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Strengthening of RC Structures Using CFRP-Near Surface Mounted Technique

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Abstract

This study reviews the literature on fiber-reinforced polymers (FRP) and their applications in near-surface mounted (NSM) applications. Since fiber-reinforced polymer (FRP) composites outperform many conventional steel reinforcing methods in terms of quality, they are nearly entirely dependent on advanced concrete technology. Many structures that will still be in use two decades from now have already been constructed. A portion of these structures must undergo enhancements or be replaced, as they are deteriorating not only from natural processes but also from mistakes made during their design and construction. Near-surface mounted (NSM) utilizing Fiber-Reinforced Polymer (FRP) bars has proven to be a successful method in enhancing the flexural and shear performance of both existing and new Reinforced Concrete (RC) elements. Structural strengthening is a challenging endeavor. Many systems might be employed to make the best use of the fiber-reinforced polymer. There is a growing need for better strengthening methods for existing concrete structures. Structuring might be difficult, but various methods can be used to make the best use of fiber-reinforced polymer. Some of these structures need to be upgraded or rebuilt because, in addition to natural deterioration, their design and construction errors are also to blame. The effectiveness of strengthening RC columns using near-surface mounted (NSM) CFRP strips with CFRP confinement was studied. Near-surface mounted (NSM) utilizing Fiber-Reinforced Polymer (FRP) bars has proven to be a successful method in enhancing the flexural and shear performance of both existing and new Reinforced Concrete (RC) elements. The efficiency of Reinforcement using Carbon Fiber Near-surface mounted (NSM) polymer strips examined was CFRP confinement to reinforced columns. Near surface-mounted reinforcement is a useful choice with numerous advantages over externally bounded reinforcement.

Keywords: Near-surface Mounted, Failure mode, Strain distribution, Strengthening applications, Concrete structures, Fiber-reinforced polymer.

INTRODUCTION

Techniques for reinforcing existing concrete structures must be enhanced as demand for them rises. There are already a lot of concrete structures built that will be operational in 20 years. Due to failings in design and implementation, as well as failing procedures, some of these structures need to be updated or replaced. Due to the many advantages of FRP strengthening, FRP materials have become a viable choice for repairs in the last 20 years. The endurance of reinforced concrete structures gradually decreases with age. Furthermore, the corrosion of steel brought on by outside factors reduces the resistance of components made of reinforced concrete.

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To enhance structural performance, fibre-reinforced polymers (FRP) retrofit has been used in many building projects across the globe. At the moment, the external bonding reinforcement (EBR) approach is the most often used retrofitting technique. This technique has been used in real-world applications for a while, and several nations have created norms in this regard. On the other hand, near-surface mounting (NSM) is a relatively recent retrofit technique that involves cutting out a groove on an existing concrete member, applying an appropriate adhesive, and then laying FRP bars rods, or strips into the groove. The early debonding of FRP during EB-FRP can provide problems that can be mitigated with the NSM approach for shear strengthening.

Because preserving structure members costs less money and work than rebuilding them, reinforcing concrete members becomes essential. Although FRP strengthening has a lot of promise, it is crucial to understand the behavior and applicability of various FRP materials and techniques. FRP reinforcements are used to externally bond wet lay-up technology [1]. They come in the form of fabrics with fibers oriented in at least two directions, or in the shape of circulars, rectangles, or pultrusion strips. The primary fibers used in fiber-reinforced polymers (FRP) are aramid (A), glass (G), and carbon (C). The fibers are typically joined by a matrix phase epoxy. Extra reinforcement to match the internal reinforcement can be added to the outside of concrete structures by attaching Flexible Reinforced Polymer (FRP) materials with high-strength adhesives. Besides the external bonding, FRP reinforcement can also be added by inserting it into holes drilled into the structure elements in a process known as “near surface mounting” (NSM) (Figure 1). Early in the 1950s, NSM reinforcement was applied to RC structures for the first time in Europe. The steel cage of an RC bridge deck in Sweden had to be reinforced in its “Negative” area in 1948 because of excessive settling during construction. Steel reinforcement bars were inserted into concrete grooves and filled with cement mortar to complete the reinforcement.

