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Effect of near and far field seismic events on the exhaustion of dissipater fatigue life

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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 the PRESSS system or Dissipative Controlled Rocking (DCR). Designing such structures using DDBD allows easy control of the deformation demands on the components of the structure so that performance targets can be met at a given limit state. However, in order to ensure satisfactory performance, strain limit definitions need to exist. Currently, strain limits to control damage levels at the design limit state (ULS) and ensure life safety at the collapse limit state (MCE) are not well defined for DCR connections especially with regards to the dissipative devices. The cyclic demand placed on the dissipaters fatigue life is highly sensitive to the characteristics of the ground motion. In this paper, the effect of current strain limits will be investigated by designing a variety of DCR connections using a particular type of axial dissipater. NLTH analysis will then be carried out where the fatigue life of the dissipaters is incorporated. Near and far field ground motions will be used in the analysis. The outcomes of the paper are to investigate the rationalization of metal axial dissipater strain limits in addition to investigating the effect of ground motion type on the exhaustion of the fatigue life of the dissipaters investigated.

1 INTRODUCTION

The hybrid PRESSS system (Priestley, 1996) also known as dissipative controlled rocking (DCR) is a type of Low Seismic Damage structural system. It consists of inserting dry joints between structural members (e.g. column-foundation, beam-column) to allow rocking; unbonded post-tensioning to clamp the components together (in addition to self-weight) to provide dependable self-centering; and internal or external dissipative devices crossing the rocking interface to provide damping and moment capacity. Currently, the state of art design document for DCR is the PRESSS Design Handbook (Pampanin, Marriott, Palermo, & New Zealand Concrete Society, 2010). This design document like others for more conventional structural systems (traditional reinforced concrete, steel, etc.) specifies a strain limit to be reached at the Damage Control Limit State (DCLS, also known as the Ultimate Limit State, ULS). For DCR, this strain limit is 0.05. However, it is based on results from quasi-static cyclic experiments whose displacement history does not reflect the typical displacement history a structure would experience in a real ground motion, and the tests used a particular kind of dissipative device (buckling restrained fuse type dissipators and partially debonded reinforcing) whose low cycle fatigue characteristics may be different to other dissipative devices which can also be used in DCR e.g. the grooved type dissipator (White, 2014). Therefore, there are three significant design related research problems which need to be resolved: one, rationalisation of the strain limit definition at DCLS so that it not only includes a value of strain but also a corresponding number of cycles able to be undergone at that strain amplitude; and two, determination of the typical level of low cycle fatigue damage which a DCLS level ground motion would cause; and three, investigation into whether specification of a satisfactory DCLS strain limit will automatically satisfy performance requirements at the Collapse Avoidance Limit State (CALS, also known as MCE). This paper aims to investigate the first two problems in particular, investigating whether near and far field ground motions impose significantly different cyclic demands given that near field motions tend to have a shorter predominant period (Kramer, 1996), have more high frequency content, and be of shorter significant duration (5-95% of Arias Intensity) than far field records (Bommer & Martinez-Pereira, 1999). The third problem was investigated in a previous study (Liu, McHaffie, & Palermo, 2018).

2 NUMERICAL STUDY

2.1 Methodology

A numerical study was devised where three different cantilever DCR bridge pier models were subject to a suite of scaled near and far field ground motions using non-linear response history analysis (NLRHA). Important engineering demand parameters relevant to this study were recorded in each analysis: e.g. the displacement history of the extreme fibre dissipative devices. The results were then collated and statistically analysed to determine the effect of those types of DCLS level ground motions on the exhaustion of the fatigue life of the dissipaters based on the current strain limit of 0.05. The pier models were designed such that they covered a large range of effective periods of vibration possible for highway bridges in New Zealand in order to capture any trends related to period of vibration of the structure.

2.2 Structural and seismic design

Three different structural models of SDOF DCR piers were used in this study and were labelled designs: A, B and C. Design A was based on a 12m span bridge using a Double Hollow Core Deck, and designs B and C (Figure 2) were based on bridges using a 20m span Super-T deck. All three designs used piers of different heights. Seismic design of the piers was carried out using DDBD and NZS 1170.5 to provide the design spectrum. The piers were all designed to target a design drift of 2%. Also, the elastic design spectrum was produced assuming that the piers were sited on a Soil Class C site; a hazard factor Z = 0.3; a return period factor R=1.3; and a near fault factor of N = 1. Structural design was carried out using the PRESSS design handbook (Pampanin et al., 2010) for guidance.

