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Structural & Civil Engineers

EPOXY RESIN INJECTION AS A REPAIR STRATEGY FOR CONCRETE

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1 Introduction

1.1 Preamble

In the wake of the Canterbury Earthquake Sequence, BMC has been engaged in the assessment of damaged structures and determining strategies to effectively repair damaged concrete structural elements, as have many of our contemporaries. To that end we considered if and when epoxy resin could be used as part of a remedial strategy and we wanted to be sure we had made informed decisions to provide appropriate advice to our clients.

This literature review was commissioned and funded entirely by BMC as an internal project to gain the best understanding we could regarding the efficacy of epoxy resin as a repair technique for damaged concrete elements.

The conclusions from this literature review are our summary of the outcomes of the latest research we could find on the topic. We encourage the reader to consider the continually developing advances in epoxy technology with a view to providing background relevant information to help make informed decisions when prescribing appropriate remedial strategies for damaged concrete elements. We intentionally make no assertions or comment on earlier guidance on the efficacy of epoxy as a remedial strategy and merely present our summary of the latest research current at the time of our review.

1.2 Background and Economic Context

Properly designed and implemented epoxy repair strategies can, and in many instances do, provide a compellingly cost-effective alternative to demolition and reconstruction of structures moderately damaged by earthquakes. If cost was not a factor and resources were unlimited, most owners would understandably prefer to replace the old and damaged with something new and fresh. However, as has been reported [1] [2], many insurers and underwriters have indicated that they will have no choice but to limit their presence, or in some cases abandon the New Zealand marketplace for natural disaster cover in the future, as they face insolvency if an earthquake sequence producing damage similar to or worse than that which resulted from the 2010-2011 Canterbury Earthquake Sequence (CES) occurred, and more cost-effective repair strategies cannot be found and broadly pursued. Already, reinsurance costs and premiums have increased and many building owners have found that insurers are reluctant or unwilling to provide any standalone earthquake cover for buildings of certain ages or in certain areas. These outcomes are not in the public interest, having a detrimental effect on society, both economically and socially. We as engineers have a vital role to play. Our charter is to restore and improve the resilience of our cities and communities as cost-effectively as possible.

Members of our professional body, Engineering New Zealand, are bound by our Code of Ethical Conduct, which includes a number of obligations in the public interest, including acting sustainably, so that we meet the needs of the present without compromising the ability of future generations to meet their own needs (Rule 2) and reporting adverse consequences (Rule 3). We are also required to conduct ourselves in a professional manner, including obligations to act competently (Rule 4) and behave appropriately (Rule 5). The latter is described as a requirement to "act with honesty, objectivity, integrity, and treating people fairly and with respect." Good judgement and decision making are central to ethical practice. If we want to maintain our reputation as a profession and make a meaningful contribution in this field, engineers need to demonstrate ethical competence in how we make decisions on the complex technical issues surrounding insurance claim repairs.

Acting sustainably is addressed in 'Rule 2' and is an important consideration when assessing repair options versus demolition to meet structural or insurance repair requirements for damage. Construction and demolition waste make up a significant portion of total landfill contributions. Recycling demolition waste typically requires more energy input than its market value/benefit. Engineers are thus obligated to thoroughly consider what actions are appropriate for damaged structures given the diverse array of repercussions and people-groups affected.

1.3 Scope

A review of literature regarding epoxy repair has been conducted to determine the efficacy of epoxy resin injection as a repair strategy for reinforced and unreinforced concrete and concrete masonry. Recent literature was sought where possible in order to incorporate advancements made in injection techniques and epoxy resin products. Particular attention was given to research presenting the effects of epoxy resin injection on low-fines unreinforced concrete.

BMC determined that their literature review should:

- Identify injection techniques and applications where a technique is notably more effective;
- Examine the effectiveness of different epoxies and key factors to consider when selecting an epoxy;
- Review literature on epoxy as a repair for unreinforced concrete and masonry;
- Review literature on epoxy as a repair for reinforced concrete;
- Identify effects of fire on epoxy resin and review of 'hot tests' and cyclical temperature tests;
- Review recommendations from industry standards;
- Identify areas where more research is needed; and
- Comment on document age.

The term 'damaged concrete' forms a spectrum based on the extent of damage. On one end of the spectrum is 'light' damage comprised of hairline cracks. On the other end of the spectrum is a 'basket of rubble' loosely contained within a reinforcement cage. Through this literature review, BMC sought to determine if epoxy resin injection is an appropriate repair technique and, if so, what portion of the spectrum of damaged concrete it is appropriate for.

2 Epoxy and Injection Techniques

2.1 Epoxy Placement Techniques

Two epoxy resin placement techniques are considered in this report: pressure injection and vacuum impregnation. Research reported by Engindeniz *et al.* [3] compares and discusses the effectiveness of both techniques. Specimens (beam-column assemblies) were tested to 'moderate damage' – yielding of reinforcement, but concrete had predominately only cracked as opposed to spalling. Both demonstrated the ability to reliably reinstate over 85% of the stiffness of the original specimens. Strength and energy dissipation characteristics were not impacted (lost through damage or reinstated by the repair).

The relative efficacy of pressure injection versus vacuum impregnation was also researched and reported on by French *et al.* [4]. Tests were completed on interior beam-column reinforced concrete subassemblies. Results indicated that the vacuum impregnation technique may be a more effective repair strategy for larger sections, sections with offshoot cracks, and hairline cracks at the crack formation boundaries/limits. Pressure injection often traps air in offshoot cracks whereas vacuum impregnation is more effective at removing the air and drawing the epoxy resin in to fill areas which often correspond with cracks related to debonding. BRANZ [5] recommends vacuum impregnation as opposed to pressure injection when repairing cracks adjacent to areas susceptible to delamination to mitigate the injection pressure within the crack created during the epoxy repair.