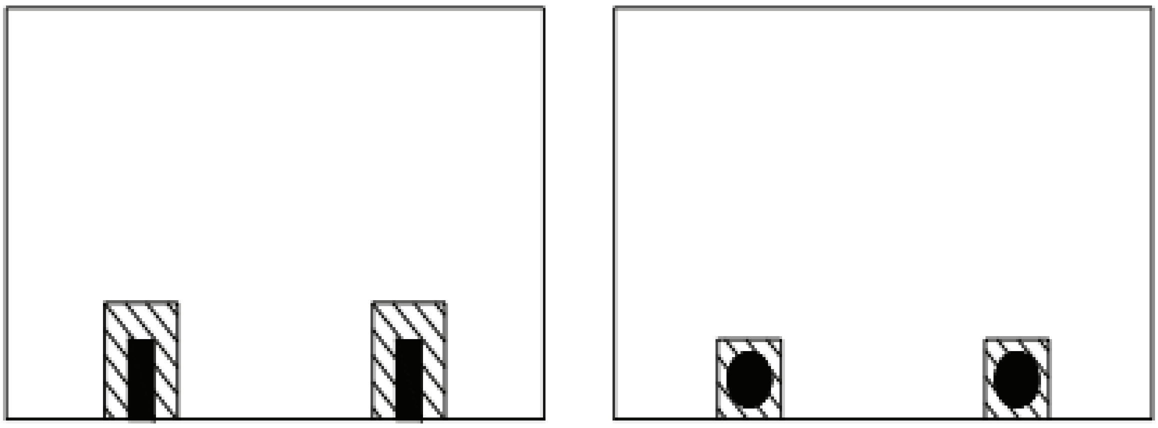

Figure 1. Near surface mounted FRP, rectangular shapes and rods.

In some applications, fiber-reinforced polymer (FRP) reinforcement can replace steel reinforcement due to its superior corrosion resistance, lightweight design, ease of application, and smaller groove size due to increased tensile strength and reduced surface deformation (sharp steel deformations cause the concrete cover to fracture).

There are several advantages when comparing the external bonding technique (EBR) to the near surface mounting approach. A greater bond surface allows for the mobilization of a higher percentage of the tensile strength due to its improved anchoring capability and increased resistance to peeling off. Installation time will be reduced because there is no additional preparation work needed beyond grooves. These techniques are attractive for strengthening in the negative moment zone since the FRP reinforcement is protected from mechanical impacts by the surrounding concrete due to its unique mounting structure [2, 3].

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The strengthening offers better protection against UV rays, high temperatures, freeze/thaw cycles, fire, and vandalism. The testing showed improved ductility, a composite action that was desired, and a final load development that was less reliant on the surface tensile strength.

While the adhesive is hardening, cycle loading is applied; however, it works best when the adhesive is in its groove filler glue state, which transfers stresses from the concrete to the FRP reinforcement. There are two types of adhesives available: cement-based and epoxy-based. The tensile and shear strengths of groove filler are by far its most important mechanical characteristics.

Due to the large circumferential tensile stresses that circular bars cause in the epoxy, the tensile strength is particularly crucial. Shear strength becomes vitally important when cohesive shear failure of the epoxy controls the bond. When it comes to performance, two-component epoxy makes the ideal groove filler. Prestressed near-surface mounted carbon fiber reinforced polymer (FRP) is subject to temperature and time-dependent material qualities that affect its long-term structural performance.

In contrast to epoxy, cement-based adhesives are less costly, provide a lower risk to the environment and laborers, may be applied to damp surfaces, perform better at elevated temperatures, and work well with concrete substrates. Its reduced tensile strength is the main disadvantage, and adequate moisture must be maintained while the cement solidifies. Cement mortar cannot be used as grove filler without specific limitations, according to a flexural test and bond investigation [4–6].

Although cementitious glue works well when hardened under static load conditions, using it while cyclic loading is applied during the hardening process is not recommended. The matrix ensures that the fibers are oriented and positioned correctly, that the composite is strong, that it is shielded from the elements, and that it won't damage itself while being made or used. Assigning the loads to the various fibers is another responsibility.

FAILURE MODES

There are usually multiple recognized failure modes for elements enhanced with fiber-reinforced polymer (FRP). It is essential to comprehend them because they significantly affect the ultimate load. It is imperative to distinguish between externally bonded and near-surface failing tangible parts.

