engineering, there are currently three main design philosophies: conventional capacity design, seismic isolation, and low damage design.

Capacity design was developed in the early 1970's (Priestley, Calvi and Kowalsky 2007) and is based on the concept of, accepting the allowance of non-linear behaviour within the members of a structure, intentionally designing weak links (plastic hinges) to control the occurrence of nonlinear behaviour, and detailing those weak links to be ductile (Fig. 1, left) in order to provide the structure with the required level of deformability to accommodate the expected plastic deformations. As one of the earlier design philosophies to be developed, its main focus is to simply to prevent collapse of a structure in a design level earthquake (ULS earthquake) with little or no regard towards post-earthquake functionality due to the allowance of damage to occur within the structure.

Seismic isolation is based on the concept of, modifying, the response of a structure through elongating the structure's natural period of vibration so that seismic demands are drastically reduced (Fig. 1, right). This idea of separating the structure from the horizontal motion of the ground is not a recent development but has been proposed many times for at least a century (Kelly 1986). However, the practical application and science of isolation is a more recent development (Kelly 1986).

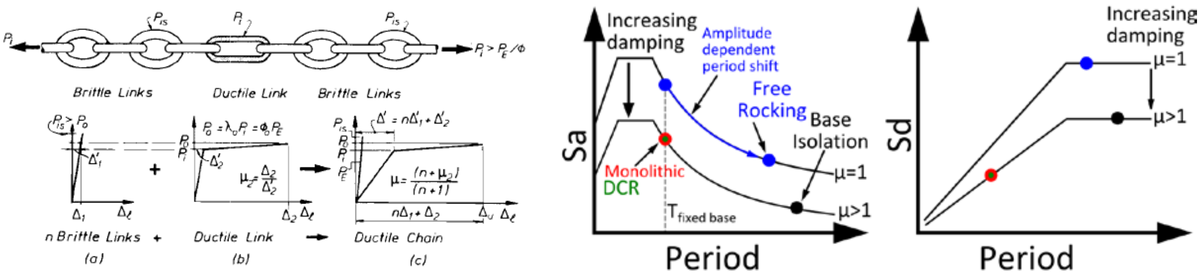

Figure 1. Underlying concept of capacity design (left), (Paulay and Priestley 1992). Underlying concept of seismic isolation and comparison with conventional capacity design and low damage design (DCR).

The benefit of isolation is that in many cases a new structure can be designed to remain nominally elastic during a design level earthquake making plastic hinging unnecessary as the main method for resisting seismic actions. Hence, in an isolated structure, damage is significantly reduced in earthquakes smaller than the design earthquake and, ideally, there is immediate post-earthquake functionality.

Low damage design also called Damage Avoidance Design (DAD) (Mander and Cheng, 1997), is the newest of the current seismic design philosophies and has been developed for concrete (Priestley and Tao, 1993), steel (Christopoulos, Filiatrault, Uang and Folz 2002) and timber (Palermo, Pampanin, Buchanan, and Newcombe 2005) structures. It is different to the other philosophies in that it does not require a strictly defined mechanism (e.g. plastic hinge, or period elongation) to describe the concept behind it. In general terms, the concept behind low damage design is to significantly reduce seismically induced damage to a structure through replacing plastic hinging of the members, with replaceable ductile connections which can undergo similar or larger inelastic deformations without causing physical damage to the members of the structure. Hence, a low damage structure is similar in behaviour to a conventional capacity designed structure (e.g. no period shift, Fig. 1 right) except the members of the structure behave elastically and return to their original positions after a ground motion. The aims of low damage design are to ensure post-earthquake functionality and reduce financial loss related to downtime, repair, and reconstruction. (Hare, Oliver and Galloway 2012) give a well-defined list of properties which a structure designed according to the low damage design philosophy should have, although the discussion of their paper is more focussed on buildings.

1.2 Design Strategy

Design strategies are the means of achieving the goals of a particular design philosophy. For capacity design it clear that the design strategy is plastic hinging (Fig. 2, far left). For seismic isolation the commonly associated design strategies are the use of elastomeric isolators, such as, elastomeric bearings (low and high damping) and lead rubber bearings (Robinson, 1982) (Fig. 2, centre left); and sliding isolators, which includes, friction pendulum devices (Zayas, Low and Mahin, 1990), and plain sliding isolators, such as pot, disk, and spherical bearings (Buckle, Constantinou, Dicleli, and Ghasemi 2006).

