Experimental investigation of the seismic residual capacity of earthquake-damaged concrete buildings: Preliminary results

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INTRODUCTION

This poster presents preliminary results of ongoing experimental campaigns at the Universities of Auckland and Canterbury, aiming at investigating the seismic residual capacity of damaged reinforced concrete plastic hinges, as well as the effectiveness of epoxy injection techniques for restoring their stiffness, energy dissipation, and deformation capacity characteristics.

This work is part of wider research project which started in 2012 at the University of Canterbury entitled “Residual Capacity and Repairing Options for Reinforced Concrete Buildings”, funded by the Natural Hazards Research Platform (NHRP). This research project aims at gaining a better understanding and providing the main end-users and stakeholders (practitioner engineers, owners, local and government authorities, insurers, and regulatory agencies) with comprehensive evidence-based information and practical guidelines to assess the residual capacity of damaged reinforced concrete buildings, as well as to evaluate the feasibility of repairing and thus support their delicate decision-making process of repair vs. demolition or replacement.

1) EFFECT OF LOADING CHARACTERISTICS
University of Auckland

- **Test Design:**
  Fourteen identical large-scale RC beams are being tested at the University of Auckland. The specimen design meets all provisions for a ductile beam as per NZS 3101:2006 (see Figure 1).
- Test setup is a cantilever beam with shear span (M/V) of 2.58. This setup neglects the effects of gravity loads and assumes an inflection point at the beam mid-span and an elastic beam-column joint (see Figure 2).
- **Test Variables:**
  Loading protocols are varied between the tests, encompassing both static and dynamic loading rates as well as cyclic/pulse-type earthquake/long duration earthquake displacement histories. Emphasis is placed on varying the strain rate and cycle content at lower levels of displacement demand and observing the effect on the ultimate limit state performance (see Figure 4).
- Selected specimens are repaired by mortar patching and epoxy injection after being initially damaged. For each repaired specimen, an identically damaged specimen is left unrepaired and tested to failure. This allows for direct quantification of the benefits of the repair.

