

Damaging Power of Alpine Fault Earthquake compared to Lyttelton and Darfield Earthquakes

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ABSTRACT

In a previous study by Hopkins et al. (2022), the role of duration on the overall damaging power of several earthquakes was examined for buildings in Christchurch CBD designed to NZS 4203:1976. The responses of elastic perfectly plastic oscillators were analysed in a way that tracked the cumulative post-yield energy demands, thus capturing the effects of shaking duration. This energy was taken as a proxy for damage potential of the earthquakes. Results for the February 2011 Lyttelton and September 2010 Darfield Earthquakes were compared for buildings with natural periods ranging from 0 to 5 seconds. Results indicated that the Lyttelton Earthquake was on average twice as damaging as the Darfield Earthquake for all buildings, but up to 12 times more damaging for buildings with natural period $<0.2s$.

This new study extends comparisons to include a case study of expected shaking in the Christchurch CBD from an Alpine Fault earthquake, and to buildings designed to NZS 1170.5:2004. The Alpine Fault Earthquake is expected to have much greater duration of strong shaking although the epicentre will be at a much greater distance from Christchurch. The cumulative energy method provides a means to compare the damaging power of the Alpine Fault Event relative to that of the Lyttelton and Darfield Earthquakes which accounts the duration of strong shaking. Results show that the longer shaking duration brings the “damaging power” of the Alpine Fault Event close to that of the Lyttelton Earthquake for buildings of 5 to 15 storeys.

The influence of duration of shaking is further examined by comparing peak inelastic response spectra with the cumulative energy demands of the chosen earthquake records. The comparisons offer strong insights into the damaging power of earthquakes and show that duration effects deserve more attention when assessing the performance of buildings in strong earthquake shaking.

1. INTRODUCTION AND BACKGROUND

Structural design procedures are commonly based on measurement of peak ground acceleration (PGA) or on response spectra derived from ground shaking records to show peak response. Observation of real events over the last several decades has shown that earthquakes with similar PGA levels can have very different damage profiles, suggesting that PGA is not the sole predictor of buildings' earthquake performance.

The Canterbury earthquakes of 2010-2011 showed that prolonged shaking, including aftershocks, caused increased damage. This highlighted the lack of consideration of duration in assessing building performance in earthquakes and the contribution of duration to the damaging power of earthquakes in current design procedures.

The energy absorbed by a structure will rise as the duration of strong shaking increases – until it reaches the limit of its capacity. Longer duration can lead to greater residual displacement through shake down effects, which compound the effects of post-elastic behaviour and can be a critical factor in building collapse.

Previous work (Hopkins et al., 2022) looked to shed light on the duration effects on the earthquake performance of buildings and on the assessment of earthquake damage, such as is made for insurance or risk management purposes. The cumulative energy absorbed by single-degree-of-freedom oscillators was compared to a reference energy to provide a non-dimensional measure of the damage potential of an earthquake, a Hysteretic Energy Ratio (HER). For buildings designed to NZS4203:1976, comparisons of the Darfield and Lyttelton Earthquakes were made for measured shaking in the CBD. The effects of the Lyttelton Earthquake yielded much higher HER values than for Darfield – on average double and for natural periods less than 0.2 seconds, up to 12 times as great.

In this paper the HER comparisons are extended to:

- Buildings designed to NZS 1170.5:2004, providing insights into the effects of varying design spectra.
- The likely effects of an Alpine Fault Event, providing a comparison of its likely damaging power with that of the Darfield and Lyttelton Earthquakes, accounting for strong shaking duration.

2. APPROACH AND METHODOLOGY

The approach and methodology are the same as for the initial study. The focus is on Christchurch buildings built since 1976, being those in Zone B designed to NZS 4203:1976 and those built to NZS1170.5:2004.

A range of single-degree-of-freedom oscillators is subject to different earthquake records using time-history analyses. The oscillators are set to yield at different levels according to their natural vibration periods, to match the chosen design spectrum. Figure 1 shows the spectrum used for NZS4203:1976 and the corresponding spectrum for NZS1170.5:2004. The oscillators range in periods from 0 to 5 seconds and are assumed to be elastic – perfectly plastic.

During the analysis the cumulative total energy absorbed by each oscillator during post-yield response is recorded. This is then compared to a *reference energy* for that oscillator to provide a non-dimensional Hysteretic Energy Ratio (HER).

$$\text{Hysteretic Energy Ratio (HER)} = \frac{\text{Cumulative energy absorbed by oscillator of period } T}{\text{Reference Energy for oscillator of period } T} \quad (1)$$

