Rapid Earthquake Loss Assessment: Stochastic Modelling and an Example of Cyclic Fatigue Damage from Christchurch, New Zealand

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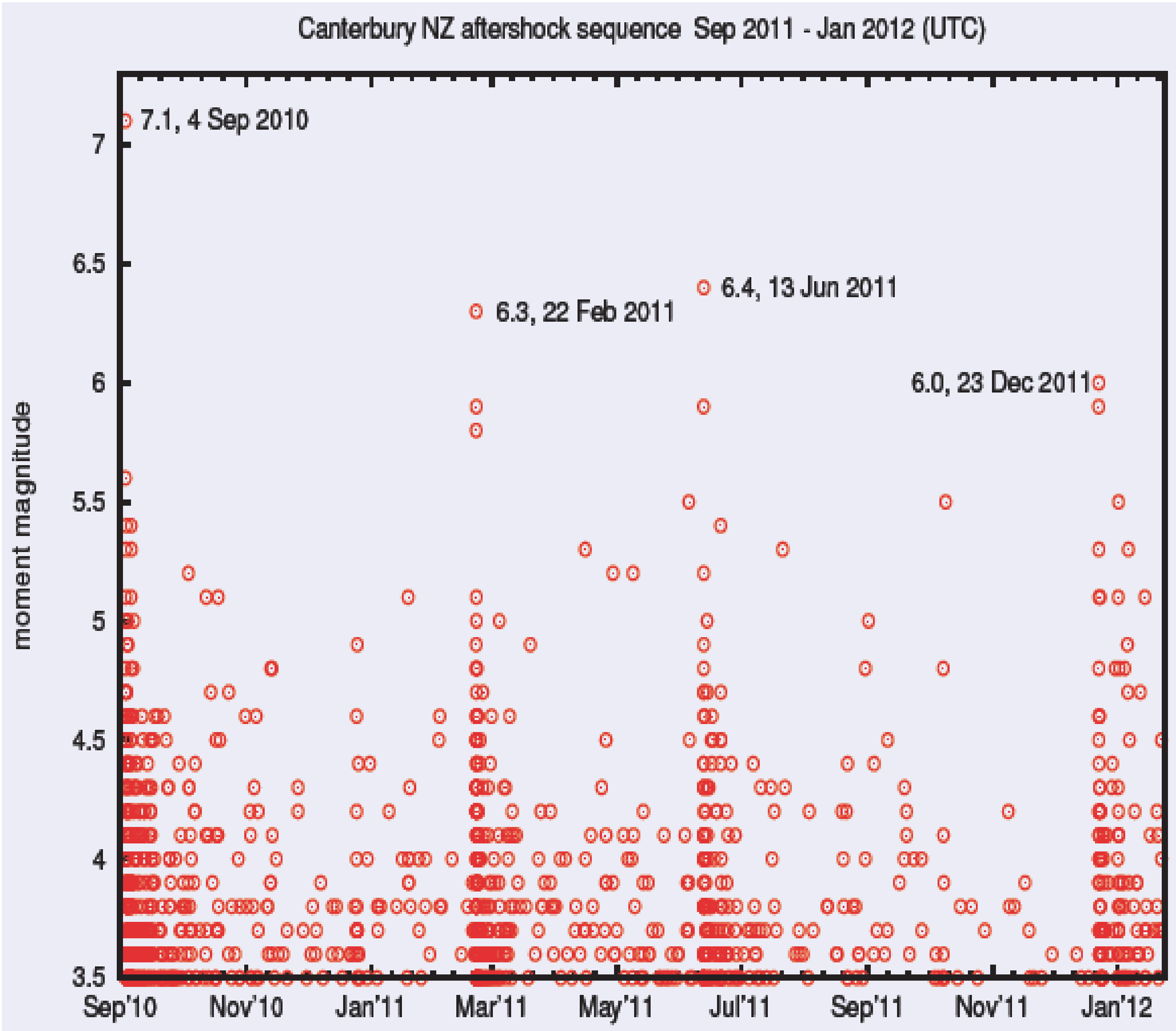
Canterbury Earthquake Sequence