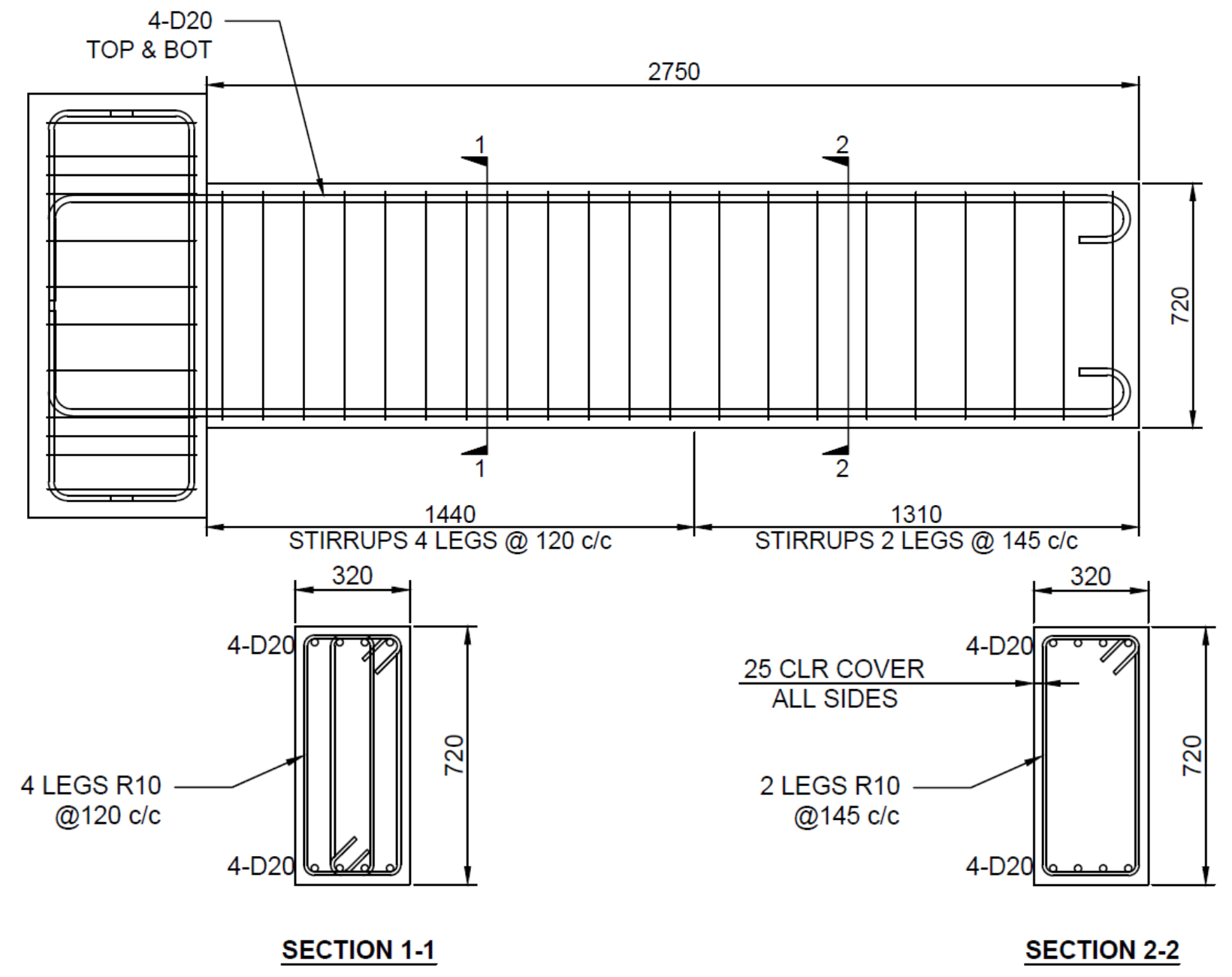


Figure 1: Specimen details.

Figure 2: Test setup.

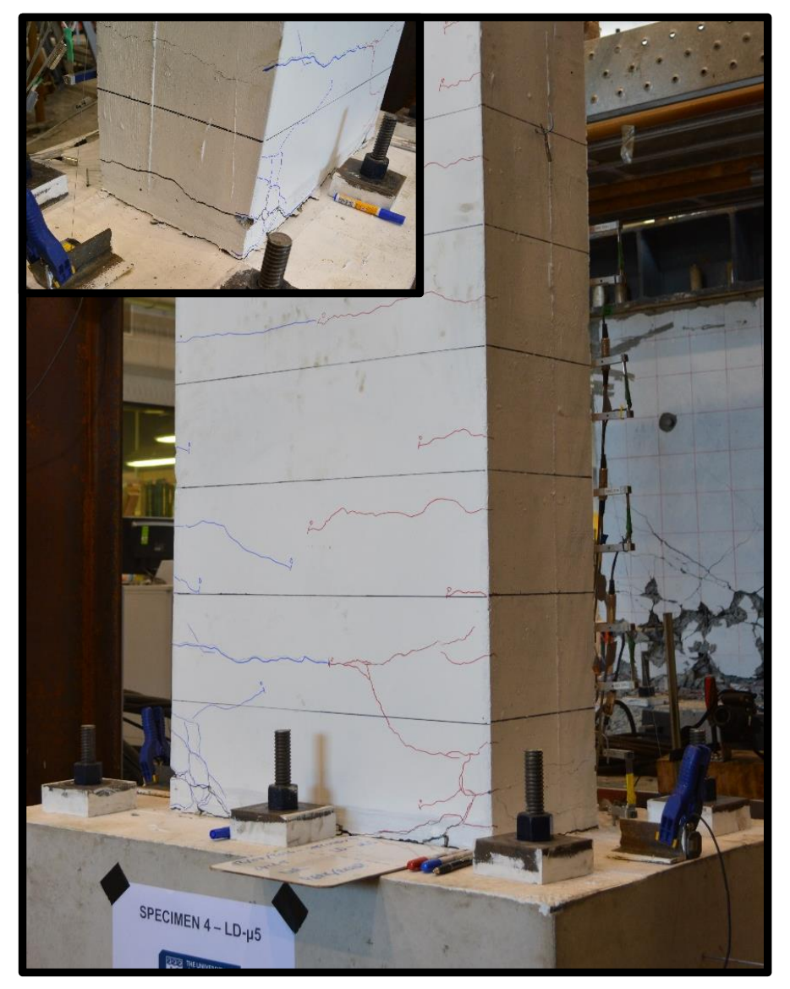


Figure 3: Damage state following dynamic long duration EQ loading to ductility 5, with close up of primary and bond splitting cracks in inset.