BMC note that, currently, as far as we can determine, vacuum impregnation is not a routinely available technique in New Zealand.

2.2 Effectiveness of Different Types of Epoxy

ASTM C881/C881M – 15 provides a specification covering types, grade, and class of epoxy resin based on flow characteristics, viscosity, bonding systems, and suitable application temperature range. Two types of epoxy resin are classed as appropriate for crack injection. The most important difference between the two types is the minimum heat deflection temperature, which is the temperature where epoxy changes from rigid to elastomeric and loses it strength and stiffness.

Extensive testing to ASTM standards was conducted and reported on by Krauss *et al.* [6] for 18 epoxy resin products. Gel time, penetration, viscosity, surface tension, contact angle, and bond strength were evaluated to assess the products. While some of these aspects are of greater significance for certain applications (as will be discussed later), overall product ranking was determined (refer to Table 1 and Table 8 of their report).

A study by Griffin *et al.* [7] was conducted at Ara Institute of Canterbury to investigate the effectiveness of epoxy injection using three types of common epoxy resin products on the flexural tensile capacity of unreinforced concrete beams. The performance of the original and repaired beams was measured by the maximum failure load in flexural testing. The epoxies were labelled Type 1, Type 2, and Type 3 and differentiated by viscosity, tensile and compressive strength, and elastic modulus. Type 1 was high viscosity and injected, Type 2 did not have a viscosity listed in its technical specification and was injected, and Type 3 was low viscosity and gravity fed. Type 1 epoxy was reported as 71% effective at reinstating the strength and continuity of the beam. The beams repaired with Type 1 cracked where repaired, indicating that the epoxy did not bond well with the concrete. For beams repaired with either Type 2 or Type 3 epoxies, the failure occurred away from the original crack. The author concluded that the strength and continuity of concrete can be reinstated if an appropriate epoxy is utilized.

2.3 Determinant Repair Factors

Moriconi *et al.* [8] found viscosity and elastic modulus were not necessarily the key factors to be considered when evaluating the efficacy of epoxy repair or determining the type of epoxy to be incorporated in a repair strategy for reinforced or unreinforced concrete elements. Viscosity strongly impacted the effectiveness of injection for narrower cracks (those less than 0.3 mm), but was found to be largely inconsequential for crack widths over 0.8 mm. Test results indicate that epoxy with a viscosity value over 400 mPa*s is less effective in restoring the mechanical properties of the injected specimen for crack widths less than 0.15 mm. Concrete microstructure and porosity were notable factors regardless of crack width. Injection of epoxy into cracks in porous concrete (low quality concrete with voids due to poor consolidation) resulted in increased strength due to the epoxy spreading into the concrete surrounding the crack.

To quantify the effect of porosity, tests were completed on notched small beams with an internal steel plate providing tensile capacity for the fully compacted/consolidated specimen and externally bonded for the partially compacted and uncompacted specimens. The repaired specimens were artificially cracked and repaired using epoxy. Results of the repaired specimens were compared to undamaged specimens. The results indicated that for fully compacted/consolidated concrete, epoxy injection restored the integrity of the concrete and the flexural strength was the same, because the reinforcement was not damaged and the concrete was low porosity. For the partially compacted specimen, a 66% increase in strength was noted and a 233% increase in strength for uncompacted specimens. The explanation for these increases was based on ultrasonic pulses in order to characterize the change in mechanical properties of the epoxy injected concrete. The ultrasonic pulse velocity increased to a greater extent in the repaired uncompacted specimens than the partially or fully compacted specimens because more voids were originally present and subsequently filled during the repair. This created an effective increase in the tensile capacity of the uncompacted concrete specimen resulting in a change (increase) in flexural strength. Overall, test results indicated that most repaired specimens produced higher velocities than the original specimens. One exception was for the fully compacted specimen with crack widths ranging from 0.10 mm to 0.15 mm repaired with higher viscosity epoxy. For this specimen, the velocity decreased because the crack could not be filled effectively due to the epoxy resin selected.

French *et al.* [4] suggested through their research that the wettability of epoxy was also important to consider. Epoxy with good wetting characteristics have low surface tension and spread over a surface with relative ease [6]. Wettability was regarded as significant especially for small crack widths and the reinstatement of bond between the concrete and reinforcement. Hassoun [9] states that epoxies with good wettability can fill micro-pores and micro-crevices increasing the contact area enhancing both the physical and chemical bond at a microscopic level.

3 Epoxy as a Repair for Unreinforced Concrete and Masonry

Research investigations using unreinforced concrete as well as unreinforced masonry (URM) is considered in this section. Research using only unreinforced concrete was limited, thus URM was also considered since test results for cracks within block specimens are applicable to unreinforced concrete and tests on brick walls are applicable to some perimeter foundations in New Zealand labelled 'rubble'. In this section, the efficacy of epoxy repair is investigated as to its ability to fill voids (reinstate shear transfer across a crack) and reinstate bond between cementitious materials. Since unreinforced concrete, particularly low-strength concrete, has minimal tensile capacity, structural elements comprised of this material have minimal capacity to act in flexure and their 'flexural strength' is not considered explicitly in the repair imperative. The design use of the element must be considered. Structural elements such as unreinforced foundations transfer load to the supporting subgrade through compression struts and shear transfer. Thus, the repair imperative for these elements is reinstatement of shear transfer (aggregate interlock) and filling gaps to reinstate the compression capacity.