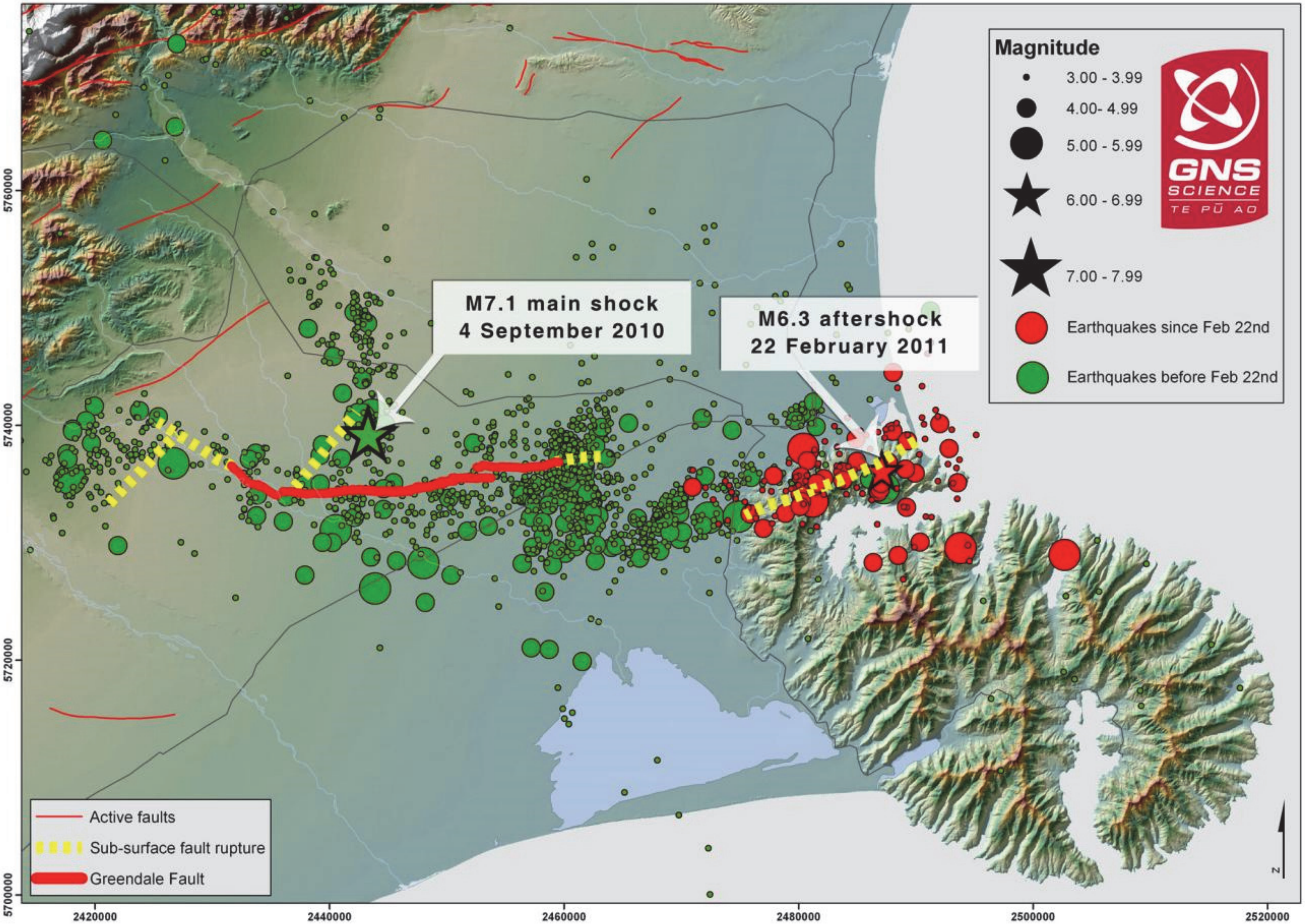
- Earthquake and aftershock sequence, starting on September 4th, 2010 and running for approximately 18 months.
- Four major large event clusters, with their own aftershock sequences and exponential decay
- February 22nd 2011 event was severe
  - M6.3, but shallow and close to the city (~5km from the city centre, 5km deep)
  - PGA within the city was up to about 0.75g, well beyond the design code, even for the MCE

Earthquake and Aftershock Sequence



Gavin, Nigbor et al. (2012)

Earthquake Shaking



How to assess damage?

With so many large earthquakes from a relatively unique earthquake sequence, how do you assess damage to structures?

Two key factors that lead to the overall damage effects on structures:

1. Maximum response displacement or drift

2. Duration of the earthquake, which leads to **cyclic loading effects**

Alternatively, we can ask: What is the remaining fatigue life of the structure?