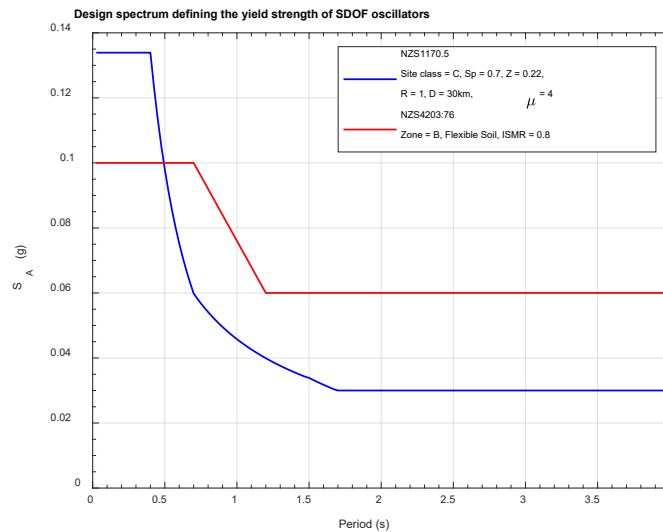
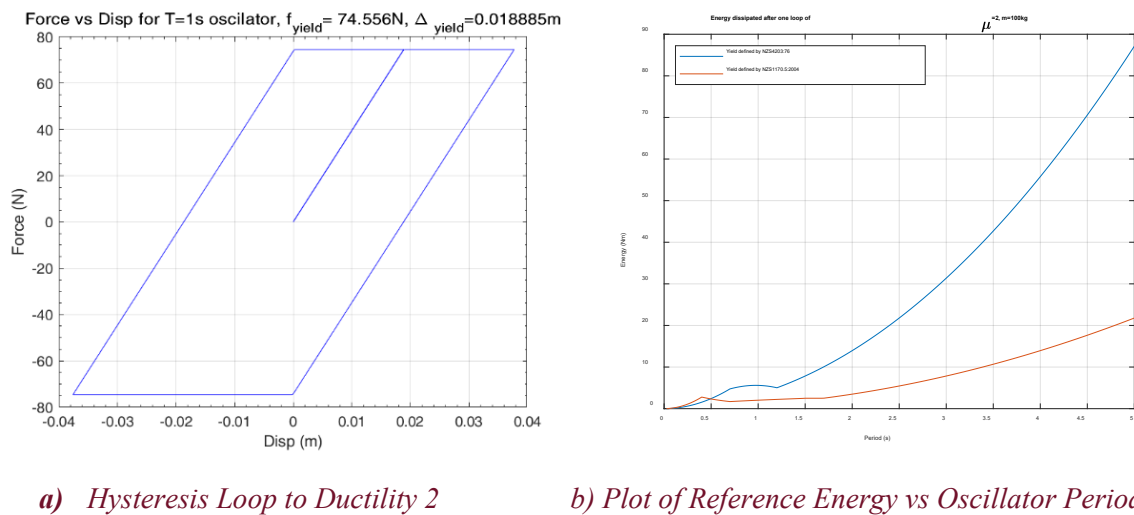


Figure 1 - Yield Spectrum used for Oscillators - from NZS4203:1976 and NZS1170.5:2004

The reference energy level for each oscillator is the energy absorbed in a single cycle of displacement to ductility 2 in each direction. The rationale behind the reference energy level is such that comparisons can be made with cyclic loading regimes in structural laboratories. Refer Figure 2.



a) Hysteresis Loop to Ductility 2

b) Plot of Reference Energy vs Oscillator Period

Figure 2 – Definition of Reference Energy

The reference yield *displacement* increases as period increases. The reference yield *force* follows the design spectrum. Being a multiple of yield force and yield displacement, the reference *energy* reflects the increase of yield displacement *and* the variation in the design spectrum coefficient.

Hysteretic Energy Ratios were determined for oscillators across the range of periods for the chosen earthquake records: Lyttelton, Darfield, and Alpine Fault.

Key output for each analysis comprises: a) Energy absorbed during inelastic response through the whole earthquake record - across the period range and b) Values of HER versus Building Period across the period range. This indicates the *relative* extent of post-elastic behaviour across the period range. Example outputs are shown in Figure 3(a) and 3(b).

The values of energy absorbed are difficult to interpret in physical terms, but the HER gives a meaningful non-dimensional reference. A HER value of 1.0 indicates that a structure of that period would have deformed the equivalent of a single cycle to displacement ductility 2. A value of 30 would suggest the equivalent of 30 such cycles, or 15 cycles to ductility 3, or 10 cycles to ductility 4. Figure 3(c) shows the relationship between HER and the laboratory testing regime used by Park (1989) which helps to set HER values in context. Two cycles to ductility 2 followed by two cycles to ductility 4 give a HER of 8.

Comparison of HER outputs provide insights into the potential damaging power of earthquakes, in a way that includes the duration effects.