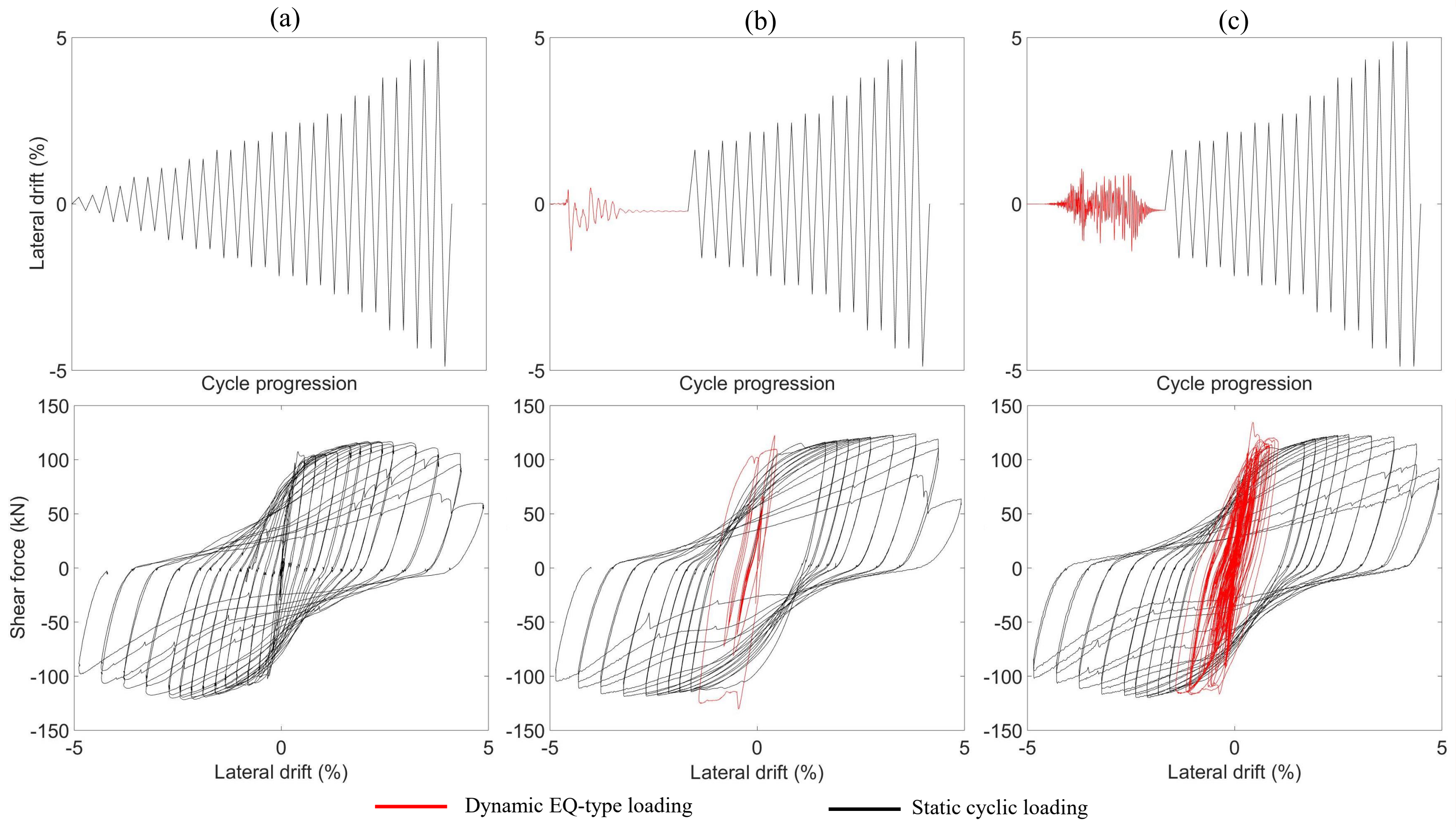


Figure 4: Loading protocol and hysteresis for three completed tests, showing: (a) static cyclic test (b) dynamic pulse-type EQ loading to ductility 5 followed by static cyclic loading (c) dynamic long duration EQ loading to ductility 5 followed by static cyclic loading.

2) LOW CYCLE FATIGUE AND STRAIN RATE EFFECTS
University of Canterbury

- **Test Specimens and Experimental Investigation:**
  Eleven half-scale specimens representative of typical RC beams designed according to NZS3101:1982, were tested at the University of Canterbury under monotonic, quasi-static cyclic and pseudo-dynamic cyclic displacement controlled lateral loading.
- In order to examine the effect rate of loading, two specimens were also cyclically tested under high speed loading at a rate of 500mm/sec. The readings were measured using a high speed video camera due to the limitations of conventional measuring devices to record displacements at such rate of loading.

Instrumentation:

Since the prerequisite for composite performance of a RC member relies upon bond between the reinforcement and the surrounding concrete, the specimens were instrumented externally and internally using fibre optics to capture strain profiles continuously along the length of specimen.