Failure Modes of Externally Bonded FRP Reinforcements

A bond is necessary to carry pressures from the concrete into the FRP; if it fails, the composite action is completely lost. Four types of bond failures are distinguished.

1. breaking away along a weak layer from the concrete cover near the surface;
2. debonding in the adhesive;
3. debonding in the concrete; and
4. debonding in both the adhesive and the fiber-reinforced plastic.

The spread of the localized debonding is linked to peeling-off failure. Debonding start timing is useful for differentiating peeling-off failures [7]. Debonding at the anchorage zone, flexural cracks, shear cracks, and uneven concrete surfaces can all lead to peeling off.

Failure Modes of Near Surface Mounted FRP Reinforcement

Interfacial Failure Modes

Cohesive shear failure in the adhesive or pure interfacial failure are the two possible types of interfacial failure. Pure interfacial failure is indicated by the lack of adhesive residue at the FRP surface after failure. Failure is shown by the adhesive that is left on the concrete and FRP following failure.

Failure at Reinforcement Adhesive Interface

The pure interfacial mode may be significant for bars with smooth or slightly sandblasted surfaces if the bond is more dependent on adhesion than on a mechanical interlock between the adhesive and the bar.

Failure at the Epoxy Concrete Interface

Because of its level surface, interfacial failure was only demonstrated to be a significant issue in precast grooves. This kind of failure occurs with lower bond stress than typical but a more ductile failure due to residual friction at the glue and concrete interface [8, 9].

Cover Splitting

While the splitting tendency of the FRP bars is less severe due to their milder deformations, the process of splitting in the case of round bars is comparable to the splitting bond failure of steel-deformed bars as shown in (Figure 2). Partitioning results from the bond stress's radial component. There were several types of cover splitting seen. The main reason for cementitious mortar adhesive splitting was the low tensile strength of the filler material, however, longitudinal adhesive splitting was also observed in situations of epoxy adhesive cracking and concrete splitting. Except for reinforcements near the edge, the perpendicular component of interactional stress in the case of NSM strips acts towards the thick lateral concrete, reducing the likelihood of splitting failure (Figure 3).

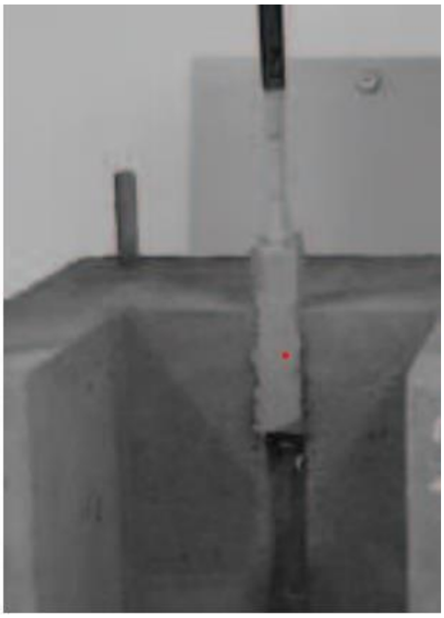

Figure 2. Failure at epoxy concrete interface.

Figure 3. Cover splitting on concrete cracking.

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Edge Splitting

Edge-splitting failure may occur when reinforcement is positioned near the concrete member's edge. The rise of interactional stress is another factor contributing to it. It is possible to prevent edge-splitting failure by maintaining a minimum distance from the edge; this should be taken into account during the design stage. The author believes that the differences in thermal expansion between epoxy and concrete can have an impact on edge splitting, but more research is needed to confirm this method of splitting [10, 11].

FRP Tensile Rupture

Tensile rupture, which is rare in no prestressed strengthening, should be avoided due to its explosive character. Prestressed fiber-reinforced polymer (FRP) systems are more prone to failure due to fiber tensile rupture since they utilize part of their strain capacity.

DETAILING

The near surface mounted reinforcement needs to be detailed; the best FRP cross-section and adhesive need to be selected. During design, it is important to consider the minimum distance from the member's edge to prevent edge splitting as well as the minimum distance between adjoining reinforcement to prevent splitting cracks from extending horizontally.