Cyclic Loading Demands Lead to Fatigue

High-cycle fatigue:

- Aircraft wing flutter
- Engine vibrations
- Bridge deck vibrations
- Material behavior must remain elastic.
- > 2 million cycles: total stress range < 150 MPa.

Low-cycle fatigue:

- Material behavior: inelastic (post-yield)
- Fracture can occur in reinforcing bars during earthquakes
- Can lead to deterioration of concrete
- Phenomena well researched, but generally not well applied in practice.

Cumulative demand assessment

Overall demand across the entire earthquake sequence:

- How does an earthquake and aftershock sequence with different ground motion magnitude, frequency content and duration compare to a single event?
- What is the cumulative damage incurred across these earthquakes?
- What is the residual capacity (or remaining fatigue life)

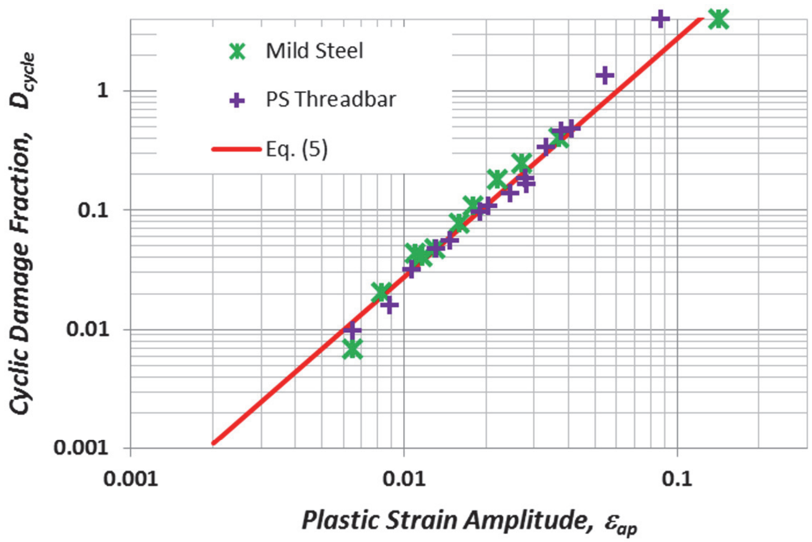
Fatigue Capacity Assessment

Steel Fatigue Tests

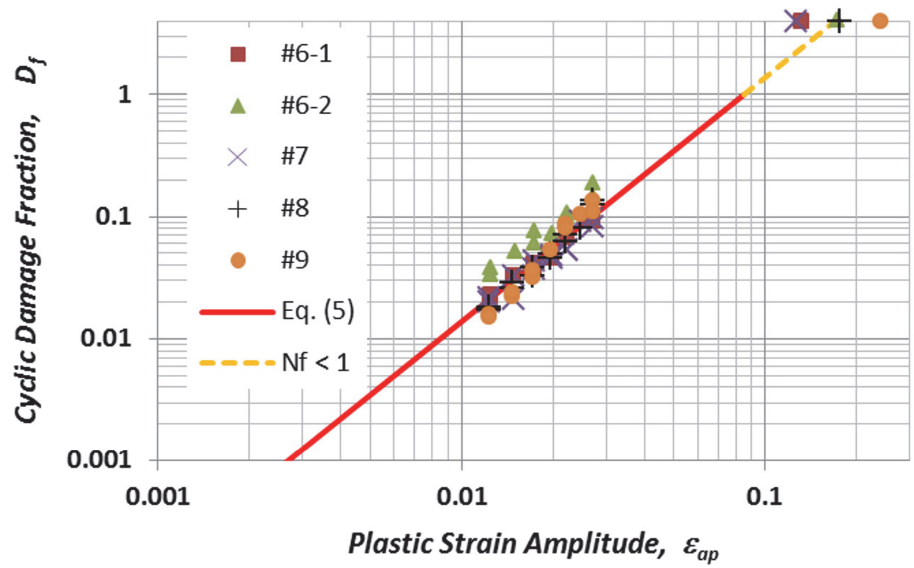
Define a 'Damage Fraction' which expresses the percentage of fatigue life consumed by cyclic loading. Loading histories are normalised to the strain amplitude for failure during a single reversed loading cycle, weighted by a fatigue exponent.