Reinforced concrete beam- reinforcement strain profile :

The preliminary measured strains from the embedded bonded fibres on the reinforcement plotted against length along the beam for the beam experiment are shown in Figure 6. The strain values increase from almost zero at the tip of the beam to the peak value at the datum exactly above the steel block level which is a representative of a fixed end support

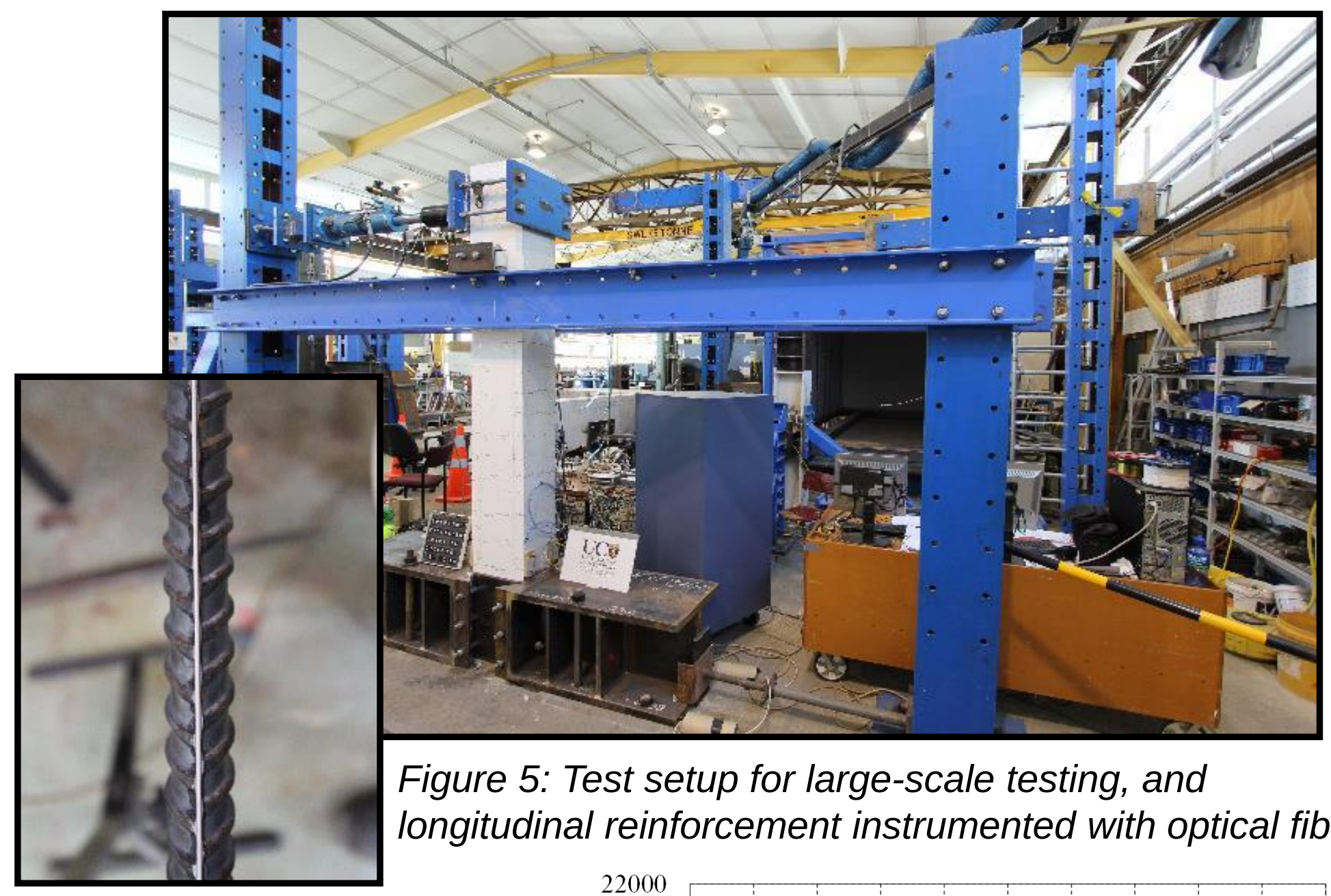


Figure 5: Test setup for large-scale testing, and longitudinal reinforcement instrumented with optical fibre.