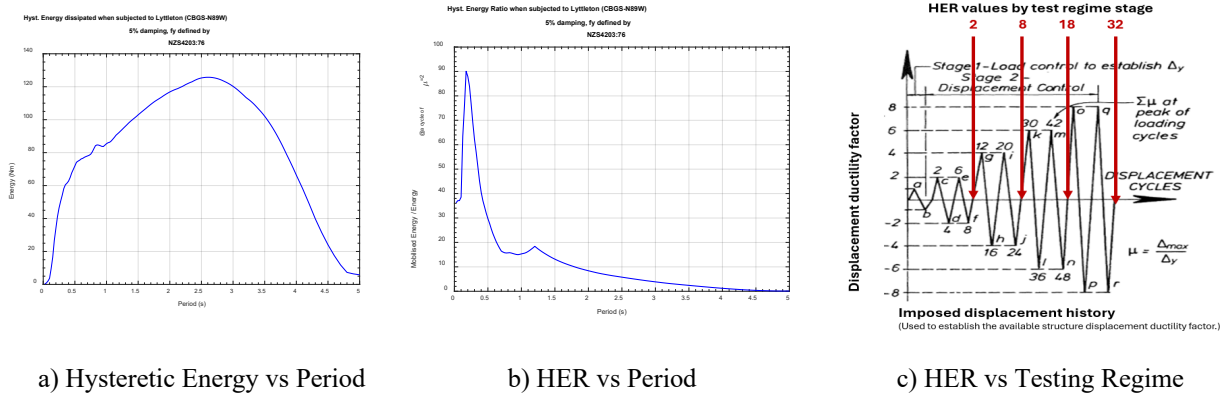


Figure 3 –Hysteretic Energy and Hysteretic Energy Ratio (HER) – Examples and context

2.1. Earthquake Records Used

To compare the damaging power of the Darfield, Lyttelton and an expected Alpine Fault Earthquakes, the earthquake records shown in Table 1 were used.

Table 1 - Earthquake Shaking Records Used in Analyses

ID	Event	Date	Station and direction	M _w	Depth (km)	PGA (g)	S _A (1s) (g)	Trifunac-Brady Duration (s)
1	Darfield, NZ	4 Sept 2010	Christchurch Botanical Gardens (CBGS-S01W)	7.2	11	0.18	0.35	23.2
2	Lyttelton, NZ	22 Feb 2011	Christchurch Botanical Gardens (CBGS-N89W)	6.2	5	0.53	0.79	9.7
3	Alpine Fault (Note 1)	Expected (11 Mar 2011)	Not applicable (Tohoku EQ Urayasu EW)	8.0 est. (9.1)	(32)	(0.16)	(0.48)	(102)

Note 1: Taken to be a similar in intensity and duration to effects in the Christchurch CBD from an Alpine Fault Event (Bradley 2012).

Geonet Ref: Darfield (3366146), Lyttelton (3468575), Kaikoura (2016p858000 or 20161113_110330)

3. HER COMPARISONS: LYTTTELTON AND DARFIELD AND ALPINE FAULT

Figure 4 presents HER plotted against period for the three earthquakes, for both the NZS4203 buildings and the NZS1170 buildings.

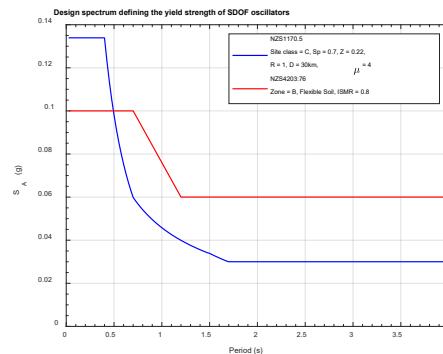


Figure 4(a) – NZS 4203 Buildings

Figure 4(b) – NZS 1170 Buildings

Figure 4 – Plots of HER values for 1170 and 4203 Buildings

The damaging power of the Lyttelton Earthquake is evident, especially for building periods below 0.5 seconds, despite its short 10-second duration compared with 24 seconds for Darfield event and 100 seconds for the Alpine Fault event. Because of its distance from Christchurch CBD, the Alpine Fault Earthquake would produce low HER in the 0 to 0.5 second range, comparable to those of the Darfield Earthquake for both building groups.

However, for periods from 0.5 to 1.5 seconds, the HER values for the Alpine Fault Event become comparable with those of the Lyttelton event, reflecting the higher input motions from the distant source and a duration which is 10 times that of Lyttelton.

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Further insights into the comparative effects can be gained from Figure 5 which shows three-dimensional plots comparing the *average* HER values in chosen period ranges, for NZS4203 and NZS1170 buildings.