3.1 Impact on Strength, Stiffness, and Energy Dissipation

Minoru *et al.* [10] performed tests on unreinforced concrete beam specimens to evaluate the bond properties of various repair materials and determine the effect substrate roughness has on bond between concrete and and the repair material. For all epoxy repaired specimens with a rough crack surface, the maximum load, flexural bond strength, and fracture energy was greater than the "uncracked" control specimens. Additionally, the repaired specimens did not crack in or directly adjacent to the repair.

Static and dynamic compression tests to assess shear capacity were conducted on epoxy repaired masonry components by Plecnik *et al.* [11]. The tests considered epoxy repair in block specimens, block joints, and grout sections with cracks ranging between 0.5 mm and 2.5 mm. From the test results, the authors concluded that with appropriate selection of epoxy and ensuring complete penetration of the crack, the repaired structural component reached equal or greater compressive and shear strengths compared to the original specimen. Additionally, the researchers noted that in the block joint tests, due to the porosity of the mortar and consequential absorption of the epoxy, the compressive strength of the repaired sections was greater than the original 'undamaged' sections.

A review by ElGawady *et al.* [12] was conducted for the 13th International Brick and Block Masonry Conference to summarize current research regarding the ability to repair and/or retrofit unreinforced masonry using epoxy injection. The review concluded that walls retrofitted by means of epoxy injection demonstrated a stiffness increase of 10-20% and a lateral resistance of 2-4 times that of the original resistance. One of the documents included in the review, *Experimental Results on Unreinforced Masonry Shear Walls Damaged and Repaired* [13], specifically tested the ability of an epoxy resin injection repair to restore the shear strength to a value equal to or greater than the original strength of an undamaged wall. This report also addressed critical repair technique considerations noted during the tests, which include: careful detection of all cracked zones, a warning to thoroughly consider the impacts on other structural elements if the injected element has a dramatic increase in strength relative to its original condition, and an acknowledgement that a large quantity of epoxy resin is necessary for this type of repair and is thus a relatively high cost repair technique. After the original walls were tested, they were repaired with cementitious grout or epoxy resin injection. The strength of the walls repaired using epoxy resin injection increased to the extent that tests were halted because the limits of the reaction system for the horizontal force had been reached. The results indicated that the repaired walls had 2.15 and 3.91 times the shear capacity of the original walls and the initial stiffness increased slightly. When the tests were stopped, cracking was not observed in the repaired zone at the centre of the panels. The researchers note that some crushing was observed at the top and bottom corners of the walls.

3.2 The Use of Epoxy in Large Void Volumes

Epoxy polymers should generally not be used to fill large volumes with a relatively low surface-area-to-volume ratio [14]. The exothermic reaction as the polymer cures liberates heat which must be effectively diffused. For this reason, epoxy polymers in applications with large volumes with a relatively low surface-area-to-volume ratio are extended with the addition of large proportions of inert aggregate. If large voids exist as in un-grouted large cavity masonry, a cementious grout is ordinarily prefered and is more cost-effective than an extended epoxy polymer.

The research document cited did not define 'large void', but provided an example, which was the key subject of their report. The example being a 10 inch (~250 mm) diameter capsule filled with 5 gallons (~19 litres) of a two-part epoxy. The capsule was welded to the Trans-Alaska Pipline, a 1.22 m diameter, ~14 mm thick pipe. Within 12 hours, the section of pipe which the capsule had been welded to was found at the next pump station down the line.

Additionally, BMC has been informed by contrators who perform epoxy repair, that they have seen one litre mixing buckets of epoxy melt to the ground when left overnight.

4 Epoxy as a Repair for Reinforced Concrete

Research investigations testing assemblies constructed for laboratory purposes and for building construction were reviewed and a summary of the results and discoveries related to epoxy resin injection are presented below. Test assemblies included beam-column subassemblies, beams, bridge girders, and bridge columns.

4.1 Conclusions Based on Building Lab Assemblies

Marder [15] focused his research on moderately damaged plastic hinges, with an emphasis on the response of typical plastic hinges in modern moment frame structures. Moderate damage does not include crushing of core concrete or buckling of reinforcement. A beam was chosen, because it is the primary location of plastic hinging for the strong-column-weak-beam mechanism of capacity design. Repair methods utilized include epoxy injection of cracks and patching of spalled concrete. Residual drifts were not corrected prior to repair. Other variables considered in the testing include loading protocol, loading rate, and the level of restraint to axial elongation. The maximum residual crack widths in specimens prior to repair ranged from 2.5 mm to 3.5 mm. Results indicate that the strength and deformation capacity of plastic hinges with modern seismic detailing are often unreduced as a result of moderate earthquake induced damage. Regarding stiffness, the initial secant stiffness to yield (defined as 0.8Mn; Mn being the nominal flexural strength of the beams calculated in accordance with NZS3101:2006) was compared. The test results indicated that most of the stiffness was restored by repairing the specimens with epoxy resin. In repaired specimens, the cracking was generally more distributed; cracks over 0.2 mm in width developed up to an average distance of 540 mm from the beam-joint interface. A shift in the plastic hinge zone, however, was not observed. Damaged concrete repaired with epoxy typically displayed a greater bond than normal concrete, meaning that epoxy injection was generally effective in keeping cracks closed. The author also found that the deformation capacity of the repaired beam was equivalent to the deformation capacity of an undamaged beam. The other implications of repair such as increased length over which damage was distributed and increased cumulative elongation, did not affect the deformation capacity.

