Strengthening Concrete Structures with Mechanically Fastened Pultruded Strips

by

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Abstract

The Mechanically Fastened-FRP (MF-FRP) strengthening system has recently emerged as a practical alternative for strengthening RC structures. It consists of pre-cured FRP strips having high longitudinal bearing strength attached to the concrete surface using closely spaced steel fasteners in the form of nails and/or concrete wedge anchors. The nails are commonly shot into the concrete by means of power-actuated tools. Concrete wedge anchors are inserted into holes drilled into concrete: they are then expanded, wedging themselves securely in the concrete. Concrete wedge bolts are one piece, heavy duty anchors that are driven into predrilled holes.

The efficiency of this strengthening technique was demonstrated in terms of structural performances, and costs, labor and time savings by means of several laboratory and field applications. This paper presents a critical analysis of the parameters affecting the performance of the connection concrete-fastener-FRP laminate, in order to show how rationally the designer can choose the type of connection depending on the restraints posed by the condition of the concrete substrate and the final purpose of the strengthening design. Recommendations and technical details for design purposes are also briefly recalled.

Introduction

Fiber-reinforced polymer (FRP) materials have emerged as a practical alternative for construction, renovation and strengthening of structures, such as bridges, deficient in flexural/shear capacity with significant cost and time savings over conventional methods. Advantages of FRP materials are that they resist corrosion, long outlive conventional materials, and have high strength-to-weight ratio. In addition, it has been shown that in this technical area nowadays the engineer has different tools available in order to find the optimal solution to each problem: manual lay-up FRP and steel reinforced polymer (SRP) laminates, adhered pre-cured FRP laminates, near surface mounted (NSM) FRP bars and, finally, MF-FRP laminates (Lopez et al., 2004).

The manual lay-up consists of dry fiber fabric plies that are impregnated with epoxy resin and adhered to a prepared concrete surface (Nanni, 2000). First, the epoxy saturant is applied to the prepared concrete surface; after that, the first ply is adhered to the surface manually and saturated by rolling; and, finally, a second saturant layer is applied over the ply to a complete impregnation. The procedure is repeated for multiple plies.

The SRP laminates consist of high strength steel cords formed by interwoven steel wires embedded in a polymeric resin (Huang et al., 2004). The installation of the SRP is similar to the procedure used for the FRP manual lay-up lamination, but using cementitious grout or another higher viscosity saturant for impregnation to avoid handling problems resulting from the higher weight of the steel laminate.

The adhered pre-cured FRP laminates consist of pultruded rigid products that are bonded on a previously-prepared concrete surface (Meier, 1995, and Saadatmanesh et al., 1998). The laminate is pressed onto the concrete surface to allow the removal of excess resin. Due to the thickness of the laminate, about 1.4 mm, neither multiple laminates nor laminate splicing by overlapping are practical.

The NSM FRP bars consist of pultruded bars embedded in precut resin-filled grooves. Each FRP bar is placed into a groove and lightly pressed to force the paste to flow around the bar. This technique does not require any surface preparation work apart from cutting the grooves, an operation that demands a considerable amount of labor. Another advantage is the feasibility of anchoring these rods into members adjacent to the one to be strengthened. NSM FRP bars technique becomes particularly attractive for strengthening in the negative moment regions of slabs and decks, where external reinforcement would be subjected to mechanical and environmental damage and would require protective cover which could interfere with the presence of floor finishes (De Lorenzis, 2002).

The MF-FRP laminates consist of pre-cured FRP strips (Fig. 1) having high longitudinal bearing strength attached to the concrete surface using closely spaced steel fasteners (Borowicz et al., 2004) in the form of nails or concrete high strength wedge anchors (Bank et al., 2004, and Rizzo, 2005) (Fig. 2). Unlike the first three bonded methods, where adhesion is used to transfer the load to and from the reinforcement, the MF-FRP technique requires minimum surface preparation because the mechanism of load transfer to and from the composite laminate is provided by steel fasteners. Usually, the surface preparation required by an FRP strengthening bond systems includes removal and patching of unsound con-
crete area, elimination of concrete surface irregularities and form lines, and abrasive sandblasting in order to clean the concrete surfaces (dust, dirt, laitance, oil and any curing substance could compromise the bond) and obtain the optimal surface roughness. All these operations are labor intensive and time consuming, while major concrete deterioration beneath slabs and girders could prevent the application of any bonded strengthening system (Fig. 3). In addition, where time is critical such as in a military environment, the curing time of the resin does not allow the immediate utilization of the structures. In addition, there is no need to clamp the FRP strip while the epoxy cures: it is enough to hold the strip in place while the fasteners are driven into the concrete. In this case, the MF-FRP method may be very effective being, at the same time, a rapid and economical type of strengthening requiring unskilled labor with simple and common hand-tools.