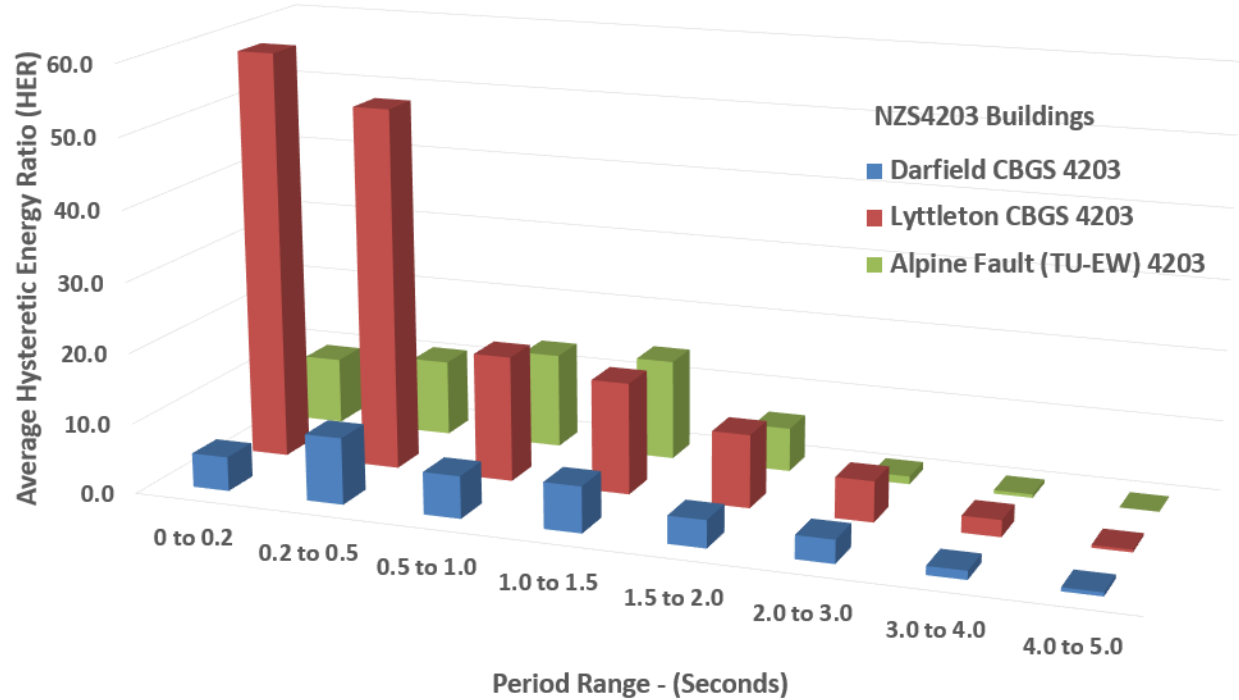


Figure 5(a) NZS 4203 Buildings

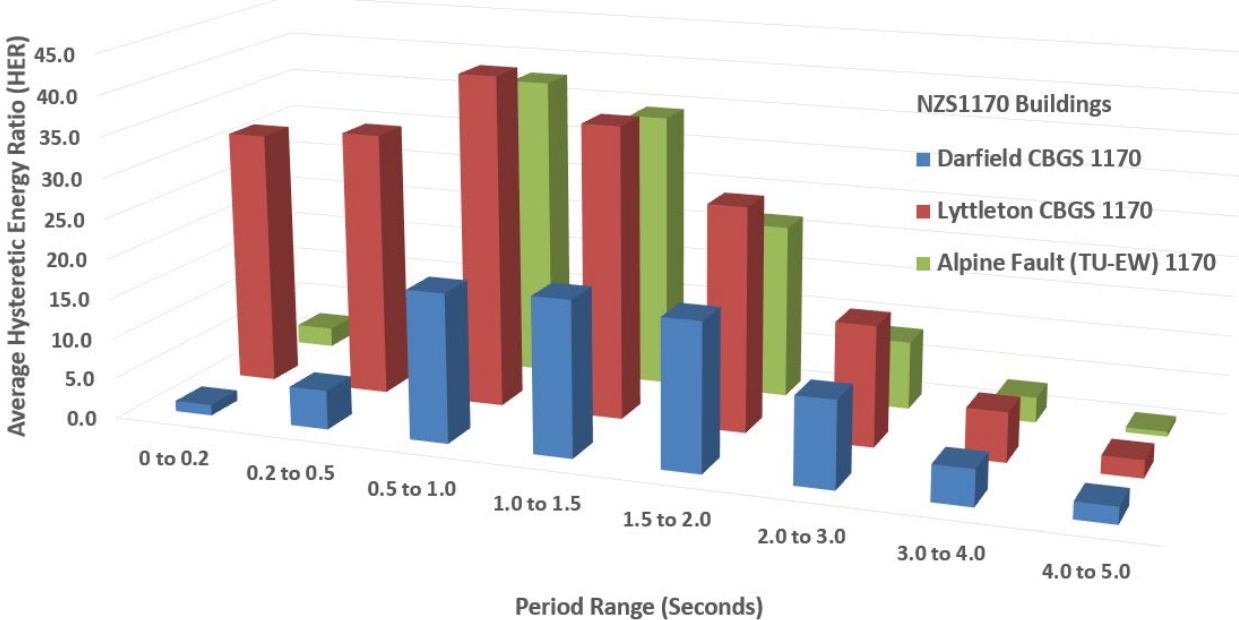


Figure 5(b) NZS 1170 Buildings

Figure 5 – Lyttelton vs Darfield vs Alpine Fault – Average HER by Period Interval

These figures highlight the comparability of Alpine Fault and Lyttelton events for buildings with periods of 0.5 to 2.0 seconds (5 to 20 storeys approximately) for buildings from the NZS4203 and NZS1170.5 eras. The effect of design spectrum values is evident when HER values are compared for say the 0.5 to 1.0 second range – where the NZS4203 design spectrum is 66% higher at 1.0 seconds. For 4203 buildings the HER is

12. For 1170 buildings HER is 36 – triple the damage potential. A HER of 36 is equivalent to 12 forward and reversing hysteresis loops to ductility 4, which would test the resilience of even the most robust of buildings. For comparison, the brutal laboratory loading regime used by Park (1989) (See Figure 3(c)) which has reverse cycles of increasing displacement ductility (2 at ductility 2, 2 at ductility 4, 2 at ductility 6 and 2 at 8) has cumulative energy demands equivalent to a HER value of 32. If the test was stopped after the two cycles at ductility 4, the HER equivalent is 8. Thus, HER values of around of eight and above indicate significant demands on structures and it is interesting to note where these occur and in which earthquakes.