(b) LD-2-R

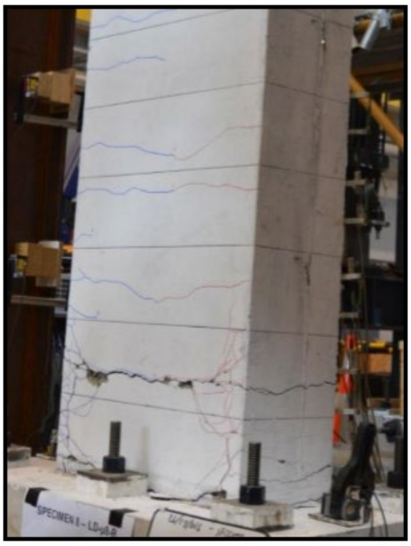

Figure 1: Example of damage state prior to repair [15].

Tsonos [16] conducted tests on beam-column joint specimens designed to the then-current Eurocode and ACI 318. The specimens were tested under reverse cyclic loading representative of strong earthquake ground motions to severe damage states, repaired using epoxy pressure injection, and tested using the same displacement history. The results were analysed to determine the efficacy of the epoxy pressure injection technique at restoring strength, stiffness, and energy dissipation capacities. The authors expressed concern as to whether the damage area would move because of the higher strength repair material used. The original specimens developed plastic hinges with severe cracking near the fixed end of the beam (adjacent to the column) and large strain in the beam's longitudinal reinforcement. Additionally, anchorage failure of the beam reinforcing bars and consequential spalling of the exterior joint face occurred in one specimen during the last three load cycles. To repair the specimens, high strength mortar or epoxy resin paste was applied to areas with spalled or crushed concrete and cracks were sealed and then injected with epoxy resin. The failure modes of the repaired specimens were similar to the original, with one specimen developing a slightly more preferable failure mode than the original. The areas of damage did not shift from the beam fixed end and results indicated that the beam-column joint areas continued to remain elastic. Also, cracks repaired with epoxy injection generally did not re-crack; new cracks developed adjacent to repaired cracks. Typically, the repaired subassemblies achieved similar strength, stiffness, and energy dissipation capacities. A strength reduction was noted in the first seven lower half-cycles of the repaired specimen 'E' because it had developed an anchorage failure during the original test and in the last 3 cycles for the repaired specimen 'A' due to buckling of some of the longitudinal beam reinforcement in compression during the original test, which then fractured near the end of the repaired test. Overall, the repaired beams in both subassemblies were assessed as stronger than the original beams.

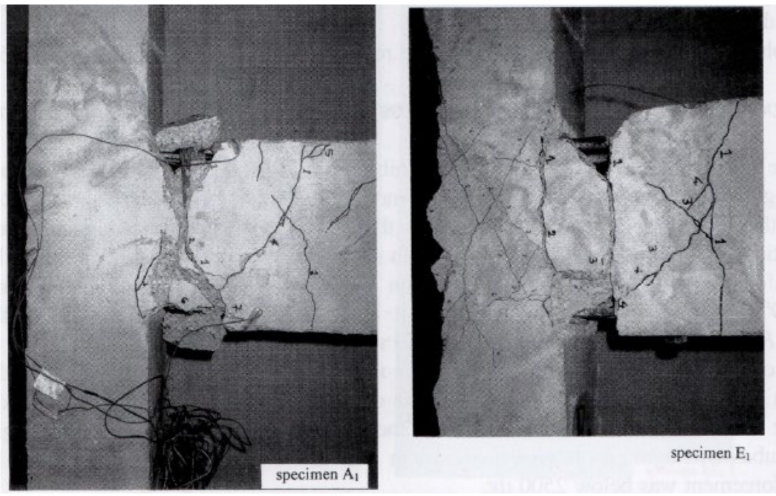

Figure 2: Images [16] of the subassemblies after the original tests illustrating the extent of damage to be repaired.

Provided in the report by Karayannis *et al.* [17] are the results from testing 17 beam-column joint subassemblies before and after epoxy crack injection. Specimens were tested to severe damage states prior to repair. Results regarding the hysteretic responses, bond deterioration, strength, and stiffness are presented. Epoxy repair was undertaken by sealing all visible cracks except for where injection ports were located, injection of low-viscosity (200-300 mPa*s) epoxy resin, and allowing the epoxy to harden for a minimum of six days before testing. Bond deterioration is indicated by the shape of the load vs. deflection plot, where pinching of the hysteretic response is indicative of severe bond deterioration. Pinching of the hysteretic response was observed in later load cycles for the repaired specimens compared to the original. A large variation was noted regarding the ability for epoxy repair to reinstate the tangent stiffness of the assembly. Data was collected both before and after the repair for the 1st, 3rd, and 10th loading cycles. Results indicated that the repairs were able to reinstate 72% - 139% of the mean stiffness of the original. Variations were attributed to the level of damage experience by the joint and the degree of epoxy penetration through the joint. When evaluating the energy dissipation capability of the joint and the effect of epoxy repair, the repaired joints were lower for the first cycle, but presented a higher energy dissipation capability than the original for subsequent load cycles. The mean energy dissipation response data demonstrated a 19% - 189% increase. Response data indicated that the strength capacity of the assemblies for the first load cycle remained the same or increased by up to 32% and sustained more complete load cycles without significant loss of strength or stiffness than the original.