The fuse length of the dissipaters was chosen such that at the design displacement, the device at the extreme tension fibre would reach a strain of 0.05. The CALS displacement was determined iteratively and it was assumed that the spectra at this limit state was 1.5 times the design spectrum (New Zealand Transport Agency, 2013). The models used the 4 groove dissipater (White, 2014), a metal hysteretic dissipative device whose low cycle fatigue properties are known from experiments previously conducted at UC. Table 1 summarizes the resulting structural properties of the piers after completing seismic design, whilst, Table 2 summarizes the low cycle fatigue properties of the dissipators.

Table 1: Summary of the structural properties of the three pier models used.

Property	Design A	Design B	Design C
Seismic Weight (kN)	1600	1900	1900
Pier Diameter (mm)	1000	1500	1500
Pier Height (mm)	3000	4000	6000
DCLS Displacement (mm)	60	80	120
CALS Displacement (mm)	101	154	226
Number of Dissipators	8	8	12
Dissipator Circle Diameter (mm)	1100	1600	1600
Dissipator Fuse Area (mm)	404.3	284.5	248.8
Dissipator Fuse Length (mm)	290	490	474
Post-tensioning Area (mm^2)	4185	1963	3205
Post-tensioning Length (mm)	4170	8377	11270
Initial Post-tensioning Force (kN)	800	380	1140

Table 2: Dissipator cyclic properties

Property	Design A	Design B	Design C
Number of cycles to failure at the DCLS level strain (0.05)	31.6	27.7	20.2
CALS dissipator strain	0.09	0.107	0.107
Number of cycles to failure at the CALS strain	7.9	4.8	3.9

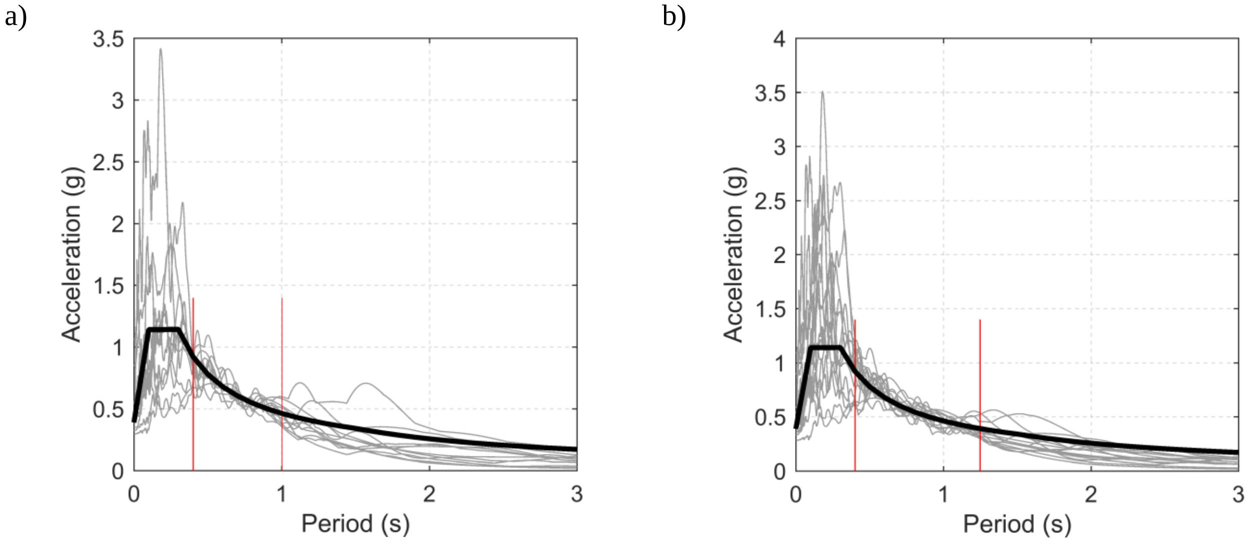

Figure 1: Ground motion scaling for: a) Design A (T_e= 0.77s) and b) Design B (T_e= 0.96s).

2.3 Ground motions

In order to examine the effect of near and far field ground motions in this study, ground motion scaling was used to select spectrum compatible records as shown in Figure 1. The ground motions were scaled to the design spectrum (described in subsection 2.2) over the period range of interest ($0.4T_e$-$1.3T_e$). Compatible ground motions were selected based on the scaling factors and their appropriate limits as defined in NZS1170.5:2004. The compatible ground motions were then split into near and far field categories: near field being defined as motions recorded less than 20km from the closest point of the ruptured area. In this study, most of the selected far field motions where recorded further than 80km from the closest point of the ruptured area. However, given the limited selection of spectrum compatible records, some motions recorded between 20km and 80km from the closest point of the ruptured area were included for use in this study as far field motions. For each ground motion category for each design (e.g. near field – design B) a minimum suite size of 10 ground motions was used.