The inclusion of the expected Alpine Fault Event allows comparison with the observed effects of Darfield and Lyttelton Earthquakes. For structural periods below $T = 0.5s$, Figure 4 shows that the Alpine Fault HERs are substantially lower than those for Lyttelton. However, for periods above 0.5 seconds through to 1.5 seconds, the HER values for the Alpine Fault Event are significantly more than those for Darfield and are comparable with and sometimes exceeding those for Lyttelton.

The influence of design code level shows up in the comparison between HER values for NZS 4203 and NZS 1170 buildings. Below $T = 0.5s$, the higher design value for NZS 1170 buildings reduces the peak HER value from 90 to 50. Above $T = 0.5s$, the situation is reversed with HER values for NZS 4203 buildings peaking at about 20 compared to over 40 for NZS 1170 buildings. This is food for thought for code writers. With this HER technique it would be possible to examine the damage potential of a range of earthquakes for any proposed design spectrum. Adjustments to the design spectrum could then be made to manage overall damage – taking account of profiles of building stock.

Further, the Alpine Fault event with a maximum PGA in Christchurch CBD of 0.16g produces HER values comparable to those from the Lyttelton Earthquake where the maximum PGA is 0.53g. This appears to be a clear indication of duration effects which has implications for all New Zealand buildings – and those in other jurisdictions.

The influence of duration effects can be examined further by comparing other key output variables such as maximum displacements, maximum accelerations and spectral response.

4. OTHER METRIC COMPARISONS

4.1. Maximum displacements

Figure 6 shows comparative plots of maximum displacements during the three earthquake records – for both NZS 4203 and NZ1170 buildings. In the critical region of around 1.0 second period, the Alpine Fault maximum displacements are significantly less than for Lyttelton. For both NZS4203 and NZS1170 buildings at $T=1.0$ second the Alpine Fault Event shows 0.2m maximum displacement compared to almost 0.5m for Lyttelton. That HER values for Lyttelton and Alpine Fault are comparable at this period is a clear indication of the duration effects. Multiple cycles at the lower displacement in the Alpine Fault Event produce comparable hysteretic energy absorption to the fewer cycles at the higher maximum displacements in the Lyttelton Earthquake.