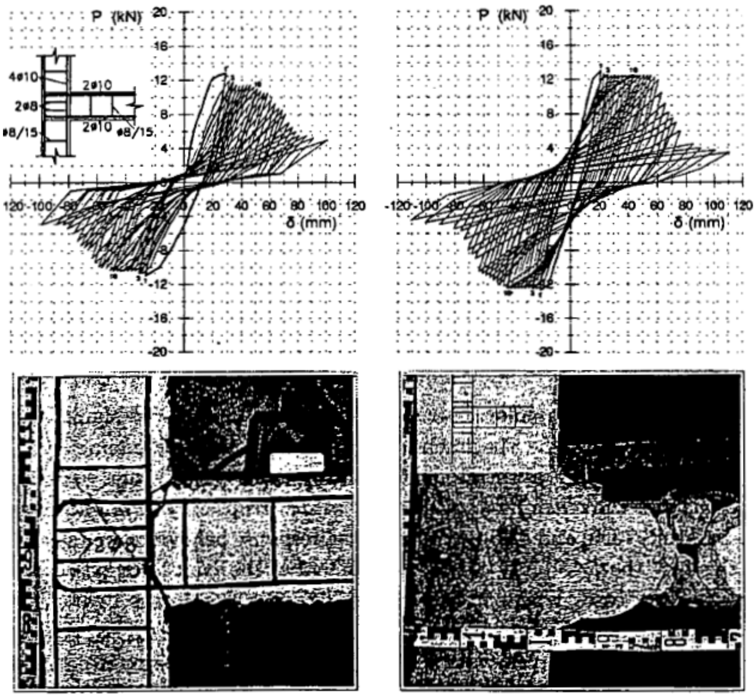

Figure 3: Excerpt [17] showing the hysteretic response and damage from one of the beam-column joint subassembly tests. Failure mode-A (observed in the initial, undamaged test) is cracking in the joint and beam end, with most of the damage localized at the end of the beam. Mode-C (observed in the repaired, post damage test) is cracks in the beam region out from the repaired region followed by spalling of the concrete.

French *et al.* [4] studied epoxy resin injection as a repair strategy for reinforced beam-column subassemblies with particular interest given to the results indicating whether strength, stiffness, energy-dissipation capacity, and bond could be restored for the specimens. Two methods of epoxy injection were investigated: pressure injection and vacuum impregnation. Large reinforcement bars were intentionally selected for the main reinforcement in the beams and columns, #8 and #10 bar (25.4 mm and 32.3 mm respectively), in order to a create a condition that would provide quantifiable results regarding the two technique's ability to restore bond. Three types of epoxies were considered for the tests with viscosities ranging from 500 mPa*s to 140 mPa*s. Ultimately the mid-range viscosity epoxy was chosen because it had the best wettability and was the most stable when allowed to set regardless of the quantity. The repaired assemblies achieved 89% and 85% of the original specimen's initial stiffness. Differences were attributed to cracks under 0.1 mm not being repaired, spalling of column cover concrete due to inadequate bearing of the end plates, and quality control issues when repairing the subassembly using the vacuum impregnation technique because the crack was wide. The authors states that both epoxy repair techniques were effective in restoring stiffness to the specimens as the stiffness of the repaired sections were 2.5 – 3 times greater than the stiffnesses observed in the final load cycles of the specimen prior to repair. Cycles with the largest lateral displacements were assessed to determine the effectiveness of the repair techniques in restoring strength, bond, and energy dissipation capacities. The original specimens and section repaired with vacuum impregnation reached similar maximum strengths. The specimen repaired using pressure injection reached a maximum strength 5% higher than its corresponding original specimen. The strength increase is attributed to the plastic hinge zone shift away from the joint due to the epoxy's higher tensile strength compared to concrete (a large crack formed in the joint area which was repaired well with the pressure injection method, but not as well with the vacuum method due to the reason mentioned above). Bond was measured using slip wires on the bar and LVDTs (linear variable differential transformer). Load versus slip plots were flattened, indicating where reinforcement slipped instead of picking up load. Severe bond deterioration occurred one half-cycle earlier in the repaired specimens concluding that bond was reinstated effectively. Flattening of the slope plots (indicating severe bond deterioration due to the reinforcement moving instead of the concrete transferring load to it) was observed in the 7^{th} cycle for the original specimens and end of the 6^{th} cycle for repaired sections. When considering epoxy repair as a means for restoring energy dissipation, the authors found that the repaired sections were similar or exceeded the original specimen's capacity.

Ekenel *et al.* [18] conducted monotonic, 4-point bending tests on four small reinforced concrete beams using an epoxy resin injection repair strategy. Two specimens were maintained under laboratory conditions while two were subjected to 50 freeze thaw cycles, 120 extreme temperature cycles with UV light exposure, and 60 relative humidity cycles. Results indicated that the epoxy injection was less effective when subjected to variable environmental conditions, although all repaired specimens performed better than the control specimen. The specimens maintained in a controlled laboratory environment had an increased initial stiffness, slightly higher capacity, and injected cracks did not reopen. The environmentally conditioned specimens had a lower stiffness than the laboratory specimens (still higher than the control specimen), similar ultimate load, and injected cracks reopened.

Nikopour *et al.* [19] performed monotonic tests on beams repaired using low viscosity epoxy resin injection in order to gauge the impact on shear capacity and stiffness compared to the "uncracked" control specimen. The repaired specimen exhibited an ultimate load capacity 21% higher than the control beam and a greater initial stiffness. The increase in inititial stiffness was attributed to the stronger epoxy-to-concrete bond strength relative to the tensile capacity of concrete.

