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Evaluation of Retrofit Methods for Reinforced Concrete Beams

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ABSTRACT: Reinforced concrete structures require retrofit due to extreme loading, change in use, strengthened design codes, and potential design or fabrication errors. Compared to demolition and rebuilding, structural retrofit can save materials, and be more sustainable and economical. There are a number of parameters that impact the retrofit efficacy for reinforced concrete beams. This paper explores three commonly used conventional retrofit methods: concrete jacketing, external steel elements, and external post-tensioning. A synthesis of the selected research studies is presented to highlight important considerations, as well as evaluate continuity between studies.

1 INTRODUCTION

There are several reasons why a structure may require repair and/or retrofit. Some of the most common include structural damage, often from seismic events or due to aging or durability issues, updated design codes, construction or design errors, reinforcement corrosion, and change in building usage. Especially for structures where the need is limited to select members, repair and retrofit methods have gained popularity as compared to demolition and rebuilding. Repairing and retrofitting can conserve time, money, and materials.

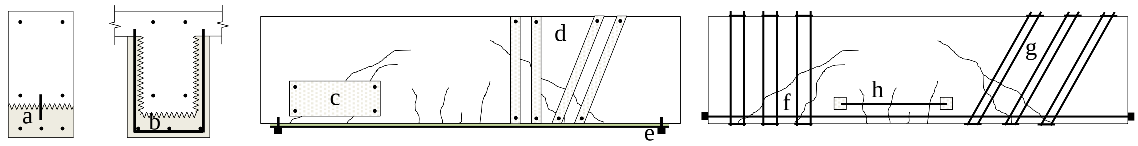
Once the decision has been made to retrofit a reinforced concrete (RC) beam, selecting the ideal method involves consideration of performance characteristics such as bringing strength, deformation capacity, and/or stiffness to a desired level, or changing the failure mode. Additionally, practical considerations such as cost, space required, and labor must be considered.

2 RESEARCH SIGNIFICANCE

The objective of this paper is the aggregation and synthesis of retrofit method information for RC beams. A wide range of methods, and variations within those methods, exist for beam retrofit. Practicing engineers need to understand the strengths and weaknesses to select the appropriate method for a given application. Knowing the areas of consensus and disagreement benefits researchers looking to advance the field. Each method has a representative sample of studies reviewed in this paper with a more comprehensive set of references available online later this year on a website being constructed by the researchers. As fiber-reinforced polymers (FRP) have been extensively documented, FRP retrofit is not within the scope of this paper. This paper will seek to advance the knowledge surrounding three of the most popular alternatives: concrete jacketing, external steel elements, and external post-tensioning.

3 RETROFIT METHODS FOR BEAMS

The suitability and performance of the three selected methods depends on several parameters. Some of the influential variables are related to the original beam including pre-existing damage, reinforcement details, concrete strength, and section shape. Other variables are related to the chosen retrofit method including material properties, geometric arrangement, and degree of composite action. Figure 1 contains generalized illustrations for each of the three methods.



a) Soffit jacket with surface roughening and dowels   b) U-jacket with bonding agent   c) Steel shear plate
d) Vertical & inclined steel strips   e) Steel flexure plate with epoxy & bolts   f) Vertical tendons
g) Inclined tendons   h) Horizontal tendons

Figure 1. Retrofit methods considered: concrete jacketing, external steel elements, and external post-tensioning

3.1 Concrete Jacketing

Concrete jacketing is generally used to increase the flexural strength of a beam by providing additional longitudinal steel to the composite section through use of a soffit jacket (Figure 1a) or a U-shaped jacket (Figure 1b) where the vertical sides can only extend partway up. The degree of composite action is dependent on the degree of load transfer along the boundary between jacket and beam. Frequently, surface roughening, dowels, or bonding agents are employed to minimize the slippage between jacket and beam as illustrated in Figure 1a and 1b.

Compared to external steel elements or external post-tensioning, concrete jacket design is more like beam design with a larger section size that follows the same flexural design procedure. Also, the jacket provides a layer of defense against environmental effects. However, concrete jacketing has drawbacks including the labor intensive nature of preparing the beam interface and constructing the forming, increased section size, curing time, and dead weight increase.

Nine representative studies were selected to evaluate four common jacketing retrofit considerations, which are presented in the following section: factors impacting composite action, original beam stirrup details, initial damage level, and jacket concrete composition. Table 1 contains a summary of the critical parameters for the nine selected studies.