$$\varepsilon_{ap} = 0.08(2N_f)^{-0.5}$$

$$D_{cycle} = \frac{1}{N_f} = \left|\frac{\varepsilon_{ap}}{\varepsilon_{pf}}\right|^2$$



(a) $\varepsilon_{pf} = 0.06$ *from test results given in Mander et al. (1994).*



(b) $\varepsilon_{pf} = 0.083$ *from test results given in Brown and Kunnath (2004)*

Cumulative demand assessment

The effective amplitude, ε_i, can be calculated relative to a given reference amplitude, A_{ref}, where:

$$\varepsilon_i = \left(\frac{|x_i|}{A_{ref}} \right)^C$$

where x_i is the i^{th} displacement points and C is the fatigue exponent. The mean, m, of all displacement point can be determined from:

$$m = \frac{\sum_{i=1}^{N} \left(\frac{|x_i|}{A_{ref}} \right)^C}{n_{points}}$$

Where n_{points} is the total number of data points for that record, ie: $n_{points} = t_f/dt$, where t_f is the final time for the record, and dt is the time step. This mean value can be transformed into an effective amplitude, based upon the integration of fully reversed sine-wave cycle. For C = 2, this analysis is the same as a root-mean-squared approach whereby the effective amplitude can be determined by multiplying the mean value by a multiplier B = 1.414. For C = 1, B = 1.57 and for C = 3, B = 1.33. Therefore the effective amplitude becomes:

$$A_{eff} = Bm^{1/C} = B \left[\left(\frac{\sum_{i=1}^{N} \left(\frac{|x_i|}{A_{ref}} \right)^C}{n_{points}} \right)^{1/C} \right]$$

The effective number of fully reversed cycles at the current design period of interest can be determined from:

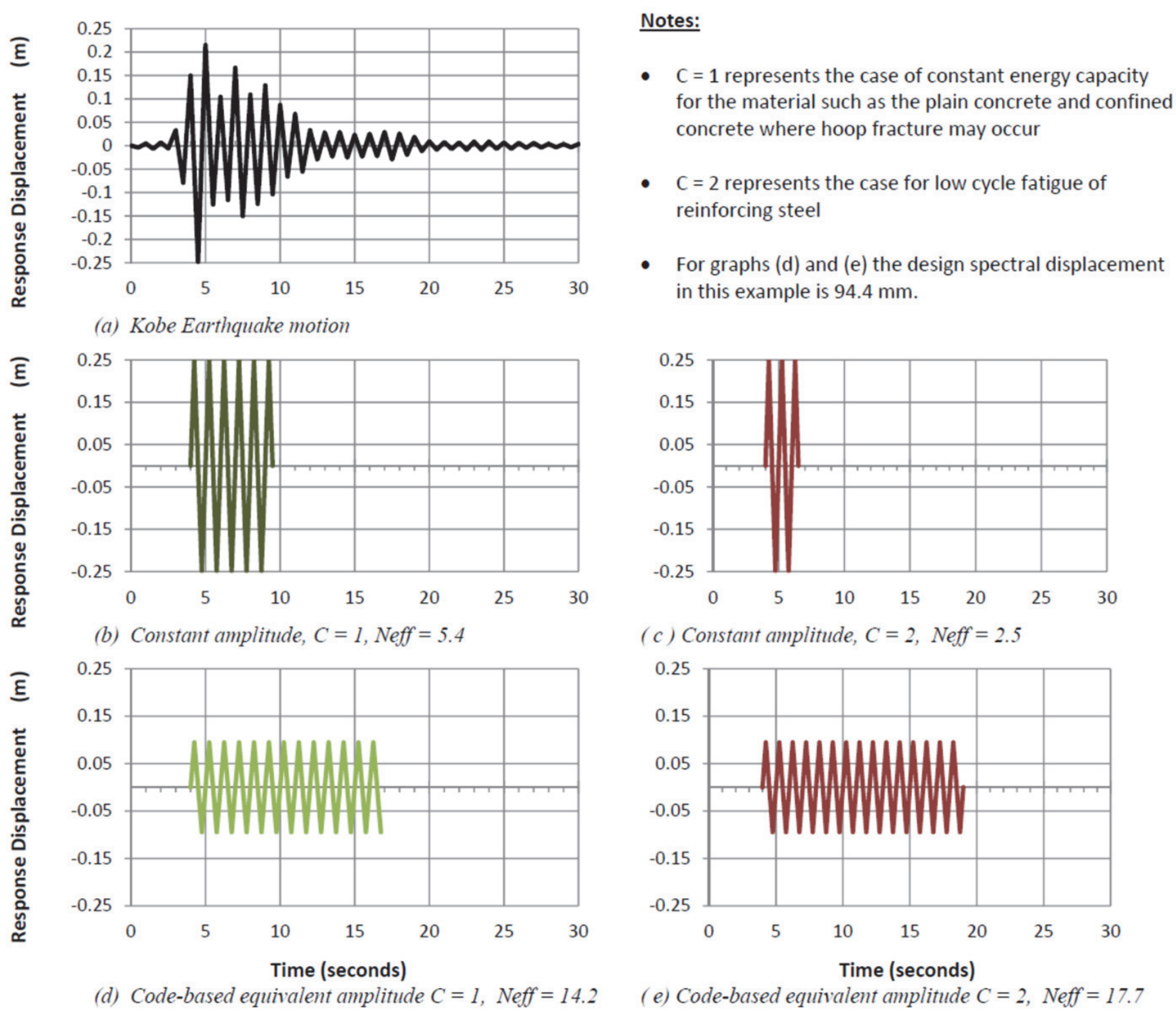
$$N_{cycles} = \frac{n_{points} \, \Delta t}{T} = \frac{t_f}{T}$$