Thermou and Elnashai [20] reviewed repair techniques for reinforced concrete buildings and considered global objectives of the intervention process. Concerning the applicability of epoxy injection as a repair technique, the researchers noted similar observations as other reports to include, the effectiveness of the repair process depends on the depth of penetration into the crack. Typically, cracks resulting from flexure and shear provided largely unobstructed paths and consistent restoration of strength, stiffness, and shear strength in concrete-to-concrete joints. Longitudinal cracks, often resulting from bond failure, were generally discontinuous which proved problematic when repairing the steel-to-concrete bond. Epoxy resin is recommended for cracks up to 5-6 mm wide. For larger crack classified as 20 mm or less, a cement grout is deemed appropriate. With regard to global objectives, epoxy resin injection is considered to be an appropriate method for reinstating the structural characteristics of a member without appreciably diminishing the global response of the structure.

4.2 Conclusions Based on Bridge Lab Assemblies

Lehman *et al.* [21] conducted tests on reinforced concrete columns conforming to modern bridge requirements for regions of high seismic risk. A "moderately damaged" column was repaired using epoxy resin injection and cover replacement. Columns were tested in an upright position with a constant axial load of 654 kN (an axial stress of 2.24 MPa) and a cyclic lateral load applied using a servo-controlled hydraulic actuator under displacement control. Damage prior to repair was classified as moderate because no spirals had fractured and longitudinal bars had not buckled or fractured. Outer longitudinal bars had yielded and the measured maximum strain in those bars was 0.03. The repaired column was tested through displacement cycles of 178 mm (7.3% drift) and results were compared to another column used for a "severe damage" test that utilized a different repair technique, but was designed and constructed the same as the column repaired with epoxy resin injection. Separation of the patching material followed by buckling of the longitudinal reinforcement and fracture of the spiral reinforcement occurred during the 127 mm (5.2% drift) displacement cycles. Longitudinal bar fracture resulting in a loss of strength over 20% of the maximum strength occurred during the second cycle to 178 mm. Results indicated that the repair did not fully reinstate the stiffness. Strength and deformation capacities were not lost. The lateral load capacities after the 3-inch tip displacement cycle (3.125% drift), which was the maximum damage cycle seen by the repaired specimen prior to repair, were the same as the original specimen for each corresponding cycle. The difference in stiffness was largely attributed to the damage initially incurred by the concrete and the inability for epoxy to penetrate all significant cracks since the applied axial load had closed up many cracks to the point where the efficacy of epoxy repair was reduced. The author sited experimental research results indicating that cyclic damage to concrete produces a reduction in effective concrete compressive strength, which was not restored through their repair procedure.

Smith [22] conducted tests on five full-scale reinforced concrete deck girders designed using typical 1950's detailing to investigate the efficacy of epoxy resin injection as a repair strategy for shear cracks. Cracks were injected with an ultra-low viscosity epoxy. Results indicated that the shear capacity increased slightly, the loads at which cracks formed increased, the serviceability stresses measured in stirrups were reduced, and repaired cracks did not reopen. Four girders were repaired while variable dead loads, axial loads, and/or live loads were applied. For one girder that was injected and cured concurrent with the application of a cyclic live load, the injection pressure was variable and small bubbles were produced within the epoxy (identified in core samples), but this did not negatively impact the girder performance when tested. The author found that the application of a dead load while repairing the girder generated the greatest improvement, likely because the diagonal cracks were "propped open" which allowed for deeper penetration of the epoxy.

4.3 Conclusions Based on Extracts from Buildings

Two H-units were extracted from the Clarendon Tower in order to investigate the effectiveness of repair strategies for earthquake-damaged buildings [23], [24]. Restrepo's Unit 4 [25] was used as the 'as when new' test results for the Clarendon Tower as the Tower was reputedly the prototype for Unit 4. Unit 4 was built and tested for a doctoral thesis comparing a typical design to a retrofit. Results from the Unit 4 test were scaled to reflect the likely result of the Clarendon Tower assemblies. The testing was completed to determine whether the structural integrity of the Clarendon Tower could have been restored through standard repair techniques. One specimen with more significant damage was repaired using removal of concrete, additional transverse reinforcement, replaced stirrup plates, additional transverse hoop ties, and reinstatement of concrete with a 60 MPa flowable mix. The other specimen experienced minor to moderate damage and was repaired with epoxy injection only. A gravity load similar to the expected building load for the respective locations was applied to the columns during testing. Results indicated similar yield drifts, greater relative strength of the repaired assemblies (60% increase for the retrofitted assembly and 40% increase for the epoxy repaired assembly), and similar strength degradation and hysteretic pinching for the epoxy repaired assembly and Unit 4. Stiffness was not commented on by the authors. A direct stiffness comparison does not appear reasonable because of the likelihood of differing loading protocols and boundary conditions. The Clarendon Tower extracts were tested using a cyclic loading protocol intended to replicate earthquake shaking as closely as possible. Restrepo's loading protocol appears to include a concentration of small displacement load cycles, generating results that may impact the ability to directly compare stiffness. Higher strength results for the epoxy repaired assembly were largely attributed to strain aging of the longitudinal reinforcement, which was assumed to have occurred as a result of loads imposed during the Canterbury Earthquake Sequence (CES). The performance of the epoxy repaired assembly was concluded to be roughly equivalent to how it likely would have performed if tested prior to being damaged in the CES, demonstrating that the assemblies could be repaired to a similar or enhanced strength capacity without reducing the displacement capacity.