3.1.1 Synthesis

There is much debate regarding the impact and necessity of taking special considerations to increase load transfer between old and new concrete to ensure composite action. Cheong and MacAlvey (2000) found the strengths of the composite sections to be ± 5% of monolithic regardless of roughening profile. Raval and Dave (2013) tested several preparation combinations resulting in a maximum increase of 15% compared to no special preparation. Cementing the lack of consensus, Guerrero et al. (1996) found strength gains up to 30% employing combinations of roughening and dowels. The necessity of interface preparations is unclear, however, all the studies show behavior closer to monolithic when roughening or dowels are employed.

When looking at utilizing U connecting stirrups or V connecting bars for jacket anchorage, Ozturk and Ayvaz (2002) revealed that the V connecting bars had ~10% increased load capacity and slightly worse energy dissipation with no trend on ductility. In contrast to many design codes, Cheong and MacAlvey (2000) found that properly anchored, both the original and new stirrups contribute fully to the flexural capacity of the beam, reducing the number of stirrups required. This conclusion is limited to undamaged beams as the steel had not yielded before retrofitting. To increase tension capacity of the retrofit, jacket concrete admixtures have been tested. Adding in metallic glass ribbon fibers resulted in an 10-15% increase in the strength and improved the

Table 1. Concrete jacketing study summary

<table>
<tr><th>Reference</th><th>Main Parameters Studied</th><th>Retrofit Method</th><th>Main Findings</th><th>Strength</th><th>Displacement Ductility</th><th>Stiffness</th><th>Failure Mode</th></tr>
<tr><td rowspan="2">Altun (2004)</td><td rowspan="2">Existing damage</td><td rowspan="2">Full jacket - Removed loose concrete; welded steel to beam steel</td><td rowspan="2">Retrofitted damaged beams exceeded theoretical performance</td><td colspan="3">Relative to original beam</td><td rowspan="2">Local crushing</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Increased</td></tr>
<tr><td rowspan="2">Chalioris et al. (2012)</td><td rowspan="2">Existing damage</td><td rowspan="2">U jacket - SCC, dowels on vertical sides</td><td rowspan="2">Strength increased and ductile behavior achieved</td><td colspan="3">Relative to original beam</td><td rowspan="2">Ductile</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Not reported</td></tr>
<tr><td rowspan="2">Cheong and MacAlvey (2000)</td><td rowspan="2">Interface preparation & stirrups</td><td rowspan="2">U jacket - Roughened surface</td><td rowspan="2">Interface preparation insignificant; properly anchored stirrups fully contribute to composite strength</td><td colspan="3">Relative to monolithic section</td><td rowspan="2">Various</td></tr>
<tr><td>Similar</td><td>Similar</td><td>Similar</td></tr>
<tr><td rowspan="4">Diab (1998)</td><td rowspan="4">Jacket concrete admixture</td><td rowspan="4">Soffit shotcrete jacket - Roughened surface; welded stirrups</td><td rowspan="4">Admixture increased strength; existing damage marginally reduced retrofit strength</td><td colspan="3">Relative to original beam</td><td rowspan="4">Not reported</td></tr>
<tr><td>Increased</td><td>Not reported</td><td>Lower</td></tr>
<tr><td colspan="3">Relative to monolithic section</td></tr>
<tr><td>Lower</td><td>Not reported</td><td>Lower</td></tr>
<tr><td rowspan="2">Hussein et al. (2012)</td><td rowspan="2">Jacket concrete admixture and steel ratio</td><td rowspan="2">Soffit jacket - Roughened surface</td><td rowspan="2">Admixture increased strength, decreased ductility</td><td colspan="3">Relative to original beam</td><td rowspan="2">Ductile</td></tr>
<tr><td>Increased</td><td>Lower</td><td>Increased</td></tr>
<tr><td rowspan="2">Guerrero et al. (1996)</td><td rowspan="2">Interface preparation</td><td rowspan="2">Top jacket - Roughened surface and / or dowels</td><td rowspan="2">Surface roughening and / or dowels improves composite strength. Dowels increase ductility</td><td colspan="3">Relative to monolithic beam</td><td rowspan="2">Ductile</td></tr>
<tr><td>Similar</td><td>Not reported</td><td>Not reported</td></tr>
<tr><td rowspan="4">Ozturk and Ayvaz (2002)</td><td rowspan="4">Connecting bars, stirrups, and existing damage</td><td rowspan="4">Soffit jacket - Clear cover removed; welded reinforcement</td><td rowspan="4">V-bars higher strength; U stirrups higher energy dissipation; existing damage results in worse performance</td><td colspan="3">Relative to original beam</td><td rowspan="4">Ductile</td></tr>
<tr><td>Increased</td><td>Improved</td><td>Increased</td></tr>
<tr><td colspan="3">Relative to monolithic section</td></tr>
<tr><td>Similar</td><td>Lower</td><td>Lower</td></tr>
<tr><td rowspan="2">Raval and Dave (2013)</td><td rowspan="2">Interface preparation</td><td rowspan="2">Full jacket - Chipping, dowels, bonding agent</td><td rowspan="2">Strength increased most for chipping, dowels and bonding agent mixed</td><td colspan="3">Relative to original beam</td><td rowspan="2">Not reported</td></tr>
<tr><td>Increased</td><td>Not reported</td><td>Increased</td></tr>
<tr><td rowspan="2">Shehata et al. (2008)</td><td rowspan="2">Steel ratio, anchorage bolts</td><td rowspan="2">Partial U jacket - Roughened surface; expansion bolts installed</td><td rowspan="2">Bolt spacing > 50mm and close to original stirrups and main steel</td><td colspan="3">Relative to original beam</td><td rowspan="2">Ductile</td></tr>
<tr><td>Increased</td><td>Lower</td><td>Increased</td></tr>
</table>