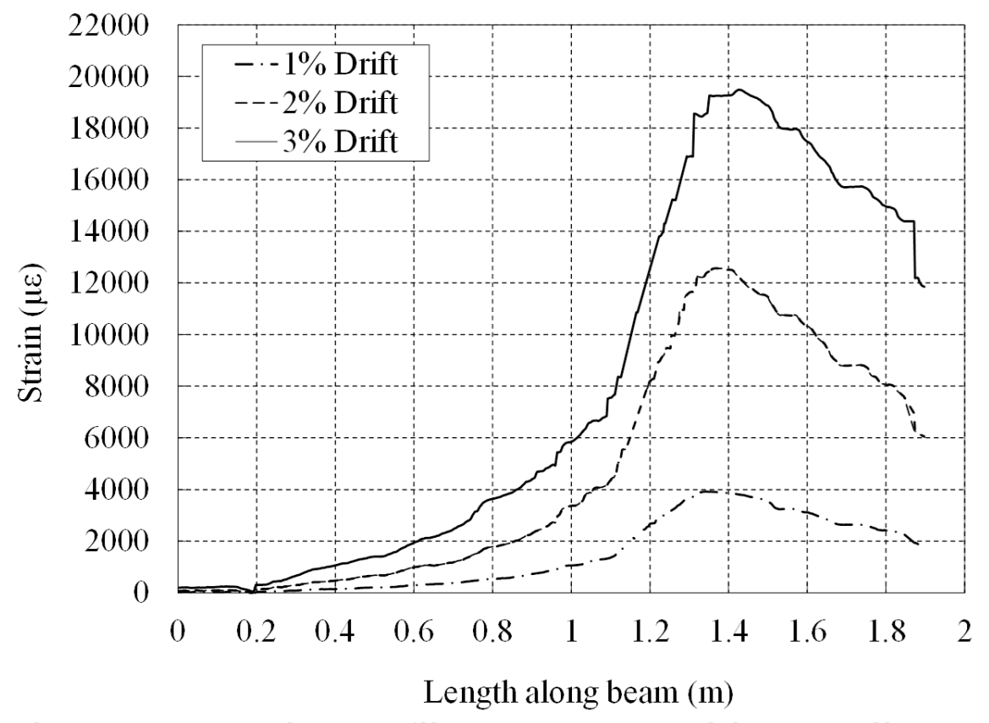


Figure 6: strain profiles measured in tensile reinforcement.

3) EFFECTIVENESS OF EPOXY INJECTION TECHNIQUES
University of Canterbury

- **Test Specimens:**
  Beam-column joint subassemblies were extracted from a 22-storey PWC building constructed in late 1980s at the Christchurch’s CBD area, damaged and demolished after the 2010-2011 Canterbury earthquakes sequence (see Figure 7).
- The building was designed following capacity design principles. The beams were provided with plastic hinge relocation details at both beam-ends, aiming at developing plastic hinges away from the column faces (see Figure 8).

Figure 7: Elevation of the PWC building during the deconstruction process (left); extraction of one of the “H” frames (upper-right); test setup (middle-right); and resin injection of cracks (lower-right).

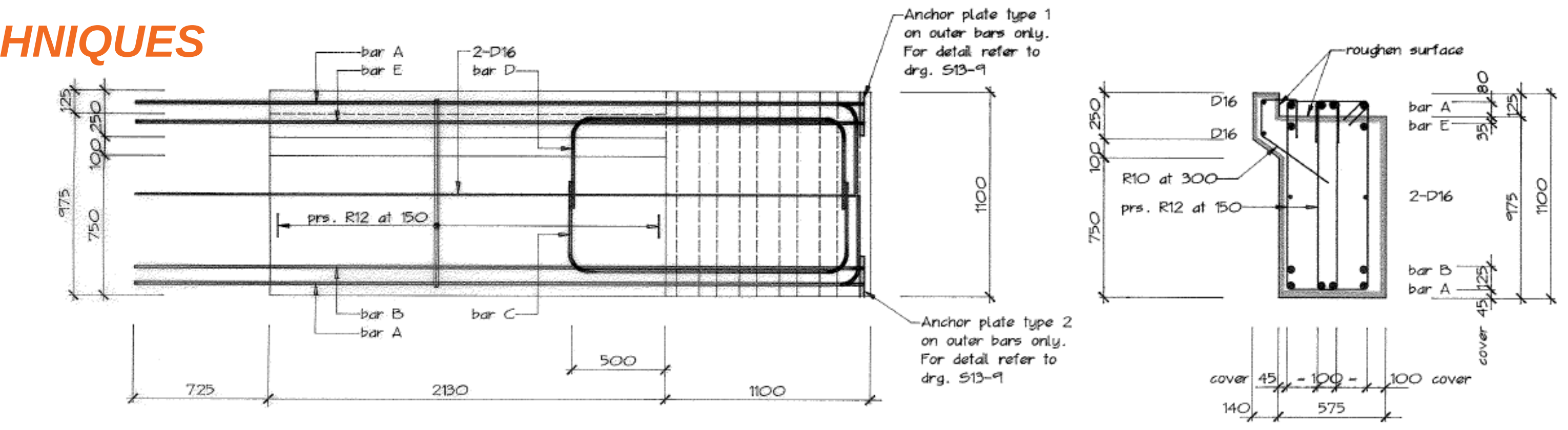


Figure 8: Typical section and elevation view of beams tested

Experimental Investigation:

Three specimens were tested at the University of Canterbury under quasi-static cyclic displacement controlled lateral loading (see Figure 9). One specimen with no visible residual cracks was cyclically tested in its as-is condition (Test 1). The other two specimens with residual cracks between hairline and 1.0mm in width, were subjected to cyclic loading to simulate cracking patterns consistent with what can be considered moderate damage (Test X.1). The cracked specimens were then repaired with an epoxy injection technique and subsequently retested until reaching failure (Test X.2).