where T is the natural period of the structure of interest. Finally, the number of effective cycles at the reference amplitude can be determined from:

$$N_{eff} = N_{cycles} \left(A_{eff} \right)^C$$

This final result, N_{eff}, presents the equivalent number of fully reversed response cycles at the reference amplitude A_{ref}.

Alternative to Rainflow analysis?



Simplified, cycle-counting approach to approximate the number of different amplitude cycles, similar to rainflow methods, to be used in a sense similar to Miner's rule.

Different Fatigue exponents place different importance on the relative amplitude of each cycle.

Structure-specific analysis

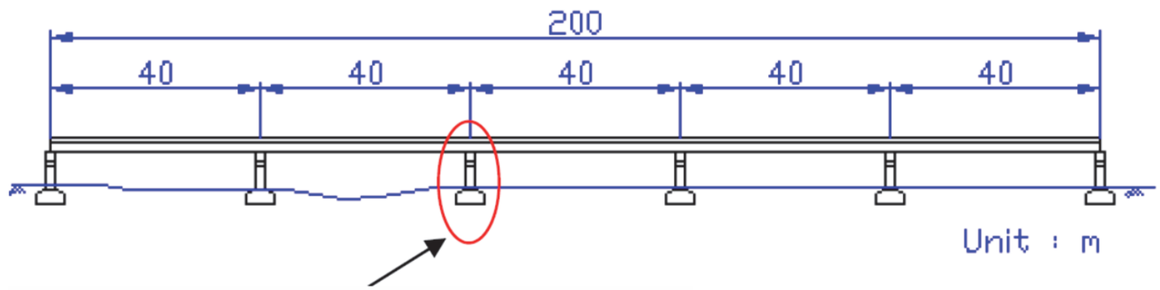
Structure-specific capacity assessment undertaken on a bridge pier designed (Tanabe, 1999) conforming to New Zealand code requirements.

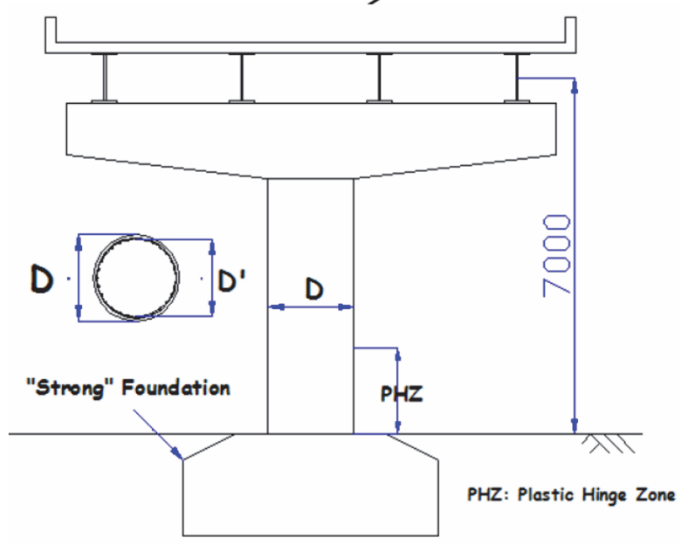
The pier is 7 m high and is taken from a "long" multi-span highway bridge on firm soil with 40 m longitudinal span and 10 m transverse width.