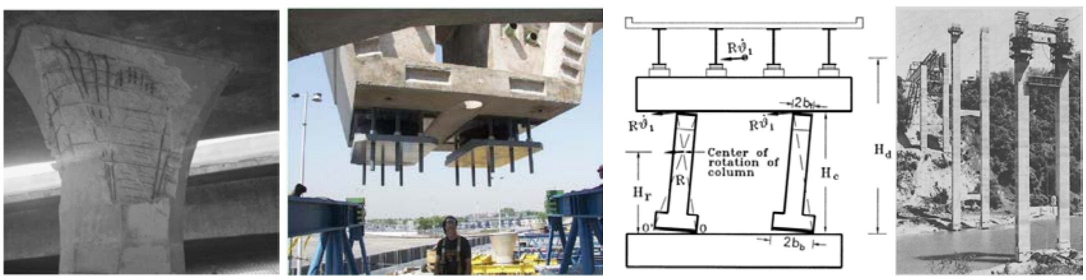

Figure 2. Examples of various design strategies: far left, plastic hinging (Roberts 2001); centre left, isolation by lead rubber bearings (Buckle et al. 2006); centre right and far right, isolation by free rocking of columns (Mander and Cheng 1997) and stepping of piers (Robinson 1985).

A less commonly associated design strategy for seismic isolation is the allowance of free rocking behaviour of a structure (Figure 2, right), which includes, stepping (Beck and Skinner 1974; Chen, Liao, Lee and Wang 2006) and shallow foundation uplift (Evision 1977; McManus 1980). Free rocking is a form of isolation because the natural period of vibration of the structure increases with amplitude of rocking displacement, hence, reducing seismic demands (Housner 1963; McManus 1980). The response of rocking structures has been studied intensively since the 60's and evidence showing the isolation effects of rocking can be easily found in literature (Anastasopoulos, Loli, Georgarakos and Drosos 2013; Chen et al. 2006; Housner 1963; McManus 1980; Mergos and Kawashima 2005). It is also important to note at this point that the effectiveness of rocking as a form of isolation depends on both the geometry of the structure and the damping available. Damping in a free rocking structure is mainly in the form of radiation (or contact) damping, which, in many circumstances may not be enough to keep displacements within a tolerable level. An example of this is the South Rangitikei Viaduct (Beck and Skinner 1974), where, supplemental damping was provided by the designers to address this issue.

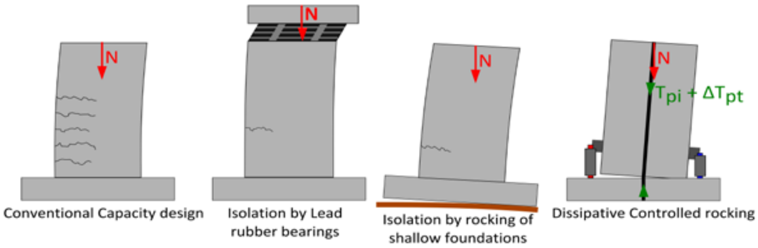

Figure 3. Comparison of the damage potential of the current design strategies.

Compared to seismic isolation, low damage design has comparatively few design strategies which not only meet the concept of the philosophy but also satisfy the corresponding aims (e.g. self-centering properties). In terms of bridges (which is the type of structure this paper is more focused on due to the expertise of the authors) there is currently only one design strategy for achieving low damage design which is dissipative controlled rocking (Fig. 3, far right). Dissipative controlled rocking (DCR), also known as the Hybrid PRESSS connection for buildings (Priestley, Sritharan, Conley and Pampanin 1999), consists of creating a discontinuity between members at a connection and connecting the two members together using unbonded post-tensioning and replaceable dissipative devices. In such a design strategy, all nonlinear behaviour once accommodated by plastic hinging is now accommodated by replaceable dissipative devices and gap opening, whilst, a dependable restoring force (enough to minimise residual displacements) is provided by the post-tensioning.