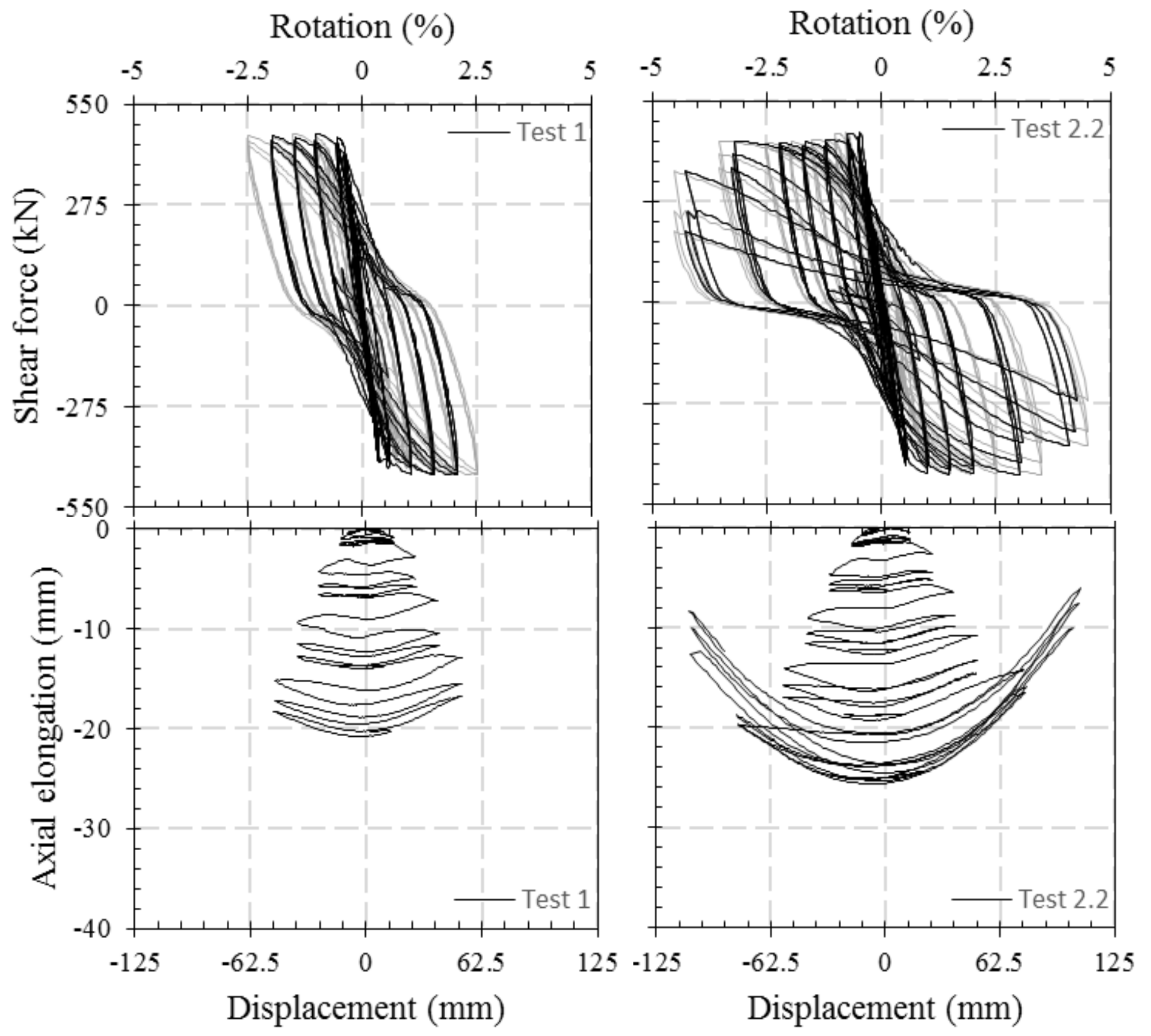