The following steps are involved in the application of near-surface mounted fiber-reinforced polymer reinforcement:

The first step is to carve a groove using a grinder or saw with one or two diamond blades, depending on the size and type of reinforcement. The next step is to thoroughly prepare the groove by clearing the surface of any dust or loose pieces with compressed air or a vacuum. After partially filling the groove with adhesive, insert the FRP rod or strip and gently press to let the adhesive flow around the FRP [12, 13]. Finally, the surface is smoothed and more paste is poured into the groove (Figure 4).

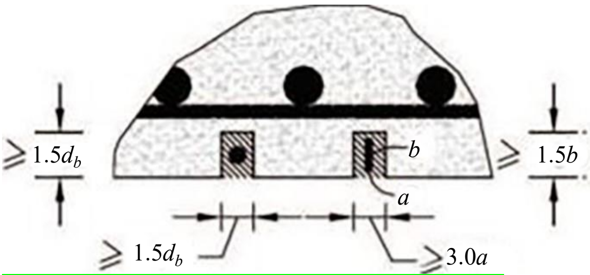

Figure 4. Spacing of NSM Reinforcement.

At least 1.5 times the diameter of the FRP bar should be the minimum size of the grooves. For a rectangular bar (strip) with a big aspect ratio, the minimum measurements should be 1.5 times the height and 3 times the breadth. In certain cases, installation criteria rather than engineering may determine the minimum groove dimension. For instance, the minimum blade size and the concrete cover may have an impact on the groove's width and depth, respectively. It is always preferable to keep the existing steel reinforcement in place. The optimal dimensions of the groove may depend on several factors, including the adhesive's characteristics, the FRP's surface treatment, the concrete's tensile strength, surface, and aggregate composition.

FRP shear reinforcement should be spaced no more than lnlet/2, or 600 mm, apart. To prevent crushing the concrete, the total reinforcement contribution—that is, the sum of the steel and fiber-reinforced polymer reinforcement—should be reduced to a minimum (Figure 5). Shear strength and flexural strength of damaged reinforced concrete (RC) sections can be enhanced with near-surface mounted (NSM) fiber-reinforced polymer (FRP) rods. As NSM FRP rods are used to augment RC elements, a detailed description of their structural behavior is required as this technology advances.

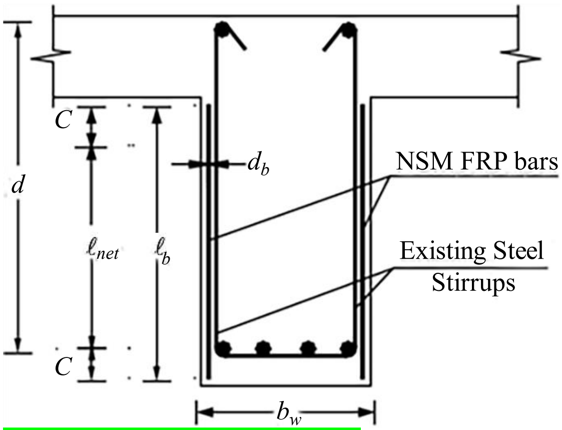

Figure 5. Shear strengthening.

EXPERIMENTAL RESULTS AND APPLICATIONS

Comparative Study on Slab Elements

Most likely, the most well-known test results are those from the early NSM trials. In this work, the effects on slab and beam elements of NSM and EBR reinforcement are compared. The bending moment vs. deflection for both the maximum moment and maximum deflection exhibits noticeable increases when NSM reinforcement is employed.

Strengthening of Reinforced Concrete Beams

Flexural Strengthening

The use of FRP reinforcement is most commonly utilized for flexural strengthening. Carbon fiber reinforced polymer (FRP) strips placed on RC beams in Portugal resulted in a twofold increase in the ultimate load of the equivalent reference beam. When the steel reinforcement began to yield, the load was increased by 32% to 47%. Furthermore, there was a noticeable increase in the cracking load. In the reinforced beams, there was greater rigidity between the yielding and cracking load. The beams collapsed as a result of the carbon fiber-reinforced polymer (FRP) strips moving. The concrete layer at the base of the beam separated, which made it stand out. With maximum strains ranging from 62% to 92% of its ultimate strain, the FRP demonstrated both the high anchoring capacity of the near-surface mounted laminates and the best possible use of the reinforcement's tensile capacity. The results of the previous test were corroborated by similar research carried out in Poland. A special test found that if the axial rigidity of NSM aramid FRP rods and EBR aramid FRP sheets were similar, then the flexural reinforcing effect might be similar [14–16].