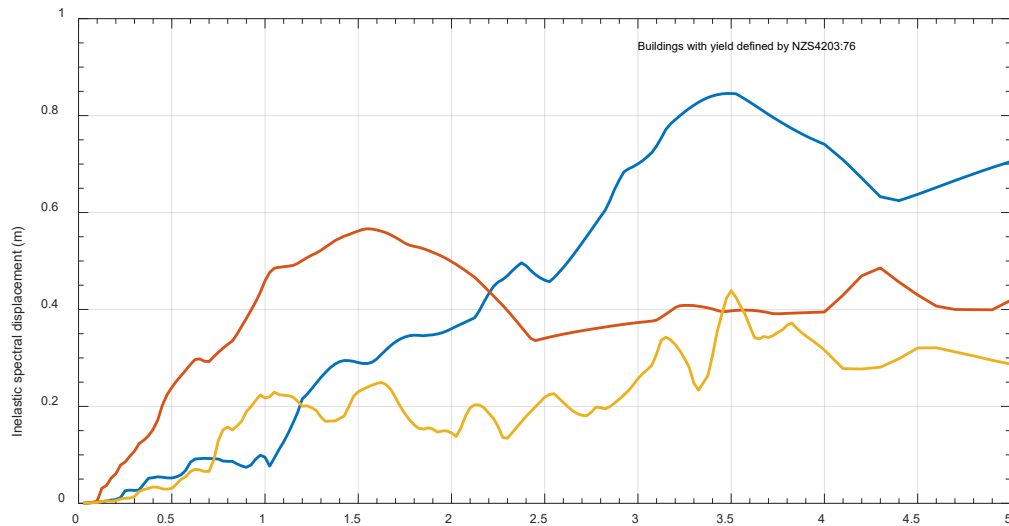


Figure 6(a) – NZS 4203 Buildings

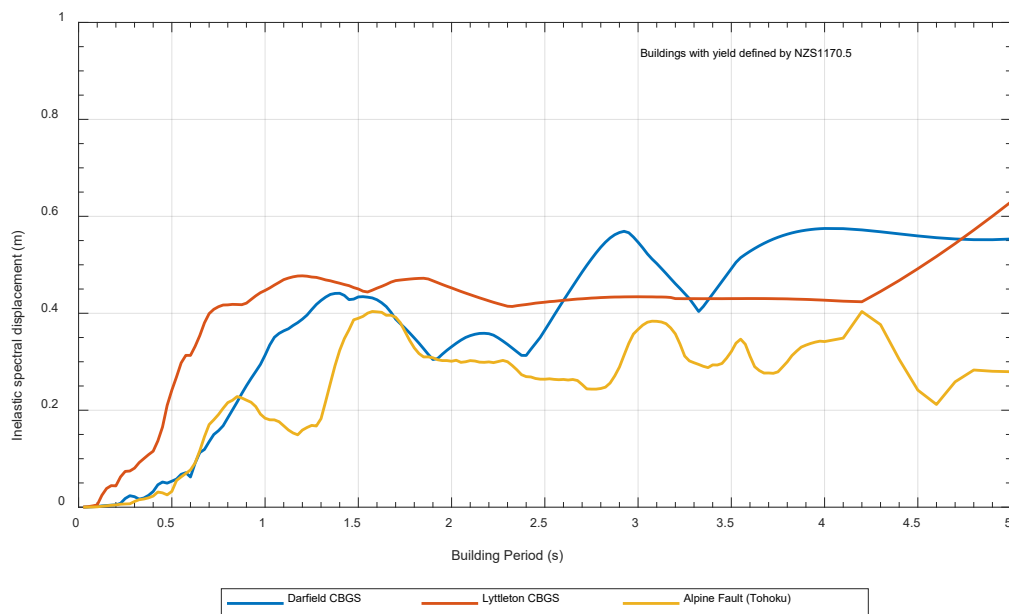


Figure 6(b) – NZS 1170 Buildings

Figure 6 – Maximum displacement for 1170 and 4203 Buildings

4.2. Maximum accelerations

Figure 6 shows comparative plots of maximum accelerations recorded during each the three earthquake records – for both NZS 4203 and NZ1170 buildings. Comparisons are less dramatic and reflect the yield levels set for the analyses.

The plots are a reminder that structural performance in earthquake relies on much more than the ability to resist accelerations. Integrity well beyond yield must be provided – for multiple cycles. Examining duration is vital to understanding the demands placed on structures and the residual capacities of a buildings that have been through a major earthquake.