It is important to underline that the flexural strengthening with MF-FRP systems results in a pseudo-ductile failure of the strengthened members. It was demonstrated that, when long fasteners were used and they were driven into pre-drilled holes, the fastened method provided increased ductility over the bonded method (Lamanna, 2002, Arora2003, Borowicz et al., 2004, and Ekenel et al., 2005). In other words, it is possible to achieve a gradual concrete compression failure mode that is not sudden and catastrophic due to the progressive bearing failure, or slotting, of the laminate. With the proper technical details (Bank et al., 2004), the FRP strengthening system can remain firmly fastened to the concrete until very large deflections are reached.

The pre-cured MF-FRP laminate was designed, produced and commercialized as the result of an investigation performed by Lamanna (2002) having as objective the development of a high bearing strength FRP plate. It consists of a glass and carbon hybrid pultruded strip embedded in a vinyl ester resin. Its thickness and width are 3.175 mm and 101.6 mm, respectively. Continuous glass fiber strand mats are used to provide transverse and bearing strength, while 16-113 yield E-glass roving and 40-48K standard modulus carbon tows are utilized to provide longitudinal strength and stiffness. The results of the material characterization tests (Borowicz, 2002, Lamanna, 2002, Arora, 2003, and Rizzo 2005) can be summarized as follows:

• the laminate behavior is linear elastic up to failure for tensile load in the longitudinal direction. For design purposes, the stress at failure and the elastic modulus found for full size specimens can be conservatively assumed to be 836 MPa and 62 GPa, respectively. The resultant strain at failure was found to be 13809 µε;

• the laminate behavior is not linear for tensile load in the transverse direction: the stress-strain curve can be assumed to be a parabola with modulus at origin equal to 7151 MPa. In addition, no size effects on the mechanical behavior of the laminate for tensile load in the transverse direction have been observed. For design purpose, the average stress and the strain at failure can be conservatively assumed to be 65.6 MPa and 13498 µε, respectively;

• the full size laminate containing a hole in the middle of the width behaves as the same laminate without hole. In other words, for design purposes, due to localized failure (such as micro-delamination, matrix cracking, fiber buckling) of the composite in bearing, the stress on the net area, the elastic modulus and the strain at failure can be assumed to be equal to the corresponding values found for full size specimens without hole. In addition, it is reasonable to state that the same conclusions are valid for laminates with a hole in a generic position along the width;

• the maximum bearing stress in the longitudinal direction for unconstrained material around the hole is equal to 235.2±17.2 MPa and it does not depend on the size of the pin. This value of bearing stress can be only reached by choosing an adequate value of the end distance: according with the experimental results, the minimum end distance that satisfied the previous requirement is about 25 mm. The bearing failure has been shown to occur through buckling and brushlike failure with consequent delamination of the outer layers in the material far away from the contact area, and elongation of the hole;

• the maximum bearing stress in the transverse direction for unconstrained material around the hole is equal to 160.1±23.2 MPa and it can be considered independent from the size of the hole. This value of bearing stress can be reached only choosing an adequate value of the end distance (15 mm for the tested laminate). The bearing failure differs from the one related with load applied in the longitudinal direction since the carbon fibers are just pushed in a more stable configuration creating a natural ring in the contact area against the pin, a fact that increased the post-bearing capacity until the final secondary net tension failure.

The fastening of the MF-FRP laminate can be made with different types of fasteners and fixing procedures mainly depending on the compressive strength and soundness of the concrete, and the hardness of the aggregates in the substrate. In the following, the parameters affecting the performance of the connection concrete-fastener-FRP laminate will be discussed and analyzed reporting, at the end, the MF-FRP systems used and validated in some recent field applications.