The super-structure reaction weight at each pier is assumed to be 7,000 kN.

Bridge designed for an earthquake with a spectral acceleration of 0.4g.

Mechanistic model developed to relate peak displacements to plastic hinge zone mechanics and reinforcing bar strains





D	1700
D'	1540
PHZ	1700
$P/A_g f'_c$	0.15
Bar	28-D32
ρ_t	0.99%
Spiral	R20@170
ρ_s	0.49%

ρ_t: the ratio of the longitudinal bars area to the pier's cross sectional area,
ρ_s: the ratio of the volume of the spiral to the volume of the confined concrete

Structure-Specific Fatigue Life Assessment

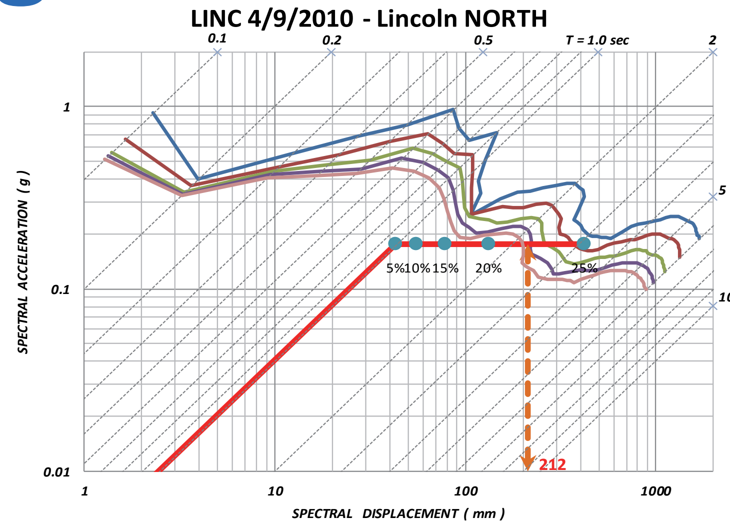
ADRS plotted on log-log scale → Period lines are diagonals

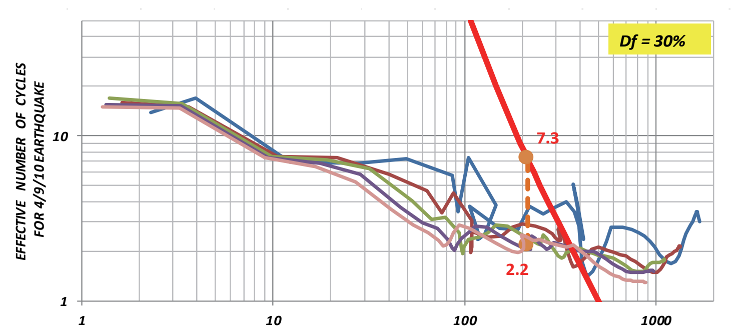
Elasto-plastic hand analysis gives capacity curve, with equivalent viscous damping from area-based methods

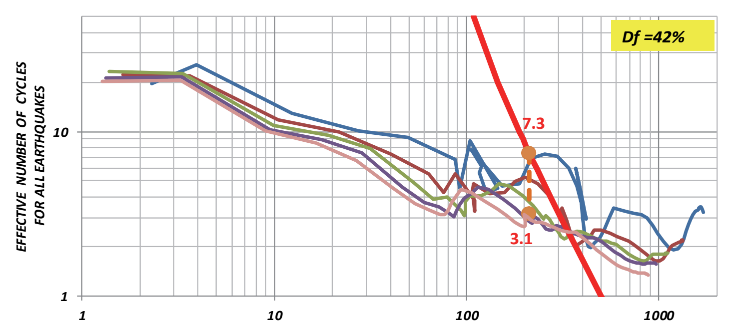
Demand curves given from spectral analyses

Intersection of capacity and demand dictates the effective peak amplitude.