cracking pattern relative to normal concrete (Diab 1998). Using strain hardening cementitious composites was similarly found by Hussein et al. (2012) to increase the strength by upwards of 30%; however, the ductility was significantly reduced.

Many studies deal with undamaged beams, which may not always be the case in the field. There is consensus that the retrofit can increase the strength ≥ 50% beyond the original section and depending on the amount of steel yielding during initial loading, also increase the ductility (Ozturk and Ayvaz 2002, Altun 2004, Chalioris et al. 2012). The amount of difference relative to the same retrofit applied to an undamaged section was generally shown to be ≤ 10% for strength and energy dissipation (Ozturk and Ayvaz 2002).

With the exception of Cheong and MacAlvey (2000) who tested continuous span T-beams, the most likely beam configuration in the field, the remaining studies evaluate simply supported rectangular beams. The study results are somewhat limited given the likelihood of different beam shapes and moment profiles found in the field. Additionally, the studies which utilize a full jacket cannot be practically implemented in the field due to floor slabs restricting available space.

3.2 External Steel Elements

The most common external steel element for retrofit is a steel plate. The beam's flexural strength is increased generally by affixing the plate to the soffit through epoxy and/or anchorage (Figure 1e). If doing so changes the dominant failure mode to shear, or the beam is susceptible to brittle shear failure, plates (Figure 1c), or vertical or inclined strips (Figure 1d) can be similarly attached on the beam sides in the critical regions.

External steel elements are advantageous due to minimal section size increase and added weight. Using such elements requires careful preparation of the steel and beam bonding interface, which is labor intensive. The use of epoxy and/or anchorage introduces new potential failure modes through shear peeling or bolt fracture, both of which are brittle. Unprotected steel elements may not be appropriate depending on the operating environment, thus limiting the number of applications. The eight selected research studies in Table 2 focus on two main parameters governing the design: plate dimensions and anchorage.

3.2.1 Synthesis

In general, it was found that minimizing the plate thickness and maximizing the plate depth to achieve the required plate cross-sectional area is best to preserve ductility and reduce complexity of securing the plate. Utilizing a thin soffit plate, Aykac et al. (2013) and Hussain et al. (1995) demonstrated a ≥ 33% increase in strength and a flexural failure mode without anchorage. Shear cracks can develop at the ends of the plates below the beam shear capacity and Oehlers (1992) presents a design method in light of this (Aykac 2013). If bolts are required and/or used to secure the plates, producing a balanced failure with the bolts, plate, and compressive concrete block can prevent brittle failure (Su et al. 2010).

Beams in the field frequently experience cyclic loading or may need to be retrofitted after yielding. Hussain et al. (1995) retrofitted beams which had sustained 85% of their ultimate load capacity. Thinner plates were found to be superior for achieving ductile failure modes and strength gains ≥ 30% over the original beam, which is consistent with reported increases for undamaged beams in other studies. Nie et al. (2011) fatigue tested steel plated sections and found that while the steel plates controlled the failure the calculated fatigue life was conservative by ≥ 50%.