Parametrical Analysis of the Connection

As a result of the material characterization tests, the bearing stress at failure of the MF-FRP laminate can be assumed to be constant independently from the size of the pin and the distance between the hole center and the free edge in the direction normal to the applied load, if
the end distance in the longitudinal direction is properly chosen. Given the bearing strength, the other parameters that characterize the connection are the following:
- diameter and strength of the fasteners;
- length of the fasteners;
- clamping force, and presence and type of washer;
- presence and type of filler in the gaps between the FRP material, the fastener and fastener accessories, and the concrete.

Obviously, the fastening procedure is another variable that can indirectly affect the performance of the connection. Its effect will be detailed in the next section together with the experimental results of the shear bond tests.

### Diameter and Strength of the Fasteners

The diameter $d$ of the fastener can be chosen by looking at the different failure modes of the connection: bearing of the FRP material, spalling of the concrete, and yielding/rupture of the fastener. In order to estimate the load at failure in the latter two cases, it is possible to refer to the state-of-art report ACI 355.1R-91 on anchorage to concrete or, alternatively, to another reference guideline and/or to the technical data sheets provided by the manufacturer of the fasteners. In this paper, the ACI 355.1R-91 recommendations were used in order to maintain a general approach to the problem. In addition, it is important to note that the most of the manufacturer data sheets report values related to service load conditions that include safety factors close, in some cases, to 8 to 10, thus underestimating the actual capacity of the connectors.

When the bearing failure of the unconstrained FRP material occurs, the load $P_{FRP}$ at failure can be calculated according with the material characterization results as shown in Fig. 5, where $\sigma_{bearing}$ and $I_{FRP}$ are the average value of the maximum bearing stress and thickness of the FRP laminate, respectively.

When the concrete spalls, according to ACI 355.1R-91, the load $P_{concrete,b}$ at failure is given by Fig. 6, where $f_{c}$ is the compressive strength of the concrete and $A_b$ is the nominal cross-sectional area of the anchor shank. For cracked concrete the reduction factor $\phi_c$ can be set equal to 0.6.

When the end distance is short (and this situation can occur anchoring the laminate over a length with numerous cracks), the concrete can fail for blow out cones and the load at failure can be assumed to be $P_{concrete,b}$ in Fig. 7, where $a$, $l_d$, and $t$ are the edge distance and the embedment length of the anchor, and the thickness of the concrete member.

When the fastener fails, according to ACI 355.1R-91 and for deep embedment length, the load $P_{fastener}$ at failure can be estimated using Fig. 8, where where $k_e$ is a coefficient that relates the shear strength of the anchor to its ultimate tensile strength (conservatively, the yield stress $f_y$ can be used).

The bearing load $P_{bearing}$ at failure of the connection will be the minimum between $P_{FRP}$, $P_{concrete}$ and $P_{fastener}$.

For example, assuming that the concrete will spall (that is assuming $a > 330$ mm), Fig. 9 plots the relations between the ultimate loads of the connection components and the diameter $d$ of the fastener for different values of the concrete compressive strength $f_{c}$ and $f_{y} = 400$ MPa. The following observations can be made according to Fig. 9:
- for diameter bigger than 10.5 mm, the desirable bearing failure in the FRP material is guaranteed for any compressive strength of the concrete;
- the failure in the fastener can occur for concrete compressive strength higher than 34.5 MPa and diameter smaller than 4.0 mm;
- the connection will fail predominantly for concrete spalling when the concrete compressive strength is smaller than 34.5 MPa and the diameter of the fastener is smaller than 4.0 mm.