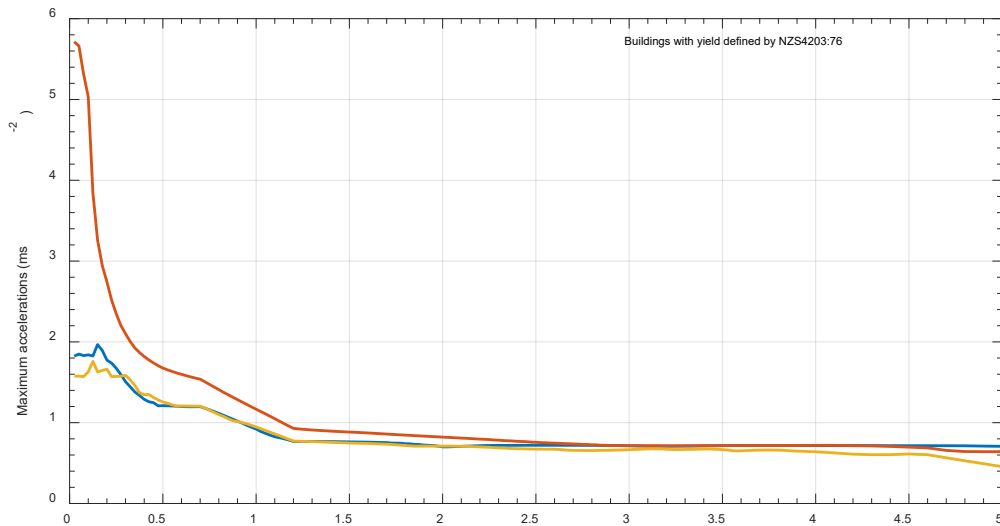


Figure 7(a) – NZS 4203 Buildings

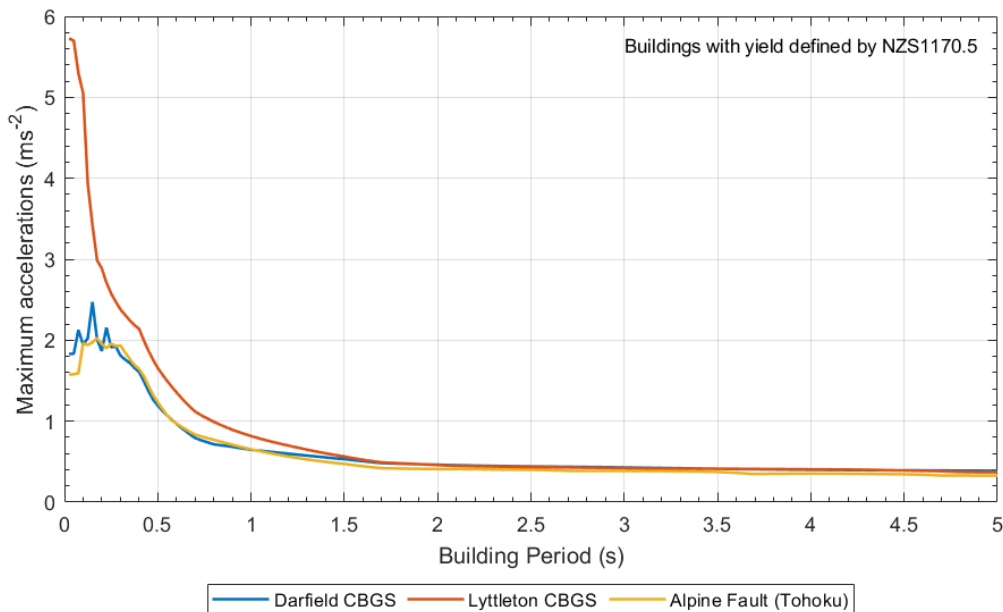


Figure 7(b) – NZS 1170 Buildings

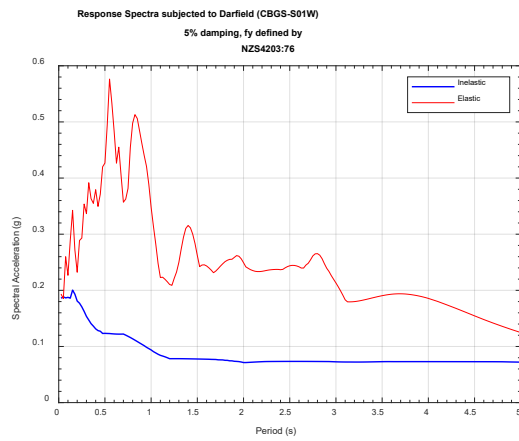
Figure 7 – Maximum accelerations for 1170 and 4203 Buildings

4.3. Response spectra

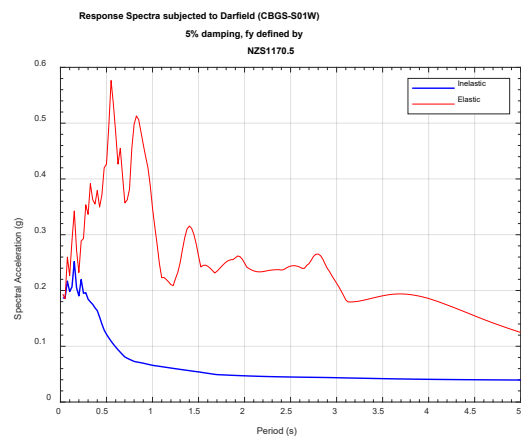
Figure 8 shows plots of elastic and inelastic spectral response accelerations for the three earthquakes for both building groups. The inelastic spectral responses are the same as the maximum accelerations shown in Figure 7 earlier, being generally limited by the yield levels set for the oscillators.

The elastic response spectra show the maximum accelerations that would be experienced by oscillators that do not yield. This gives an indication of the vigour of the shaking but does not capture the duration effect. Interestingly, though, the Alpine Fault values are higher than Darfield values from $T = 1.0\text{s}$ to $T = 2.0\text{s}$. This suggests that the impacts would be similar or more because of acceleration effects alone, *but the HER plots indicate that impacts would be greater than for Darfield in this period range - due to duration effects.*

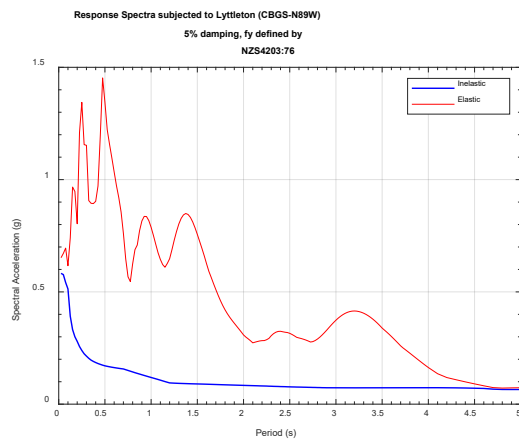
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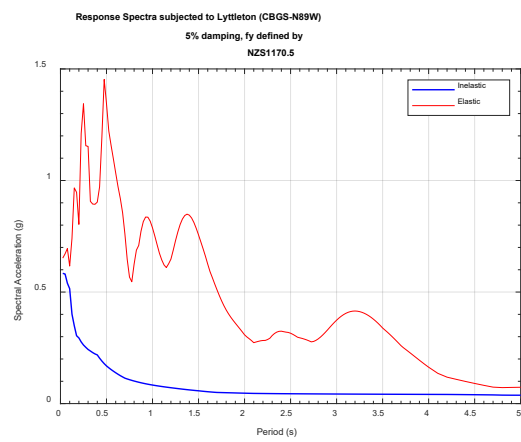
Darfield