2 DISCUSSION: THE DIFFERENCE BETWEEN SEISMIC ISOLATION AND LOW DAMAGE DESIGN

Based on the description of the underlying concepts of seismic isolation and low damage design, it is natural to ask whether seismic isolation is the same as low damage design. The premise behind this proposition being that, because the seismic demand due to a design earthquake is reduced to a level such that the isolated structure remains elastic, the structure is expected to sustain no damage under a design earthquake, hence qualifying isolation as a way of achieving low damage design.

At first sight, this proposition appears to be true. However, there are a few flaws to this argument. Firstly, isolated structures are still designed according to conventional capacity design principles (this being especially true for retrofitted structures). This means that in the event that the accelerations experienced by the structure are large enough, or if the isolation devices fail, or if the travel of the isolation devices is exceeded so as to mobilise the shear keys, then the structure will still become damaged due to the formation of plastic hinges (Fig. 3, centre left). Even free rocking structures (unless specifically designed for such as in the study undertaken by (Antonellis and Panagiotou, 2014)) are not entirely protected from the development of plastic hinges (Fig. 3, centre right and Fig. 4, left). This is because the reduction in curvature ductility demand from rocking isolation may not be enough to preclude plastic hinging. In addition to this, for rocking foundation structures, the potential for higher than anticipated soil cohesion or unexpected placement of overburden on top of the foundation could result in fixed base response of the structure causing unintended damage.

Figure 4. a) Plastic hinge formation occurring at the base of a pier designed to rock on a shallow foundation (Espinoza and Mahin 2012). b) Residual deck displacement of the seismically isolated Bolu Viaduct in Turkey following the 1999 Duzce Earthquake (Roussis, Constantinou, Erdik, Durukal and Dicleli 2002).

The second point to the argument that isolation and low damage design are different is that, without the hindsight of the desirable properties of low damage design, such as, self-centering, one could very easily design an isolated structure which does not meet the objectives of low damage design. This being especially true for bridges. For example, according to (Buckle et al. 2006) Italian engineers design seismically isolated bridges to exhibit elastoplastic behaviour with no regard for restoring force (an example of a bridge which utilised this design strategy is the Bolu Viaduct in Turkey). Therefore, these isolated structures are designed to satisfy only the seismic isolation philosophy because they may develop significant residual displacements (Tsopelas and Constantinou 1997),which not only affects immediate post-earthquake functionality (Fig. 4b), but also, the future response of the structure under another earthquake. The consequence of the latter point being, possible damage of the structure due to the isolators displacement capacity being reduced by the previous earthquake or further accumulation of residual displacement depending on the ground motion characteristics (e.g. being “pulse like” (Cardone, Gesualdi and Brancato 2015; Tsopelas and Constantinou 1997)) rendering the bridge unusable.

3 DISCUSSION: THE MISCONCEPTION THAT DCR AND FREE ROCKING WORK IN THE SAME WAY

Dissipative Controlled Rocking (DCR) is most often related to the design strategy of free rocking due to both strategies utilising discontinuities between structural members and the belief that DCR is simply the combination of free rocking, post tensioning, and dissipative devices. However, other than the obvious similarities between the strategies these two design strategies are different in their behaviours which consequently affects the design philosophies to which they belong to.

Consider for example the free rocking (Fig. 6) and ground motion response (Figs 7 & 8) of the HBD5/PT2 pier specimen (Fig. 5, right) taken from (Marriott 2009) and modelled in OpenSees using a simple 2 gap-spring SDOF (Fig. 5, left) in three different configurations: free rocking of the pier, post-tensioning only (controlled rocking), and post-tensioning with dissipators (DCR).