The situation analyzed before depicted the connection at the ultimate conditions. The fundamental assumptions made before were mostly based on the complete plasticization of the fastener section. At service, local plasticization of the fastener can be reached and this can result in a local disengagement of the FRP strengthening. Known the shear $T_s$, the moment $M$, and the axial load $N_t$ transferred by the connection, the equivalent stress $\sigma$ for the generic point of the cross section of the fastener can be written according to von Mises criterion (Fig. 10). The moment $M$ can be expressed as a function of the shear transferred by the connection known the depth $t_{GAP}$ of the concrete spalled during the drilling or the fastening (Fig. 11). In addition, when the fastener is close to fail, all the pre-stress given by the clamping force can be assumed to be lost ($N_t = 0$ kN). Depending on $I_{FRP}$, $I_{GAP}$ and $d$, the maximum value of the equivalent stress will be reached for in the point B or A of Fig. 11. Fig. 12 shows the relation between the diameter of the fastener and the service reduction factor $k_s$, defined as the ratio between the load for which the steel starts to yield and the load at failure in tension of the fastener (that is, when all the section is yielded). As one can see from Fig. 12, fixed the ratio $i_{GAP}/i_{FRP}$ the relation between the diameter $d$ and $k_s$ is linear up to a certain value of the diameter; after this point, $k_s$ is equal to 0.433 independently from the fastener size. To be noted that the higher is the moment applied to the connection the lower is the service reduction factor $k_s$ for a fixed value of the diameter.

Such approach shows the necessity to choose a diameter large enough to avoid failure and/or local plasticization of the fastener, and to use a fastening system that limits to the minimum the damages to the concrete around holes and, therefore, $t_{GAP}$ and $M_s$.

Obvious considerations can be made varying the strength of the fastener and the bearing capacity of the FRP laminate.

From a technical point of view, upper limits on the diameter of the fasteners are fixed to avoid intersection...
of failure cones if close spacing is used. From a practical point of view, larger diameters increase the labor required to make them; this results in a more time consuming operation and, above all, in a wider damaged area of concrete around the drilling point which could affect negatively the overall efficiency of the strengthening.

**Length of the Fasteners**

The fastener lengths mostly depend from practical issues. In fact, whether from a technical point of view longer fastener lengths provide better anchoring allowing transferring load to a sounder inner concrete, the use of longer lengths increases the amount of work and the risk to bit or damage the steel reinforcement. Therefore, fasteners shorter than the usual cover of the steel reinforcement (about 38 mm) are generally preferred. Longer fasteners can be used only when it is possible to localize accurately the layout of the steel bars.

**Clamping Force, and Presence and Type of Washer**

For mechanically fastened composite laminates, joints with torque tightened fasteners usually have significantly higher failure loads than corresponding joints without fastener torque. In fact, the tightening of the fastener makes that part of the load is transferred by friction, and introduces a lateral constraint in the washer area which prevents delamination and buckling of the longitudinal fibers. Therefore, it can be expected a higher performance of the connection by introducing a proper combination of clamping force and washer diameter.

The lower and upper ultimate capacities of the connection can be derived considering unrestrained and perfectly constrained (corresponding to an infinite clamping pressure and stiffness of the washer) conditions, respectively. The ultimate capacity of the connection can be calculated multiplying the bearing stress $\sigma_{\text{bearing}}$ at failure of the FRP material for the thickness of the laminate $t_{\text{FRP}}$ and fastener diameter: for perfectly constrained conditions, the outer diameter of the washer $d_{\text{washer}}$ can be used. For example, using fasteners having a diameter $d = 9.525 \text{ mm}$, the load at failure of the connection results 7.1, 15.4 and 19.0 kN for unconstrained connection, and for perfectly constrained connections and washers with diameter 20.6 and 25.4 mm, respectively.

In reality, it is very difficult to create a perfectly constrained connection. In fact, if steel washer of proper thickness can be considered relatively much stiffer than the laminate, the clamping force is limited and determined by the applied torque which is chosen in the range of values suggested by the manufacturer of the fasteners. On the other hand, the lateral constraint, provided by washer and clamping, and the consequent friction at the concrete-FRP interface will raise undoubted the ultimate capacity of the connection. In addition, it is important to note that the presence of any washer will prevent localized crushing in the FRP material during the fastening. Stiffer washers also allow a better spreading of the clamping load around the hole enlarging the constrained area. Since the effect of the clamping is localized nearby the fastener, wide washers are efficient only if they have high stiffness.