2.4 Numerical models

Two dimensional models of the piers were constructed in OpenSEES (Figure 2a). The rocking behaviour, dissipative devices and post-tensioning were modelled explicitly. The rocking interface was modelled using the multi-spring element approach (Marriott, 2009); the dissipative devices were modelled as truss elements and used both the Steel02 and Fatigue materials; and the post-tensioning was also modelled as a truss element which used the Steel01 and initial strain materials. The multi-spring elements were distributed in a Lobatto distribution and the stiffness calibrated so that the neutral axis and moment – rotation response of the joint agreed with results from the widely accepted monolithic beam analogy model (Marriott, 2009). The coefficients for the fatigue materials used were calibrated off experiments previously conducted at UC. Table 2 summarizes the fatigue properties of the dissipaters used in the models. Figure 2b presents the resulting cyclic quasi-static force-displacement response of the three pier models. The peak displacements each model reached in Figure 2b corresponds to the calculated CALS level drift whilst the design level drift of 2% is annotated on the same figure.

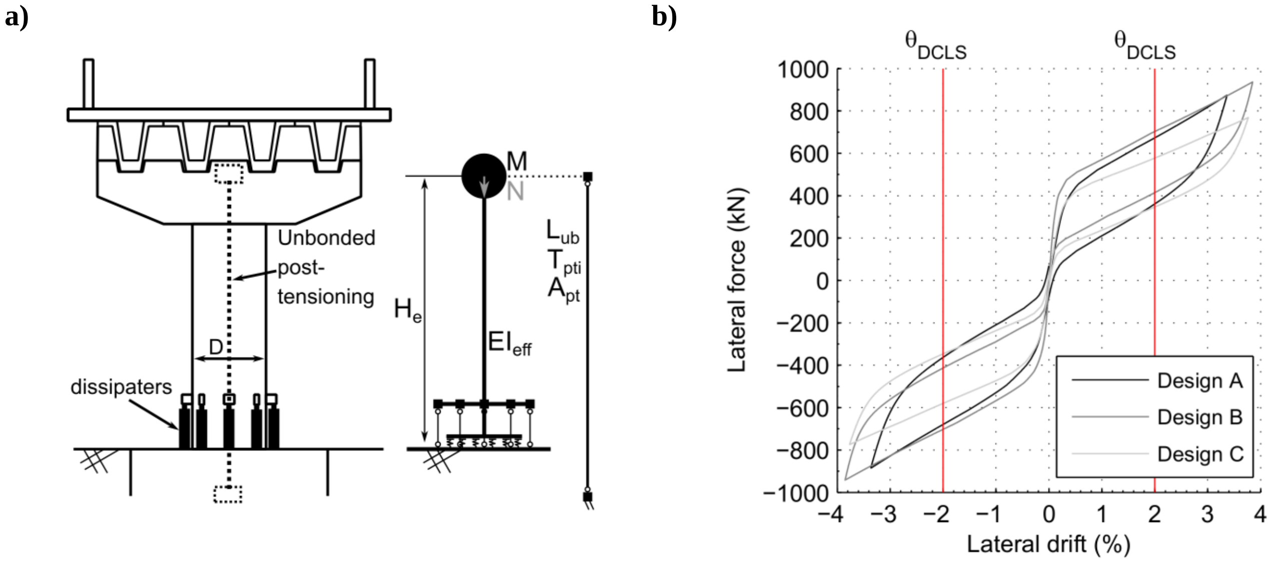

Figure 2: a) Sketch of prototype pier and numerical model; b) Quasi-static cyclic response of the three piers modelled in OpenSEES.

3 RESULTS

Three piers: Design A, Design B and Design C, with effective periods of vibration of 0.77s, 0.92s and 1.26s respectively were modelled and subject to NLRHA. Table 3 presents a summary of the results obtained. The three piers exhibited only small differences in peak drift and peak dissipater strain between each other indicating that the effective period of the structure has little effect on the fatigue demand of the dissipaters. The mean of the dissipater damage experienced by all three piers in response to the far field ground motions was 4.5%, whilst the corresponding average damage due to near field motions is 3.5%. This corresponds to about 25% more damage being caused on average by a far field motions than a near field motion. As the mean peak drift and mean peak dissipater strain are similar for both the near and far field ground motions for a given design, it can be concluded that the increased damage experienced in the far field motions is not a result of higher peak strains being reached but rather a result of this type of ground motion imposing a higher level of cyclic demand. Therefore, the results imply that far field ground motions are more critical when determining the appropriate low cycle fatigue capacity of dissipaters to prevent fatigue fracture at DCLS.