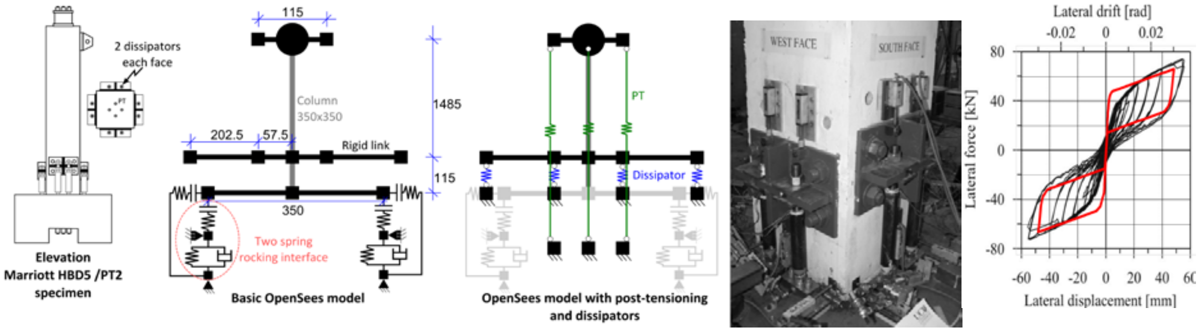

Figure 5. Left, OpenSees models of test specimens HBD5/PT2 taken from (Marriott 2009). Middle, photo of HBD5 specimen from (Marriott 2009) with external buckling restrained fuse dissipators, and concrete to steel rocking interface. Right, comparison of the model and experimental flag shaped hysteresis curves.

It can be seen in Figure 6 that the addition of post-tensioning immediately reduces the initial period of vibration due to the additional restoring force provided by tendon elongation. The combination of post-tensioning and rocking is called controlled rocking due to the adjustable nature of the post-tensioning in controlling the self-centering ability of the structure. It can also be observed that the addition of post-tensioning has little effect on the damping of the system as it remains elastic, meaning, 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 due to the continuous supplemental damping provided by the dissipators quickly diminishing 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.

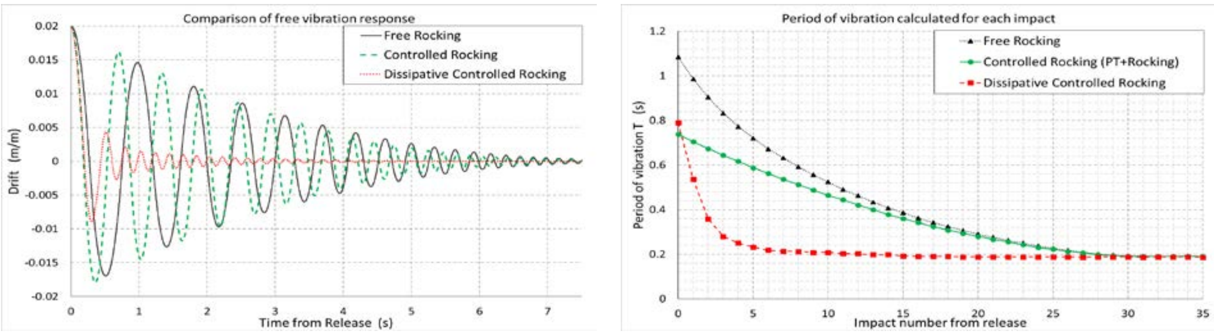

Figure 6. a) Free vibration response since release from 2% drift. b) Variation in the period of vibration as a function of the number of rocking impacts since release.

Inspecting the response history (Fig. 7) of the same pier, in the same three configurations, subject to seven different ground motions (Fig. 7, 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. 7) clearly shows the period elongation effects of free rocking which are not observed for the controlled rocking (post-tensioning plus rocking) or DCR configurations.