4.4 Durability and Applicability of Epoxy Repair

Apart from considering epoxy resin injection as a repair strategy to reinstate strength, stiffness, or energy dissipation, repair strategies to address the durability of steel reinforcement must be considered. Repair using epoxy resin injection is particularly beneficial for restoring the durability of reinforced concrete elements exposed to corrosive environments. Epoxies are highly resistant to attacks from acid, alkalis, and solvents [26] allowing for the reinstatement of protection for the reinforcement. The chemical properties of epoxy provide equivalent or improved protection relative to concrete.

The effectiveness of epoxy resin as a repair technique is dependent on the bond established between the concrete and epoxy. S. Ahmad *et al.* [27] notes that if cracks are actively leaking, this will impede the epoxy from bonding well with the concrete. Special techniques have been developed and used with success to seal leaking cracks. These special techniques utilize polyurethane or methacrylic acrylate resins. Both of these resins are considered to have low strengths and should be used only to resolve water leakage issues prior to using epoxy resin for structural repairs [28]. For applications where the crack width is less than 0.13 mm, methacrylic acrylates should be used because of its exceedingly low viscosity. Tests were completed by Krauss *et al.* [6] to determine the average bond strength of different epoxy resins when applied to a moist substrate. Results indicated a wide range of results depending on the epoxy, but several specimens presented a bond strength greater than the tensile capacity of the concrete leading to cracks developing in the concrete section of the specimen as opposed to the epoxy-concrete interface. The bond strength results did not necessarily correspond with good performance in the other areas tested (viscosity, gel time, penetration, surface tension, and interfacial tension) indicating that there may be room for product development and appropriate care should be taken when selecting an epoxy resin based on the specific application requirements.

5 Effects of Fire on Epoxy Resin

Epoxy resins generally volatilize at temperatures above 300°C [26]. In tests by Khalil [26], specimens were heated in a room at 70°C for six hours. When removed, the core temperature of concrete and epoxy was measured as 62°C and the specimens were tested in flexure. For tests done on uncracked and cracked concrete beam specimens, the ultimate load capacity was reduced by 17% - 24% due to an increase in temperature from 20°C to 62°C. Beam specimens repaired with epoxy varied based on the type of epoxy used and ranged between a 32% and 75% reduction in capacity. The beams tested were unreinforced. Flexural tests were completed in accordance with applicable ASTM standards.

Plecnik *et al.* [29] studied the behaviour of epoxy repaired reinforced concrete beams under fire conditions. Their research found that the strength reduction in repaired elements is dependent largely on the presence or lack of fire protection coatings, the thermal gradient, and type of cracks. For flexural tests on small-scale beams, failure generally occurred in regions away from the epoxy repaired areas for temperature below 93°C and at epoxy repaired areas for temperatures above 93°C. The ability to reinstate strength and stiffness of elements with shear related cracks is directly proportional to the mechanical properties of the epoxy, which are negligible above 204°C. For cracks related to flexure outside of the compression zone repaired with epoxy, the strength of the beam was reinstated, but the stiffness decreased significantly as temperature increased.

BMC note that for flexure, if the tensile strength of the epoxy (and concrete) is a key load path, then fire warrants consideration. Alternatively, if the reinforcement provides the tensile load path, then fire effects on the member are as they would be regardless of the epoxy repair. For shear transfer, where aggregate interlock has been reinstated by epoxy injection, fire protective coatings are required to preserve the integrity of the epoxy repair.

6 Recommendations from Industry Standards

Many industry standards, specifications, recommendation documents, and guidelines have been produced including epoxy resin injection specifications, guides to crack repair, instruction on identifying the cause of cracking in order to select the appropriate repair method, and guidelines for verifying field performance. Examples of these documents are presented below:

- ACI 224.1R-07 [30] – causes and control of cracking, evaluation of cracking, and methods of crack repair.
- ACI 503R-93 [31] – presents properties, uses, preparations, mixtures, application, and handling requirements of epoxy resin systems when applied to and used with concrete and mortar.
- ACI 546R-04 – documents standard techniques for concrete repair with cementitious materials and polymer materials.
- ACI Committee E 706, RAP1 – structural crack repair by epoxy injection.
- ASTM C881-15 – Standard specification for epoxy resin based bonding systems for concrete.
- BRANZ Bulletin issue 535 [5] – provides guidance on assessment of cracks in concrete and appropriate repair techniques.
- FEMA 308, Table 4-1 [32] – provides a summary of repair procedures based on repair requirements and material.
- ICRI Technical Guideline No. 210.1-1998 – guideline for verifying field performance of epoxy injection of concrete cracks.
- Japanese Building Disaster Preparedness Association (JBDPA) – 2016 Guideline for Post-earthquake Damage Evaluation and Rehabilitation.

7 Literature Summary

A summary of the results from literature reviewed is presented in the following table.