Table 3: Condensed relevant engineering demand parameters recorded from response history analysis.

Property	Far Field			Near Field		
	Design A	**Design B**	**Design C**	**Design A**	**Design B**	**Design C**
Mean peak drift (%)	1.73	1.61	1.64	1.69	1.69	1.37
Mean peak dissipater strain	0.037	0.038	0.035	0.037	0.038	0.028
Mean dissipater damage (%)	5.11	5.83	5.46	4.01	3.94	2.65
Max peak dissipater strain	0.054	0.055	0.050	0.049	0.066	0.047
Number of equiv. cycles at the DCLS level strain	1.62	1.61	1.10	1.27	1.09	0.54

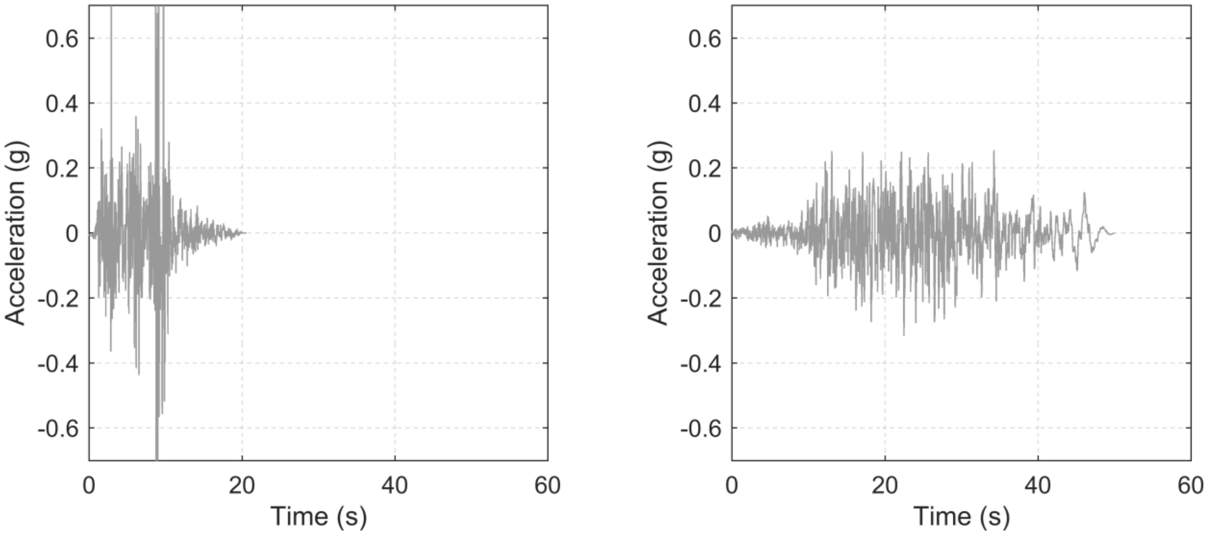

Figure 3: Scaled accelerograms, a) Near field - Nahanni, Canada (1985) 6.8km from epicentre , b) Far field - Landers (1992) 193km from epicentre.

Further examination of the ground motion characteristics shows that the near field ground motions typically have a higher peak ground acceleration, higher frequency content and a much shorter duration compared to far field events (Figure 3). It was also noted that the far field motions tend to have several acceleration peaks whose amplitudes are equal to or close to the peak ground acceleration of the record which is in contrast to the near field motions. These observations can be seen in typical near field and far field accelerograms shown in Figure 3. These observations are also consistent with (Bommer & Martinez-Pereira, 1999). The average Arias duration of the near and far field records used in this study was 22.69s and 7.8s respectively. The average far field motion duration was almost 3 times longer than the average near field motion.

Figure 4 illustrates the lateral drifts and dissipater strains for the same near and far field events plotted in Figure 3. It can be seen that although the peak accelerations are much higher for near field event, the peak lateral drift and dissipater strains are not any higher than for a far field ground motion. This is an expected result since the ground motions have been scaled to ensure the peak drift is near the design drift. Therefore, fatigue demand will always be larger for the far field motion as the number of significant cycles is much higher.