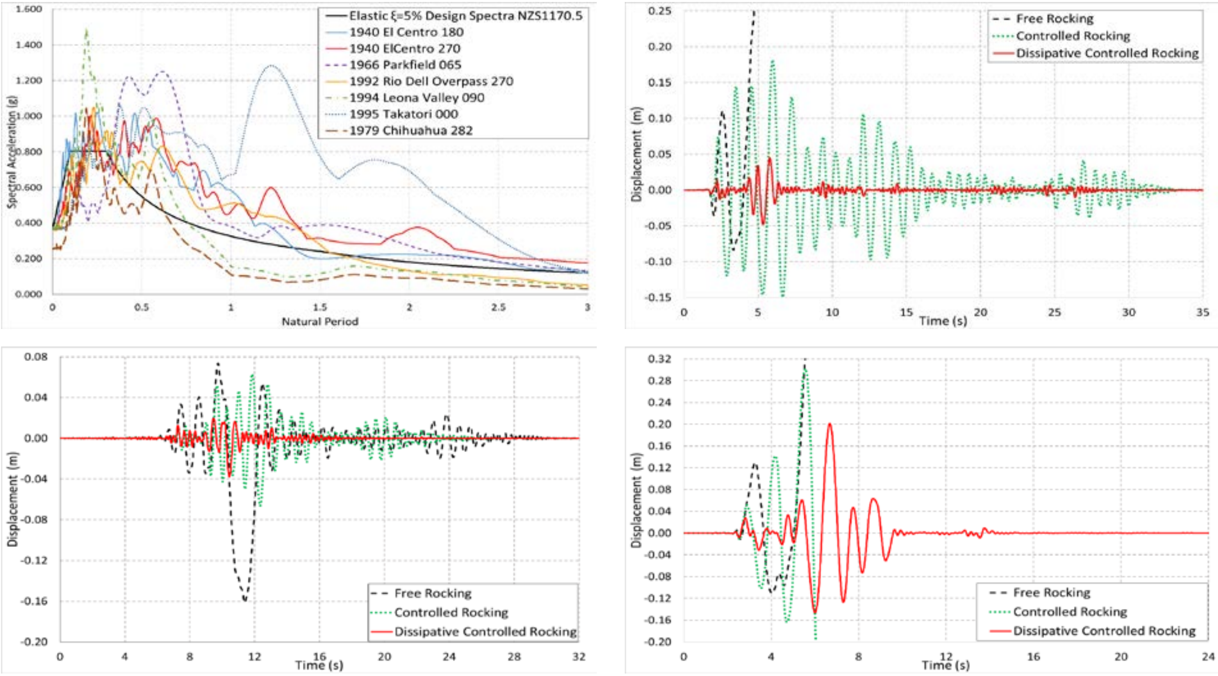

Figure 7. Top left, 5% damped elastic acceleration spectra used for nonlinear response history analysis. Top right, bottom left, and bottom right, displacement response of the three pier configurations subject to the 1940 ElCentro 180, 1994 Leona Valley 090, and 1995 Takatori 000 records respectively. The 1994 Leona Valley 090 record was the only record which did not result in overturning of the free rocking configuration.

This conclusion can also be drawn from Figure 8 which provides a graphical representation of the average and peak accelerations measured prior to overturning of the free-rocking configuration. It shows in general that the free rocking configuration experiences the lowest accelerations; the controlled rocking configuration experiences the highest accelerations; and the DCR configuration experiences the second lowest accelerations due to the significant amount of damping from the dissipators. It should be noted that the isolation effects of the pier in the free rocking configuration are not very significant (Fig. 8) due to the pier not being designed to utilise free-rocking as a form of seismic isolation in the first place. In addition to this, free rocking is very sensitive to the characteristics of the ground motion (Makris and Roussos 2000). This is why the overturning of the free rocking configuration occurred in all of the ground motion simulations except for the 1994 Leona Valley 090 record (Fig. 7, bottom left). The DCR configuration did not overturn in any of the simulations and the controlled rocking configuration only overturned when subject to the 1995 Takatori 000 record (Fig. 7, bottom right).

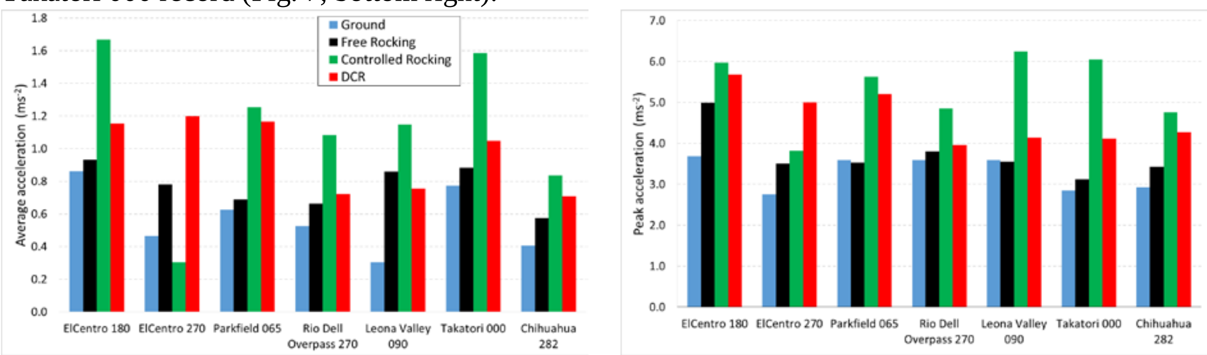

Figure 8. Left, the average acceleration experienced prior to the free rocking pier overturning. Right, the peak acceleration experienced prior to the free rocking pier configuration overturning.