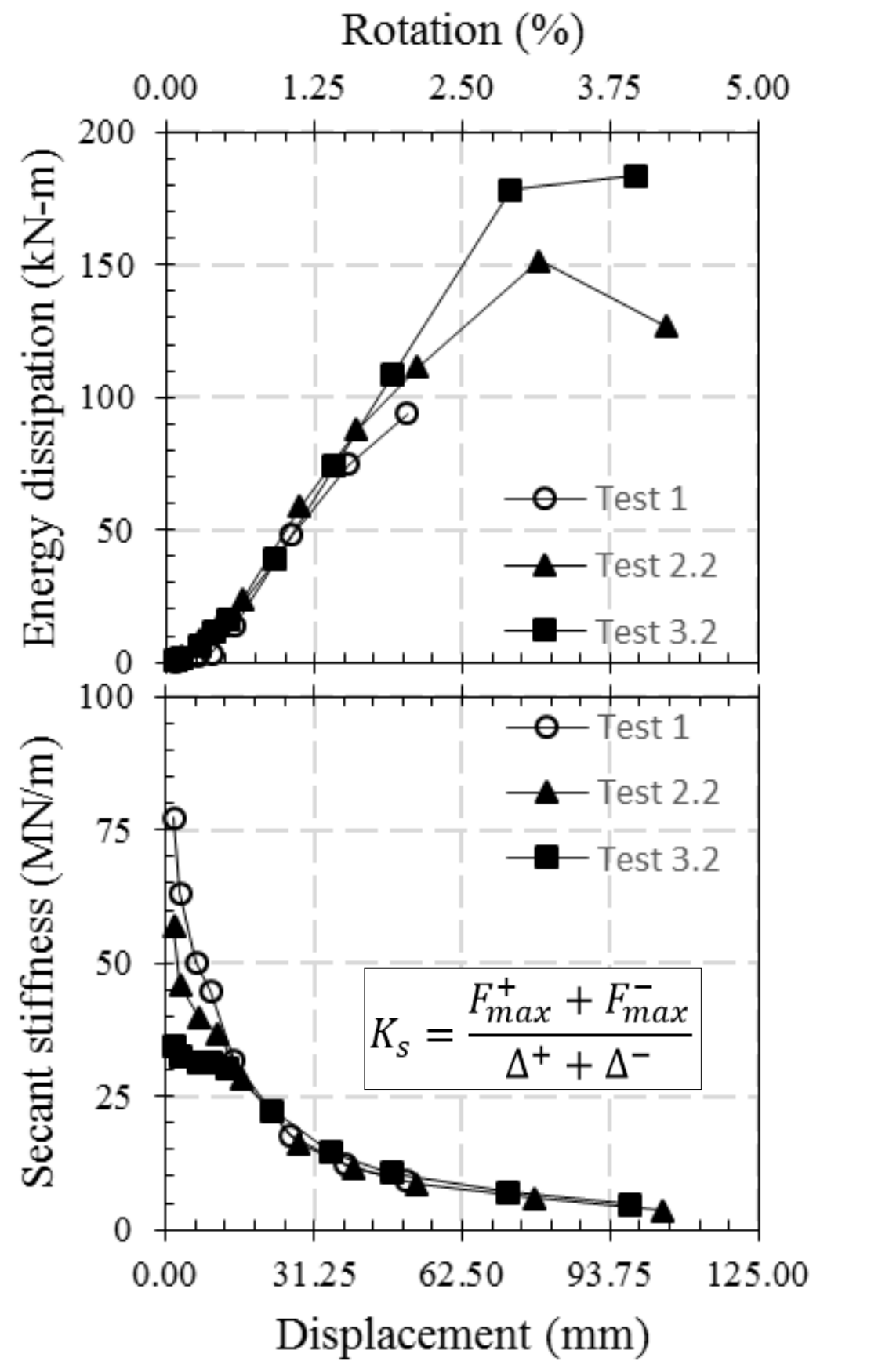