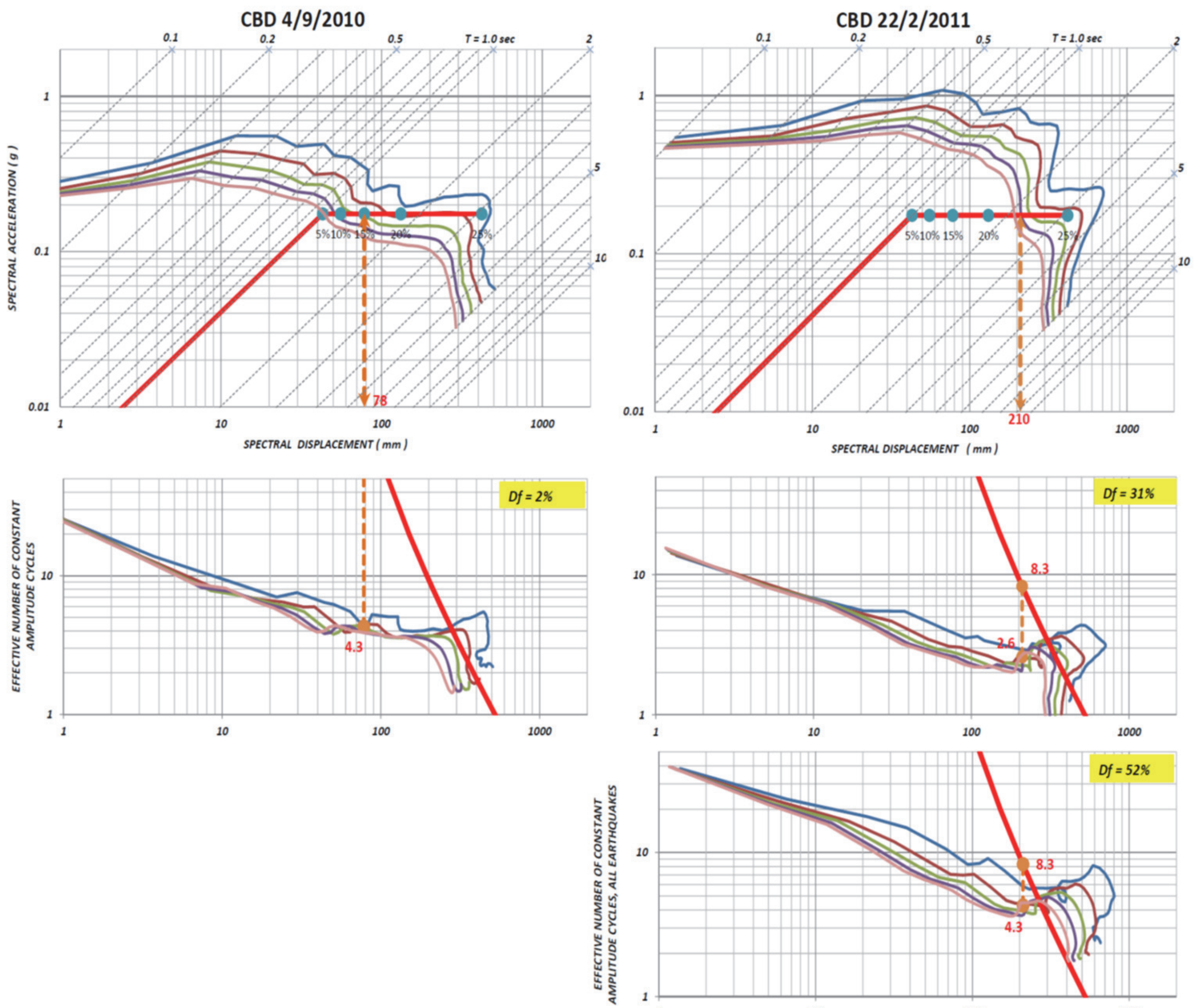
From this, an equivalent number of cycles and damage fraction can be calculated







CBD comparison – Sept. 2010 vs Feb. 2011



Demand in September 4th, 2010 is low, damage-fraction of only 2%.

Feb 2011 demand is much higher with a damage-fraction of 31%

When all major records are "daisy-chained" together, the cumulative damage fraction becomes 52%

Conclusions

Simplified, rapid, cycle-counting method developed to enable an estimate of the cumulative fatigue demand on structures from successive earthquakes.

Intended to promote further discussion on the concept of low-cycle fatigue and the way in which we assess the remaining fatigue life of a structure.

Ongoing research is looking into the rainflow methods and other alternate cycle counting methods to validate the simplified approach presented here,

How much fatigue life has been or can be allowed to be "used-up"?

How much is too much??