Shear Strengthening

Shear failure depends on several factors and should be avoided because it is brittle. FRP adds further layers of complexity when it comes to shear strengthening. These include the behavior of linear elastic materials, the FRP concrete bond condition, and the several strengthening configurations and methods that can be used. In a Portuguese test run, it was discovered that the quantity and orientation of carbon fiber-reinforced polymer strips strengthened RC T beams. The most effective strip orientation was 60, with an average 24% increase in service load (deflection of L/400) over only RC and 14–15% over beams strengthened with strip orientations 45 and 90 (Figure 6).

The beams with the highest percentage of reinforcing strips experienced the biggest increase in service load (30%). In the sequence of beams with 45˚ strip orientation, this tendency was not noted. Another experiment that looked at the behavior of RC beams enhanced under shear with NSM FRP reinforcement produced results similar to these. When strips were used in place of round bars, the fractional reinforcement found in the shear capacity decreased. Because the separation of the concrete side cover at the level of the steel stirrups was invariably the cause of failure, reducing the spacing or increasing the inclination did not increase the beams' shear capability [17, 18].

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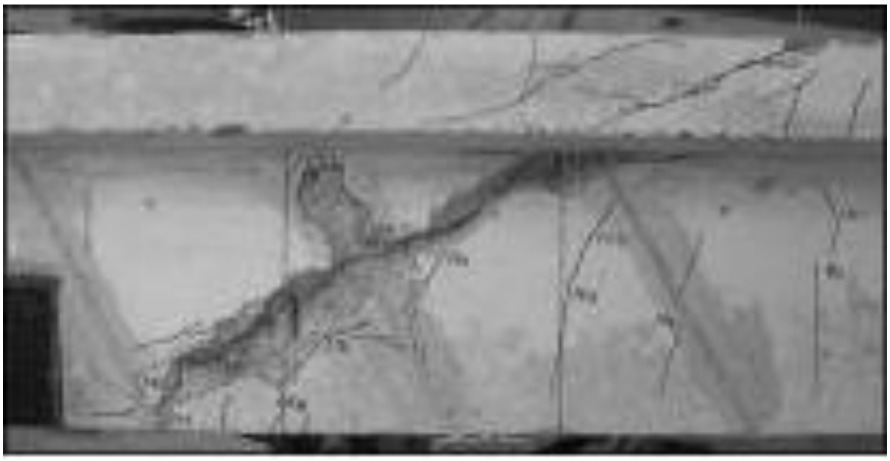

Figure 6. Failure of Shear strengthening of RC beams.

Column Strengthening Experiments

In structures made of reinforced concrete, columns play a crucial role because when they fail, the entire structure collapses. Three sets of RC columns were evaluated to evaluate the efficacy of NSM strengthening: the non-stronger columns, the strengthened columns with CFRP strips PRE, and the tested columns of the non-series strengthened with CFRP strips POS respectively. The columns experienced both a cyclic horizontal load and a static axial compression force. The strengthening method has a few special features [19, 20]. First, epoxy mortar was used to replace the concrete at the non-linear hinge area (located between 100 and 150 mm from the bottom of the column) (Figure 7). Grooves were cut into tensile stress-prone faces, and 100 mm of perforations were needed to lock the FRP reinforcement in place for the footing's alignment. The test findings showed a considerable increase in the load-carrying capacity of both the PRE and POS strengthened columns.