To simplify the design and labor needs for beam retrofit, external unbonded longitudinal bars can be used. Cairns and Rafeeqi (1997) demonstrated up to an 85% increase in flexural strength by

Table 2. External steel element study summary

Reference	Main Parameters Studied	Retrofit Method	Main Findings	Strength	Displacement Ductility	Stiffness	Failure Mode
Adhikary and Mutsuyoshi (2005)	Plate thickness, plate depth/beam depth ratio	Side steel plates - Interface roughened; epoxy and bolts	Deeper plates preferable to thicker plates; plate depth/beam depth > 0.75 produces marginal shear strength gains	Increased	Relative to original beam Not reported	Increased	Shear
Aykac et al. (2013)	Plate thickness and perforation, anchorage	U and soffit steel plate - Interface roughened; epoxy and bolts	Bolt contribution increases with plate thickness; thin plates on soffit do not need anchorage	Increased	Relative to original beam Lower	Increased	Flexure and shear peeling
Cairns and Rafeeqi (1997)	Reinforcement effective depth	Side steel bars - Unbonded bars anchored to beam ends	Unbonded external bars are effective at flexural strengthening	Increased	Relative to original beam Lower	Increased	Not reported
Hussain et al. (1995)	Plate thickness, anchorage, damage level	Soffit steel plate - Interface roughened; epoxy and bolts	Anchorages and plates too thick negatively impacted ultimate load due to changing failure mode	Increased	Relative to original beam Lower	Increased	Multiple
Jones et al. (1988)	Anchorage	Soffit steel plate – Epoxy bonded, anchorage plates, bolts, or none	Epoxied plates on soffit with anchorage plates provided best strength and ductility	Increased	Relative to original beam Similar	Not reported	Plate yield and crushing
Kothandaraman and Vasudevan (2010)	Slack level in external reinforcement	Soffit steel bars - soffit anchorage	Moment strength increase up to 70%; simple method from design and labor standpoint	Increased	Relative to original beam Not reported	Increased	Crushing
Nie et al. (2011)	Fatigue, steel-concrete composite	Soffit steel plate - Interface roughened; anchor bars; plate beam void concrete filled	Steel fatigue controlled failure; thin and high-strength steel are not suitable	Increased	Relative to original beam (theoretical) Not reported	Increased	Plate fatigue, ductile flexure
Su et al. (2010)	Bolt-plate arrangement	Side steel plates – Bolt anchorage	Strong bolt weak plate design best for strength and ductility	Increased	Relative to original beam Lower	Increased	Crushing or bolt fracture

mounting steel bars on the sides of the beam with anchors on the beam ends. Kothandaraman and Vasudevan (2010) placed the bars at the soffit face and improved the strength and ductility compared to the proposed side mounted bar method by Cairns and Rafeeqi.

3.3 External Post-Tensioning

Relative to the other methods, external post-tensioning achieves similar performance gains while decreasing the total amount of material needed by utilizing tensioning forces. However, high-strength steel tendons are susceptible to corrosion and creep that may result in sudden failure.

There are three basic tendon configurations explored: vertical, inclined, and horizontal (Figure 1f, 1g, 1h). These three profiles can be continuous along the span, or discontinuously placed in select regions. The tendons are typically secured with anchor bolts or strung between steel plates. Tendon orientation, tensioning amount, and the damage state of the beam are three primary parameters that must be considered and are investigated in the six selected studies in Table 3.

3.3.1 Synthesis

When increasing flexural strength, assuming shear will not control, placing horizontal tendons in the positive moment regions increased strength ≥ 38% while providing adequate ductility and stiffness at service level loading (Tan and Tjandra 2007, Aravinthan 2006). At ultimate loading, a parabolic shape overlapping at the interior supports was superior, but not drastically different. For shear strength focused retrofit, Kim et al. (2006) showed a 5-10% increase in strength for inclined tendons compared to vertical. Regardless of orientation, gains of 30-70% were realized.

The tensioning amount has been shown to have minimal impact once it exceeds the minimum amount of force required to close the shear cracks, which is dependent on the concrete compressive strength (Shamsai et al. 2007, Aravinthan 2006). Testing only under monotonically increased loading, Sirimontree et al. (2011) found that a 1640% increase in the tension force in only resulted in a < 10% increase in strength. However, Kim et al. (2006) found increases up to 18% strength as the tensioning force increased. Given that the tendons are typically being stressed between steel plates on opposite beam faces, to avoid local crushing it is important to check the compressive capacity of the bearing area.