Year	Reference	Reinforced (Y/N)	Specimen	Drift or Displacement Prior to Repair	Loading Type	Strength	Stiffness	Energy Dissipation
1990	[4]	Y	B/C Assembly	4.6% drift	Static Cyclic	5% (I)	11% (D)	(U)
1991	[8]	Y	Beam	-	Monotonic	(I)	-	-
1998	[17]	Y	B/C Assembly	7.27%- or 9.09%-drift	Cyclic	(U) - 32% (I)	28% (D) - 39% (I)	19% - 189% (I)
2001	[21]	Y	Bridge Column	3.125% drift	Cyclic	(U)	(D)	(U)
2002	[16]	Y	B/C Assembly	7.22% drift	Reverse Cyclic	(U) - 10% (I)	20% (D) - 5% (I)	(U)
2007	[22]	Y	Bridge Girder	15 to 20 mm mid-span	Dynamic	(I)	(I)	-
2011	[27]	Y	Beam	-	Monotonic	(I)	-	(I)
2011	[19]	Y	Beam	-	Monotonic	21% (I)	(I)	-
2013	[23], [24]	Y	H-Unit	Unknown - EQ	Cyclic	40% (I)	(U)	(U)
2018	[15]	Y	Beam	1.36% or 2.17% drift	Cyclic	4% - 7% (I)	12% - 21% (D)	(I), degraded to (U)
1976	[11]	N	Masonry Grout Components	-	Monotonic	(U) - Shear	-	-
1994	[13]	N	Brick Wall	10 to 20 mm horizontal displacement	Monotonic or Cyclic Shear	215% - 391% (I) - Shear	6% - 18% (I)	-
2001	[10]	N	Beam	-	Monotonic	15% (I), fractured	-	20% (I), fractured
2017	[7]	N	Beam	-	Monotonic	16% (D) - Flexure*	-	-

* Epoxy repair was completed using gravity as opposed to the pressure or vacuum injection techniques.

The table categorizes research with regard to the year and whether test specimens were reinforced and then provides the post epoxy repair results. (I) indicates an increase relative to the original, (D) indicates a decrease, and (U) indicates substantially unchanged.

Many factors influence the apparent effectiveness of the epoxy resin repairs reported in the journal articles and reports reviewed. Effectiveness was assessed by the percentage of stiffness reinstated and whether injected cracks remained closed. Some of the factors specifically relating to epoxy and addressed in the literature reviewed are discussed above in Section 2. We recommend that the reader refresh themselves with Section 2 at this time. Additional factors include, but are not limited to failure mode (shear or flexure), quality of repair, experience and competency of contractors, epoxy to concrete or reinforcement bond (impacted by the epoxy resin product, and the presence of dust, moisture, or other foreign substances), and extent of damage to concrete, reinforcement, and bond. Specific factors for the tests summarized above, recognized by the report/article authors can be viewed in detail in the corresponding documents.

Appropriate engineering judgement should be utilized when developing a repair strategy, identifying the cause of cracks, likely extent of damage to the structure (with consideration not limited to residual crack width – consider damage to or extent of yielding of reinforcement), selection of the best product based on the crack location and size, selection of the optimum injection method, and selection of an experienced and competent contractor.

BMC note that axial load appears to have a relatively significant impact on the efficacy of epoxy repair (refer to Section 4.2). Results changed dramatically between the two examples; one where an applied axial load closed the cracks and the other where an applied axial load propped the cracks open. BMC consider that further testing is needed to evaluate the implications of applied axial load and its impacts on the efficacy of epoxy injection.

8 Conclusion

8.1 Consideration of Report/Article Age

Developments in epoxy resins and repair techniques are ongoing. From the literature review, it was evident that as techniques are advanced and studied to optimize efficacy, the results generally improved. This is particularly true regarding the ability for epoxy repair to restore bond between the reinforcement and concrete. Earlier research and guidance (e.g. UNIDO 1983 and NEHRP 1985) found that epoxy injection was not effective in restoring bond, but research produced in 1990 [4] provided strong evidence that epoxy repair, especially using the vacuum impregnation technique, was effective in restoring bond.

8.2 Literature Review

From the literature review conducted, BMC concludes that epoxy resin injection, when carried out using appropriate quality assurance measures, optimum method of placement, and an appropriate epoxy resin product, is an effective means of repairing reinforced and unreinforced concrete structural elements. Epoxy resin injection was found to reliably reinstate stiffness and durability. Strength and energy dissipation were largely not influenced by the repair because they are dependant on the condition of the reinforcement, which cannot be repaired through epoxy injection. Initial stiffness is important for SLS considerations/criteria; however, elements are required to be designed with a cracked section modulus since the adoption of NZS3101:1995. For ULS considerations, strength is more important. Also, the research reviewed indicted that after 3-4 cycles, the stiffness of the original specimen and the repaired specimen were approximately the same.

Further industry developments in the vacuum impregnation technique may be desirable (since it is a much less common technique compared to pressure injection) particularly when considering repair of beam-column joints or other repair applications where reinstatement of bond is very important or delamination is a significant risk. Epoxy resin injection is viable in wet or dry conditions, although special techniques are required for wet conditions. Additionally, research indicated that epoxy resin injection is still viable in variable/extreme environmental conditions, but requires fire protective coatings for applications where elements are designed for fire loads as epoxy resin loses strength rapidly at higher temperatures.

BMC notes that although epoxy injection can reinstate bond between reinforcement and concrete, it cannot repair or in any other way alter the capacity of the reinforcement. As was indicated in the research reviewed, reinforcement can be subjected to a determinate quantity of extreme loading cycles prior to fracture regardless of the quality or efficacy of the epoxy repair technique, thus the cause of cracking and extent of damage to the reinforcement should be thoroughly considered prior to the selection of a repair strategy. Similarly, the imperative for repair must also be considered, along with the required standard of repair pursuant to the applicable insurance response for earthquake damage. Epoxy repairs are not a universal cure that will deliver a step change in performance. In the appropriate situation and conditions however, the research detailed in this literature review demonstrates epoxy can provide good quality repairs.

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