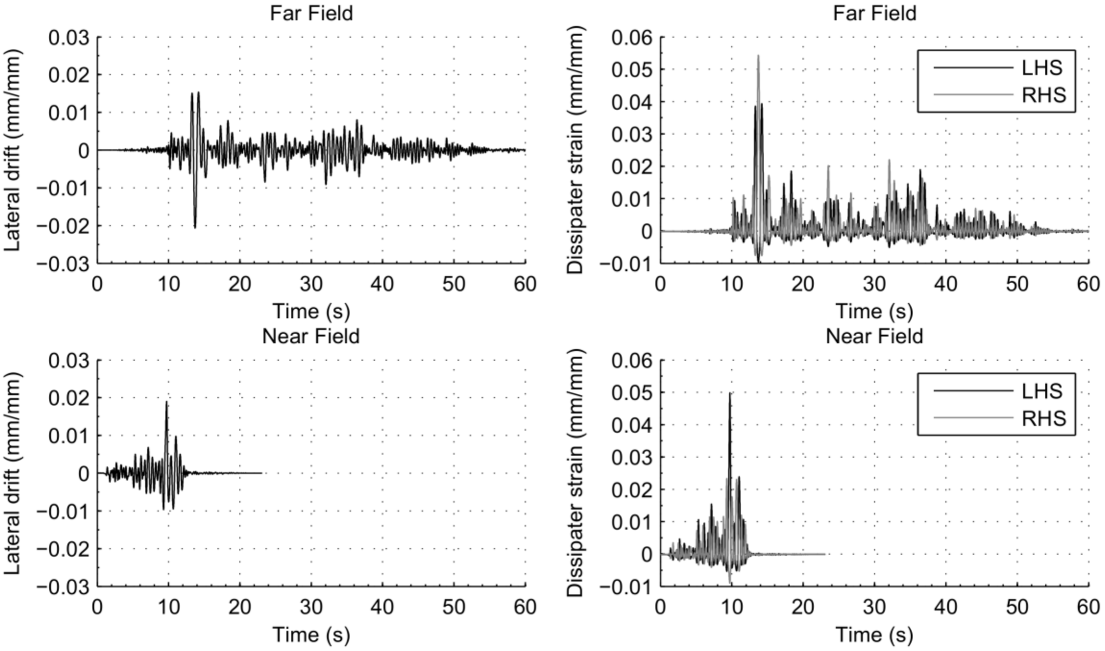

Figure 4: Comparison of the typical response (lateral drift and extreme fibre dissipater strain history) of pier design B to near and far field ground motions.

4 DISCUSSION

This study has indicated that ground motion characteristics due to site to source distance has an influence on the low cycle fatigue demand (in terms of the number of cycles of loading) experienced by the dissipaters of a DCR structure. This obviously has implications on the way that low cycle fatigue considerations should be handled in the seismic design of structural types such as DCR where this phenomena can be easily controlled. A caveat of this study was that the near and far field motions were scaled to the same design spectrum (so that the effect of characteristics other than the intensity of the motion could be compared) meaning that site to source ground motion attenuation effects were ignored. In terms of continuation of this work, the authors feel that it could be taken in two directions: scenario based analysis, where near and far field strain and cyclic capacity limits respecting both DCLS and CALS could be developed based on knowing the distance and properties of faults around a given structure; or undertaking more envelope/worst case type analysis, to develop more general strain and cyclic capacity limit recommendations applicable for any site to source distance scenario. Also, further investigation should be undertaken into investigating appropriate CALS strain and cyclic capacity limits by themselves. Although, (Liu et al., 2018) has investigated this, that study did not discriminate between near and far field records (meaning that intensity attenuation effects were not respected) and the effect of piers of different periods of vibration was not investigated either.

5 CONCLUSIONS

Three piers, designed to achieve a drift of 2% at the DCLS, were subjected to ground motions scaled to the design spectrum over the period ranges of interest. The three piers had effective periods of 0.77s, 0.92s and 1.26s. The piers were modelled in OpenSEES using the multi-sping element approach and NLRHA was undertaken to investigate the effect of the characteristics of spectrum compatible near and far field motions on the low cycle fatigue demand imposed on the dissipaters within the piers. The following conclusions can be drawn from this study: the effective period of the structure does not seem to have any significant effect on the fatigue demand placed on the dissipaters; comparing the near and far field motions used, it was found that typically the near field motions have a higher peak ground acceleration, a shorter duration (according to Arias Intensity) and far less significant acceleration peaks; when near and far field records are scaled to the same spectrum there is no significant difference in the peak drifts or peak dissipater strains reached; and far field motions were found to place a higher low cycle fatigue demand (125% more damage on average) than a near field motion and this is attributed to the longer duration of the far field motion. Further research is warranted to further this study for the Collapse Avoidance Limit State as well as investigate ways to incorporate either scenario compatible seismic hazard or worst case scenario analysis to form strain and cyclic capacity (number of cycles able to be handled) limit recommendations.

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