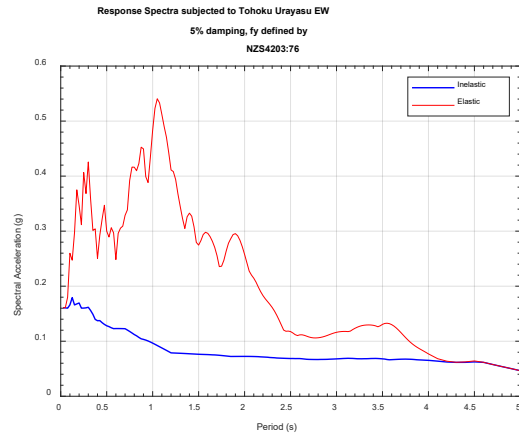
Darfield



Lyttelton

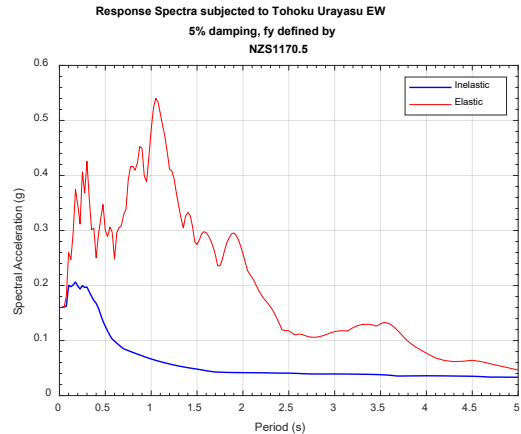


Lyttelton



Alpine Fault

NZS 4203 Buildings



Alpine Fault

NZS 1170 Buildings

Figure 8 – Elastic and Inelastic Response Spectra for Darfield, Lyttelton and Alpine Fault Earthquakes

Duration effects were further explored by examining the comparative elastic responses and the HER values. For NZS4203 buildings at $T = 1.0$ s, the HER for the Alpine Fault was 1.2 times the Lyttelton value while the maximum spectral inelastic displacements were 0.5 times the Lyttelton value. Similar values were derived for NZS1170 buildings at both $T = 1.0$ s and $T = 1.5$ sec. These examples clearly show a very different perspective on the relative severity of an earthquake can emerge when energy and duration are taken into account.

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5. KEY POINTS

5.1. Duration Effects

Shaking duration emerges as a dominant contributor to damage potential, particularly for the Alpine Fault scenario, which involves approximately 100 seconds of strong motion. The results indicate that, for buildings in the range of roughly 5 to 20 storeys, the Alpine Fault event is likely to produce greater damage than the Darfield earthquake. For periods around $T = 1.0$ s, damage potential of the Alpine Fault Event exceeds that for Lyttelton Earthquake despite much lower ground shaking levels, highlighting the influence shaking duration.

At periods less than 0.5 seconds, the Alpine Fault Event places greater energy demands than Darfield with a peak HER of 15.

5.2. NZS4203 vs NZS1170

Differing design yield levels can have a disproportionately strong influence on HER and thus damage potential. The HER approach could be used to examine implications of code changes by exploring the effects of changing yield levels on the HER values for a range of earthquakes to be considered in design. This would take account of duration and could lead to reductions in overall damage with judicious choice of design spectra.

5.3. Relating HER to Physical Demands

HER values of 10 or above indicate several cycles of structural deformation at a displacement ductility of 4.

The test loading regime used in university laboratory tests of two cycles to displacement ductility = 2, followed by two cycles to ductility = 4 represent a HER of 8. This is a high demand on real structures.

If the test regime is extended to add two cycles at displacement ductility = 6, and 2 cycles at displacement ductility = 8, the total energy absorbed is equivalent to a HER of 32 (See Figure 3(a)). Laboratory tests to this level and extent often resulted in destruction of the test specimens well before the intended test regime was complete - something to remember when looking at the HER values shown in Figures 4 and 5.

6. CONCLUDING REMARKS

The principal aim of this work was to compare the damaging power in the Christchurch CBD of the Alpine Fault Event with that of the Darfield and Lyttelton Earthquakes whose physical effects are known. The comparative graphs provide strong insights and can be useful tools in communicating the likely effects of the Alpine Fault Event.

Comparison of the HER values for the two building groups (NZS4203 and NZS1170) highlights the influence of design spectra values on behaviour of buildings in strong earthquake shaking. The HER analysis process could help assess the effects of any proposed design spectra, enabling fine tuning to reduce overall damage.

It would also be possible to quickly assess the likely impact on groups of buildings following a future earthquake event once the ground shaking record is available, identifying the structures most likely to have suffered. The HER analysis could also shed light on the likely residual capacity of structures. The approach of tracking hysteretic energy as described in this paper provides unique insights into the response of buildings to earthquake ground motions. It prompts users to think about the energy demands on buildings of different periods and to consider the effects of duration of shaking, whether in a single event or in successive events.

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David Hopkins is a consulting engineer specialising in earthquake risk management and is a Life Member of NZSEE. From 2003 to 2016 he was an advisor to DBH / MBIE on structural and earthquake engineering matters. His interest in the damaging power of earthquakes stems from several NZSEE learning-from-earthquake missions and estimating expected losses for insurance purposes.

Quincy Ma is an associate professor at the University of Auckland. Quincy has research interests on a range of earthquake engineering topics, such as risk-based cost-benefit analysis, low-damage design, seismic structural health monitoring, the modelling and performance of non-structural elements and machine learning.

Charlotte Toma teaches general design at first year level and design in concrete, steel and timber within the fourth-year structural courses. Following a BE(Hons) Civil and PhD from the University of Auckland, Charlotte worked as a consulting engineer on new build designs, multi-storey structures, analysis and assessment of existing buildings.