4 INTRODUCING A NEW DESIGN STRATEGY AND THE COLLAPSE LIMIT STATE CONCEPT

Despite the benefits which DCR has to offer, such as, ensuring post-earthquake functionality and reduced financial losses, the design strategy does suffer somewhat from a lack of structural redundancy and robustness. This is because, currently, cantilever rocking bridge piers have the rocking interface situated at the bottom of the column with only one set of hysteretic dissipators which activate at a set level of earthquake loading (Filiatrault, Restrepo and Christopoulos 2004; Mander and Cheng 1997; Marriott 2009; Palermo, Pampanin and Calvi 2005). Because the dissipators are all designed to activate at a set level of earthquake loading and all have the same ultimate capacities, then the redundancy and robustness of this design strategy is purely provided by the post-tensioning and multiplicity in the number of dissipators. 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. 9). This issue is of particular importance in the case of cantilever DCR piers being subject to sequential earthquakes due to the initial earthquake consuming the majority of the capacity of the dissipators leading the structure to become vulnerable to excessive displacements and possible collapse in the following ground motion.

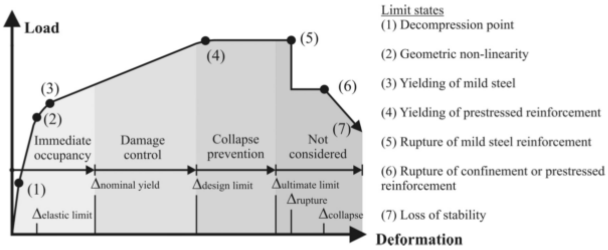

Figure 9. Performance objectives and limits for a DCR pier (Marriott 2009).

To remedy the aforementioned redundancy issues, research is being conducted by the authors at the University of Canterbury on a new design strategy based on dissipative controlled rocking called "Multi-Performance Dissipative Controlled Rocking". The robustness of DCR is increased through discretizing the capacity of the structure provided by dissipative devices and or mechanisms, such that, the devices and or mechanisms are activated in a hierarchical manner under increasing levels of shaking. In this way, under more frequent seismic loading (ground motions more common than the ULS earthquake) only one set of dissipative devices or a single mechanism is relied upon for resisting the resulting earthquake loading. If however, the intensity of the ground motion exceeds that of the ULS earthquake then a second set of dissipative devices or mechanism is activated in addition to the first set of devices or mechanism. A similar idea was used by (Marriott, Pampanin, Palermo and Bull 2008) in undertaking shake table testing of rocking walls which combined both metal hysteretic dissipators and viscous dampers. Two obvious benefits of such an arrangement is that for the case of having two sets of dissipators across the rocking interface: firstly, the first set of dissipators can be designed to use more of their cyclic load capacity than they currently are, meaning that these dissipators are more optimized; and secondly, under "normal circumstances", only the first set of dissipators designed to activate under more frequent seismic loading would need to replaced, with the urgency of immediate replacement lessened due to the presence of the second unused set on standby.

To this end the authors will be investigating three ways of achieving such a design strategy. The first two ways of achieving such a strategy are to have multiple sets of dissipators across one rocking interface (Fig. 10, left), or to segment the column to have multiple rocking interfaces with one set of dissipators across each rocking interface. These two arrangements are termed hierarchical DCR. The third way is to combine a cantilevered DCR bridge pier with either a rocking shallow or rocking pile foundation (Fig. 10, right), hence, utilising the benefits of rocking isolation. This arrangement is termed "hierarchical foundation rocking-DCR".