Initial damage level is important for post-tensioning as the method is frequently used to retrofit beams that have existing cracking or yielding. Using horizontal tendons, Aravinthan (2006) found a 33% decrease in strength between no epoxy shear crack repair and repair. Shamsai et al. (2007) used vertical tensioning and found insignificant difference between an unrepaired beam and an uncracked control beam. El-Shafiey and Atta (2012) also used vertical tensioning and reported ≤ 70% decrease in strength relative to a crack repaired beam. While there is some disagreement in literature, it is recommended to repair the beam before retrofit given the cheap and quick nature.

4 CONCLUSIONS

In addition to general agreement within each method regarding strength, ductility, and stiffness impacts, and failure modes, there are several key conclusions: 1) across the methods, the initial damage level was shown to not inhibit the ability of the retrofit to exceed the original beam strength as long as the original beam is not severely damaged, e.g., steel rebar did not yield, 2) considering the labor and performance implications more work is needed to ascertain the necessity of surface preparation for concrete jacketing, and 3) all the methods noted the importance of considering the impact of the retrofit on un-intentionally shifting the failure mode or damage location within the element or to a connecting element.

Table 3. External post-tensioning study summary

<table>
<tr><th>Reference</th><th>Main Parameters Studied</th><th>Retrofit Method</th><th>Main Findings</th><th>Strength</th><th>Displacement Ductility</th><th>Stiffness</th><th>Failure Mode</th></tr>
<tr><td rowspan="2">Aravinthan (2006)</td><td rowspan="2">Initial damage, epoxy repair</td><td rowspan="2">Horizontal tendons - preloaded; shear cracks epoxied; tendons anchored at beam ends</td><td rowspan="2">Epoxy repair of shear cracks necessary; epoxy did not impact stiffness</td><td colspan="3">Relative to original beam</td><td rowspan="2">Not reported</td></tr>
<tr><td>Increased</td><td>Not reported</td><td>Increased</td></tr>
<tr><td rowspan="2">El-Shafiey and Atta (2012)</td><td rowspan="2">Initial damage level, crack repair, CFRP plates</td><td rowspan="2">Vertical tendons - beams preloaded; CFRP U-plates in tensile regions</td><td rowspan="2">Shear crack repair significantly increases strength, CFRP plates raise strength additional ~15%</td><td colspan="3">Relative to original beam</td><td rowspan="2">Flexure</td></tr>
<tr><td>Increased</td><td>Improved (derived)</td><td>Increased</td></tr>
<tr><td rowspan="2">Kim et al. (2006)</td><td rowspan="2">Tensioning force, tendon orientation, span-to-depth ratio</td><td rowspan="2">Vertical and inclined wire ropes - shear cracks epoxied; sets of three wire ropes installed</td><td rowspan="2">Inclined tendons provided greatest strength increase; spacing had little impact</td><td colspan="3">Relative to original beam</td><td rowspan="2">Improved</td></tr>
<tr><td>Increased</td><td>Not reported</td><td>Increased</td></tr>
<tr><td rowspan="2">Shamsai et al. (2007)</td><td rowspan="2">Tensioning force, reinforcement, initial damage, concrete strength</td><td rowspan="2">Horizontal tendons - rubber between steel angles on beam top and bottom</td><td rowspan="2">Marginal strength gains for increased tensioning force; initial damage and reinforcement insignificant on shear strength</td><td colspan="3">Relative to original beam</td><td rowspan="2">Flexure</td></tr>
<tr><td>Increased</td><td>Not reported</td><td>Increased</td></tr>
<tr><td rowspan="2">Sirimontree et al. (2011)</td><td rowspan="2">Tensioning force, beam depth</td><td rowspan="2">Vertical PC tendons - bolt plates on top and bottom secure strands</td><td rowspan="2">Marginal strength gains for increased tensioning force</td><td colspan="3">Relative to original beam</td><td rowspan="2">Mixed</td></tr>
<tr><td>Increased</td><td>Increased</td><td>Increased</td></tr>
<tr><td rowspan="2">Tan and Tjandra (2007)</td><td rowspan="2">Tendon orientation and material</td><td rowspan="2">Horizontal or draped tendons - steel or CFRP tendons; steel deviators define tendon profile</td><td rowspan="2">Tendon material performance similar; tendons anchored in positive moment regions best at service level, parabolic at ultimate</td><td colspan="3">Relative to original beam</td><td rowspan="2">Flexure</td></tr>
<tr><td>Increased</td><td>Varied</td><td>Increased</td></tr>
</table>

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