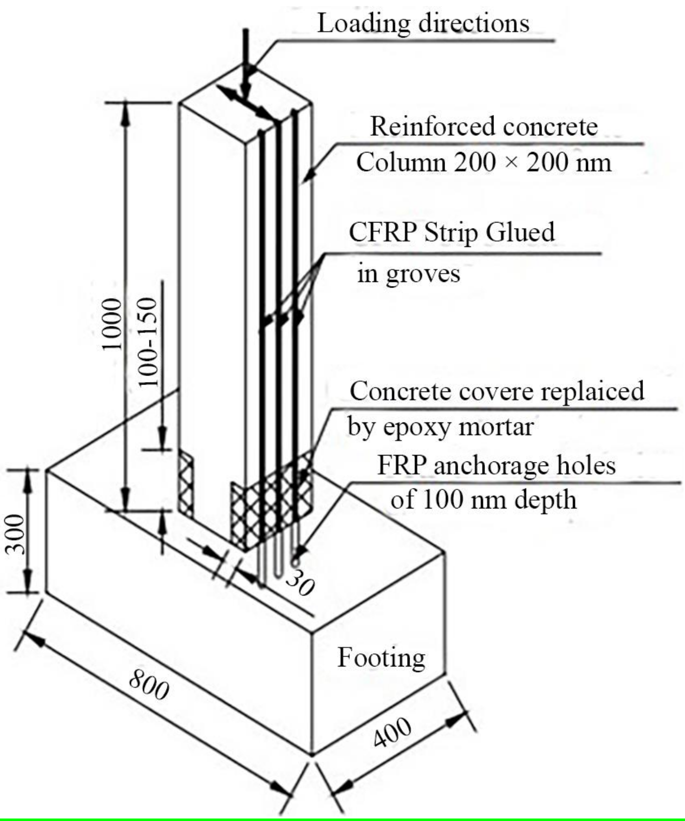

Figure 7. Strengthening techniques in specimens of RC Columns.

Silo Repair and Upgrading

Six cement silos in the Boston area were updated at a reasonable cost by employing near surface-mounted FRP rods, an ingenious approach. Approximately thirty percent of the planned vertical and hoop steel was missing from the reinforced concrete silos, which led to the discovery of concrete spalls and structural flaws during inspection [21–23]. Because the silos were built in groups of two and four, there was no way to reach the entire outside edge.

The main benefits of near surface mounted fiber-reinforced polymer (FRP) rods are as follows:

- The groove dimensions were minimized because of the bars' high strength and corrosion resistance;
- There were several chances to anchor;
- To guarantee the rods' strength growth, they were dowelled into the common silo walls to a depth;
- The 45-meter bars were mounted in a single piece because of the FRP's lightweight nature.

Strengthening Using Prestressed FRP

Using more FRP material is made possible by pre-stretching, which is essential to guarantee that the structure receives the proper force transfer. Shear and normal stresses can be transferred to the structure more successfully in near-surface mounting circumstances without the need for mechanical anchoring devices.

There are several advantages to using prestressed FRP. Using the reinforcing material more effectively is the first option. The structure will likely be more robust and stiffer if there is a greater first cracking load, a smaller crack size, and more space between cracks. Unloading the steel reinforcement improves the fatigue behavior. Pre-stretching also benefits from higher steel yielding and a final load with a smaller midpoint deflection. However, there is a drawback as well. The majority of FRP materials have linear elastic characteristics up until failure. We prestress them to use some of the strain capacity [24]. This information also clarifies why fiber rupture is the primary cause of failure for most prestressed fiber-reinforced structures.

CONCLUSION

A thorough analysis of the literature on the behavior and possible applications of near surface mounted (NSM) reinforcements is given in this work. NSM is a new kind of reinforcement in addition to externally bonded reinforcement (EBR). The same quantity of NSM reinforcement, as opposed to externally bonded reinforcement, results in a larger deflection up to failure and a higher load-bearing capacity in the structural behavior of flexure and shear-strengthened reinforced concrete beams.

The specimen's carrying capacity rises in tandem with an increase in concrete strength, which causes the failure mode to transition from debonding to FRP strip rupture. Additionally, specimens that exhibit greater resistance to FRP epoxy interfacial debonding are those with higher concrete strengths.

There is no indication of the impact of groove width variation on bond capacity because all concrete specimens tested with different groove width values fail because the CFRP strips tear. However, specimens with a wider groove are more resistant to Fibre Reinforced Polymer-Epoxy interfacial debonding because they have a shorter area of its debonding length.

The components reinforced with NSM reinforcements show distinct failure modes compared to EBR because the fiber-reinforced polymer (FRP) elements have a bigger bond surface and an increased anchoring capability.

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