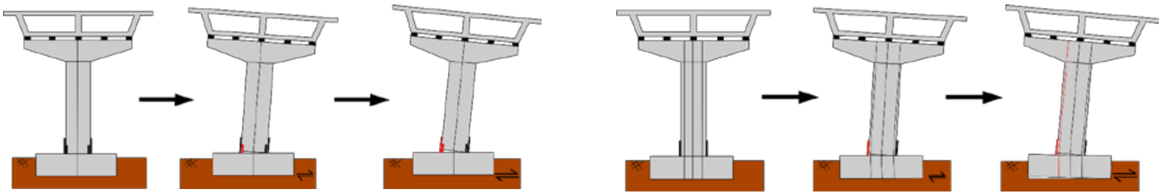

Figure 10. Left, an example of hierarchical DCR.
Right, an example of hierarchical foundation rocking DCR.

Following on with the discussion of the robustness of DCR piers, a way of measuring this would be to inspect the push over curve of the structural system utilising the design strategy (Fig. 11). In likeness to inspecting the push over curve for a monolithic concrete structure, labelling the behaviour as ductile or brittle, and also labelling the salient points of interest indicated by changes in behaviour; a similar concept can be applied to DCR piers, except that, because the components of a DCR pier are physically separate, it is easier to correlate changes in behaviour of the structure to events pertaining to the components within the structure e.g. yield of the post-tensioning or rupture of a dissipator. Hence, the "collapse limit states" of a DCR structure can be defined past the collapse prevention limit state and used as a measure of robustness (Fig. 11).

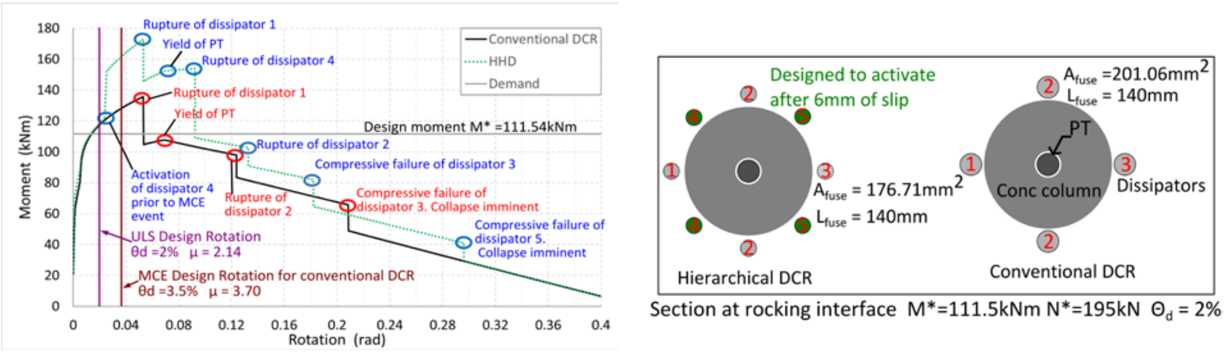

Figure 11. Left, M-θ pushover curve (including P-Δ) comparing hierarchical DCR with conventional DCR. Right, the corresponding DCR connections analysed for producing the pushover curves.

5 CONCLUSION

In conclusion, this paper has clarified the definitions of low damage design and seismic isolation. It has shown that these philosophies are different because seismic isolation still relies on conventional capacity design and because a seismically isolated structure may not satisfy the aims of low damage design. However, the choice of choosing a design philosophy to design a structure may not be purely based on the potential for reduced damage but also other factors which include, construction and maintenance costs; ground conditions affecting the seismic response of the site; and aggressiveness of the environment.

It was shown through preliminary free-vibration and nonlinear response history analyses that DCR and free rocking exhibit very different behaviours and that DCR behaves more like a fixed base structure, whilst, free rocking displays isolation effects. Based on these preliminary results and the aforementioned differences between seismic isolation and low damage design, the authors propose the possibility of combining isolation devices with dissipative controlled rocking to create a structural system utilising the benefits of seismic demand reduction as well as the elimination of plastic hinging of the structural members altogether.

Finally, this paper has proposed two new design strategies to increase the structural robustness of DCR called "hierarchical DCR" which, utilises multiple sets of dissipative devices activated under different levels of loading; and "hierarchical foundation rocking-DCR" which, combines rocking isolation with DCR. This paper has also shown the benefits of these strategies over conventional DCR, and presented the concept of "collapse limit states" for these systems.

6 ACKNOWLEDGEMENTS

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