Stiffness Degradation in Earthquake Damaged and Repaired Reinforced Concrete Beams

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Introduction

Following the 2010/2011 Canterbury earthquake sequence and the 2017 Kaikoura earthquake, major challenges were faced by engineers and local authorities on the assessment and post-earthquake decisions making processes, for low to moderately damaged reinforced concrete (RC) ductile frame structures (Kim et al., 2017 & Henry et al., 2017). In particular, the need for data and guidelines on the reparability of these structures was a major issue. Largely meeting life-safety performance objectives, an appetite was created for guidance on the effectiveness of simple repairs which would allow re-occupancy of ductile moment-frame structures, following low to moderate earthquake damage. Results from component testing of ductile beam specimens show that under low to moderate damage, deformation capacity and strength are not greatly impacted or are completely recoverable via simple repairs. However, the results for the impact of such repairs on stiffness recovery shows greater variability in effectiveness and are outlined in this study.

Testing of Extracted Beam Specimens

Prior Testing on Epoxy Injection of Slender Beams

A prior experimental program at the University of Auckland conducted by Marder (2018), investigated the effectiveness of epoxy mortar and injection repair on moderately damaged ductile beam elements. The results showed that the repairs were able to fully recover the deformation capacity, strength and energy dissipation capacity of the beams. The impact of the epoxy injection on stiffness recovery were also seen to be successful with up to 88% recovery in secant stiffness to yield, compared to undamaged conditions. These beams were constructed to adhere to the modern ductile detailing requirements of NZS 3101:2006 and were tested at a reasonably slender shear span to depth ratio of 3.58, with damage patterns indicating a flexure dominated deformation response.

Further Experimental Investigations

- Building on the previous research outlined above, a two phase experimental program was conducted investigating the effectiveness of epoxy injection on ductile beam elements of varying aspect ratio and deformation characteristic.
- This included a set of tests on beam-column subassemblies extracted from a Wellington building damaged in the 2017 Kaikoura earthquake. The building was subsequently demolished as a result of damage to the precast flooring system, however suffered only light to moderate damage in the perimeter moment frame.
- A second set of tests were conducted, involving beam specimens, modelled after another structure which was damaged and subsequently demolished following the Kaikoura earthquake. This building suffered partial collapse of its precast flooring system but again only low to moderate damage was observed in the perimeter moment frame.
- Research is ongoing to address issues in seismic performance of precast flooring at the University of Auckland and the University of Canterbury and as such this study is focussed on repair of frames only.

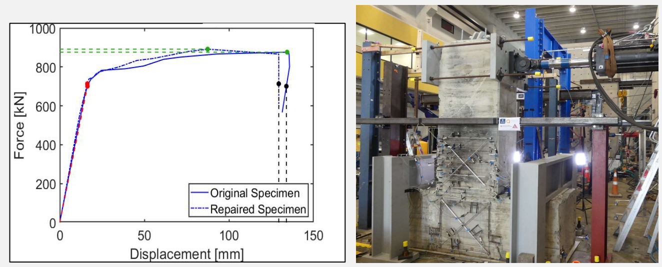

Figure 1: Test configuration and backbone curves for repaired specimens extracted from a damaged RC moment frame in Wellington following the Kaikoura earthquake.

Specimens Extracted from Building Following Kaikoura Earthquake

- Specimens were tested in a cantilever beam configuration at a shear span to depth ratio of 2.1 as shown in Figure 1. The estimated peak drift during the Kaikoura earthquake for these specimens was 1.5%.
- Damage consisted of cracking up to 6mm in width and spalling of cover concrete.
- Strength and deformation capacity were not impacted by the earthquake damage.
- One specimen was tested as damaged and one tested following epoxy injection and mortar repair.
- Comparison of initial secant stiffness to yield showed a 25% increase in stiffness following repair (Figure 1), much less effective than slender beams testes by Marder (2018).

Replica Specimens constructed in Laboratory

- Six specimens were tested in a cantilever configuration at two shear spans of 2.9 and 2.5 respectively. Dynamic earthquake loading with a peak drift of 2.5% was applied to specimens to simulate damage. Damage consisted of cracking up to ~2mm in width in the plastic hinge region.
- Strength and deformation capacity were not impacted by the earthquake damage.
- One beam was tested in an undamaged, damaged and repaired condition at each shear span.
- At both shear spans an increase of 40% in secant stiffness to 80% of nominal strength (calculated in accordance with NZS 3101:2006) was seen, reaching ~70% of undamaged specimen stiffness.
- The testing configuration and an example of the variation in stiffness for the specimens tested at a shear span of 2.9 is shown in Figure 2.

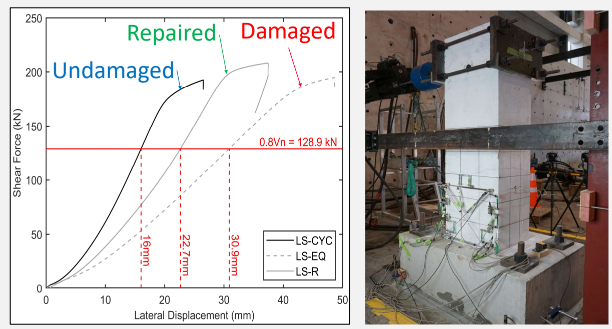

Figure 2: Test configuration for laboratory constructed ductile beam elements and variation in secant stiffness to 0.8Mn for undamaged, damaged and repaired conditions.

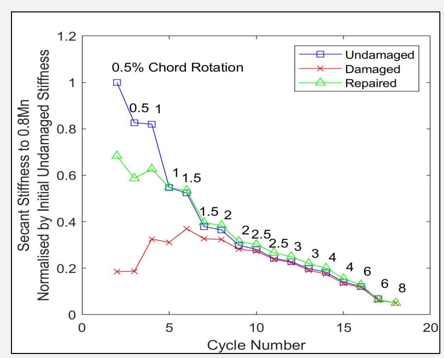

Figure 3: Degradation in stiffness for undamaged, damaged and repaired beams tested at a shear span to depth of 2.9. Results are representative of tests done at other aspect ratios.

Degradation of Stiffness in Beam Components

- To further understand the impact of epoxy injection on stiffness recovery, the degradation in stiffness at varying levels of displacement were also analysed as shown in Figure 3, for the laboratory constructed specimens. The results shown represent the secant stiffness to 80% of nominal strength for each displacement cycle applied during cyclic loading.
- These results indicate that at or above the prior peak earthquake demand, the stiffness of all specimens is very similar, pointing to the limited impact of epoxy injection in larger design level or above earthquakes.
- However at smaller displacement amplitudes (< 1% drift) the largest variation in stiffness was observed, with the damaged component having much lower stiffness as a result of a significantly pinched hysteretic behaviour at small drifts.
- This result indicates that stiffness recovery via epoxy injection can have a tangible improvement in component behaviour at small displacements, such as deformations expected in serviceability type earthquakes.

Conclusions and Further Research

- Repairs of low to moderately damaged ductile frame elements via epoxy injection are found to be successful in restoring component strength, deformation capacity and energy dissipation capacity.
- The effectiveness of epoxy crack injection in stiffness recovery can have a more varied response, with the impact of epoxy injection diminishing under loading at higher displacement amplitudes.
- Stiffness recovery was seen to be more pronounced under small amplitude loading (<1% drift), suggesting that epoxy injection can have a significant impact on the performance of repaired components during serviceability level earthquakes.
- Further research is required to extrapolate the impact of epoxy injection at the component level on the expected changes in deformation at the global building level, particularly under serviceability level earthquakes.

References

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