Figure 9: Force-displacement curves and beam elongation of unrepaired (left) and repaired (right) specimens⁽¹⁾.



$$K_s = \frac{F^{+}_{max} + F^{-}_{max}}{\Delta^{+} + \Delta^{-}}$$

Figure 10: Energy dissipation (top) and secant stiffness degradation (bottom) at 1st cycles.

4) CYCLIC FATIGUE TESTS OF CONFINED AND UNCONFINED CONCRETE
University of Canterbury – University of Hannover

- **Test Design:**
  85 concrete cylinders 300mm x 150 mm were fabricated at the University of Canterbury and tested at the University of Hannover in Germany.
- The confinement effect was provided by GFRP wrapping the cylinders.

Experimental investigation:

- Phase 1: Specimens were subjected to cyclic loading to 70% and 90% of their maximum compressive strength, up to reaching failure, and $N_{f,70\%}$ and $N_{f,90\%}$ (the number of cycles to failure) were determined.
- Phase 2: New specimens were cyclically pre-loaded with 70% and 90% of their $N_{f,70\%}$ and $N_{f,90\%}$. Their residual capacity in terms of both strength and strain after being preloaded is being investigated.

Instrumentation:

Laser measuring technique was implemented along with 4 strain gauges to precisely capture post-peak behaviour of damaged concrete. Figure 11 shows test set-up and also monotonic compressive behaviour of both undamaged and damaged concrete samples after applying 90% of the cycles that it can undergo up to failure at stress level equal to 0.9*f’c* .

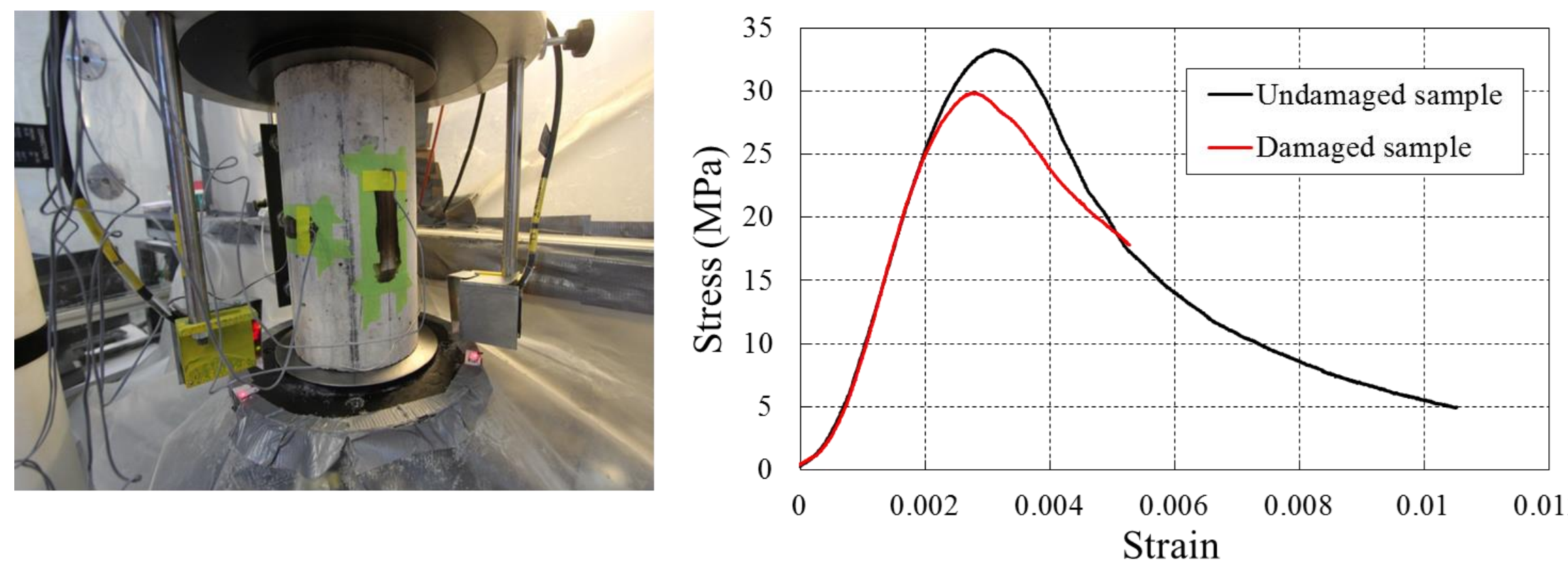


Figure 11: Test specimen (A) Plain concrete sample (B) Compressive stress-strain behaviour

PRELIMINARY CONCLUSIONS

1. For low-to-moderate ductility demands, the loading rate and characteristics of the damaging earthquake have limited effect on residual energy dissipation and displacement capacities (see Figure 4).
2. Distributed fibre optic sensors are able to detect not only cracking, but also offer the potential capability to measure strains along the length of the specimen. The measurements from both internally embedded fibres on the reinforcing and also externally bonded fibres on the concrete surface are a promising alternative for detecting localised damage.
3. Epoxy injection techniques seem to be efficient in partly, although not fully, restoring the energy dissipation capacities of the damaged specimens at all beam rotation levels. The stiffness was partly restored within the elastic range and almost fully restored after the onset of nonlinear behaviour (see Figure 10).
4. Concrete cylinders show no strength degradation after applying 90% of their fatigue life, $N_{f,90\%}$. However, the strain capacity is significantly reduced.

(1) In Figure 9, solid grey lines represent force-displacement curves measured in “total” displacement units, whereas solid black lines are in “effective” displacement units (i.e., the “total” applied displacement minus the equivalent lateral displacement at the beam end due to rigid body translation and rotation)