**Presence and Type of Gap Filler**

The presence of gap filler between the FRP material, the fastener and the concrete is extremely important and can significantly affect the overall efficiency of MF-FRP strengthening system applied on concrete structures. Its beneficial effects can be summarized as follows:

- the filling of the hole with resin avoid rigid motions of the fastener, detrimental to the engagement of the FRP laminate;
- the filling of the hole with resin allows eliminating secondary bending effects that promote the spalling of the concrete in contact with the fastener (Fig. 13). The spalling of the concrete increases the arm of the applied shear transferred to the fastener reducing drastically its ultimate capacity according to Fig. 12;
- the filling of the hole with resin allows a reduction of the stress concentration in the concrete that in the new configuration, due to the gap filler, is not in direct contact with the fastener. Since in most of the cases the resin used as filler is stiffer than the concrete substrate, the introduction of the filler can be modeled as a virtual anchor with diameter equal to the hole diameter, fact that increases the load at failure for spalling of the concrete (Fig. 9);
- the presence of resin between the FRP laminate and the concrete acts in two directions. It increases the bearing stress of the laminate since it functions as a natural washer that forms itself during the insertion of the fastener in the cratered concrete around the hole. As secondary effect, it allows a modest transfer of the load by means of the bonding area. The latter strength contribution can be neglected at ultimate loads since debonding will occur prior to the bearing failure;
- the use of resin allows the filling of the gap between the FRP material and the fastener corresponding to the hole. This benefits the connection in two ways. First of all, it eliminates rigid motions of the FRP laminate with respect to the fastener improving the engagement of the strengthening to the structure. Then, it increases virtually the size of the fastener and, therefore, the bearing capacity of the FRP material (Fig. 13) reducing at the same time the stress concentration on the contact area. The latter effect is more considerable when studs are used since their head might cut or damage the laminate irremediably;
- the use of a relatively deformable gap filler, as epoxy resin, is favorable to the stress distribution of the load between the fasteners in multi-bolted connections, thus preventing a progressive failure of the anchors.
Fastening Procedures

The different fastening procedures will be described in the following. To be noted that the FRP material needs to be cut to the desired length using a circular saw with a masonry blade. Then, the pattern of the fasteners will be marked on some strips: securing more laminates in a column with tape or clamps, it will be possible to pre-drill more strips together. The pre-drilling can be performed with a masonry drill bit at fasteners locations. Particular attention must be posed to minimize the damages in the FRP avoiding vibrations of the drill.

Powder-Actuated System

It consists of pins embedded into the base material by means of a gunpowder charge (PA system). Best results are obtained using partially pre-drilled holes in the concrete reducing the detrimental cracking phenomena. When the PA fastener is driven in to the concrete the concrete in the vicinity of the fastener head sinters due to the high temperature caused by friction and this “bonds” the end of the PA fastener to the concrete. If the fastener is pulled out, concrete remains attached to the end of the fastener (Fig. 14).

Wedge Bolts System

The concrete wedge bolts are one piece, heavy duty anchors that are driven into predrilled holes. This procedure required longer time than the PA system since the depth of the holes must be higher than the length of the fasteners, according to the specifications of the fasteners manufacturer. The driving of the wedge bolt can be performed with common rotary drill or impact wrench. The latter can provide a higher fastening torque.

Wedge Anchor System

Concrete wedge anchors are inserted into a hole drilled into concrete. The anchors are then driven through the laminate into the anchor hole until the nut and washer are firmly seated against the laminate. Use of a pneumatic gun with a particular fixture built on purpose can speed up the entire operation. Finally, the anchors are tightened by turning the nut with an electrical drill with torque control, according to the specifications of the fasteners manufacturer.

To be noted that it is possible to use this type of anchors with any type of concrete. In addition, the embedment length can vary between a maximum and a minimum depending on the concrete cover. Disadvantages of the utilization of wedge anchor are related to the installation time consisting of hammering of the fastener, and clamping of the nut.

The last two systems (anchor systems) can be modified using resin as gaps filler. The filling of the holes can be performed using a compressor and an epoxy gun, calibrating the pressure depending on the fluidity of the resin. More than half a hole must be filled in order to be sure that all the gaps between the concrete, the fastener and the FRP laminate will be eliminated. Before the filling with resin, the holes must be blown to clean them from dust and other material. All these operations make the anchor systems slower than the PA system.

Laboratory Test Results

Single-bolted shear tests were conducted to investigate the failure modes and the behavior of the connection between fastened FRP laminate and concrete member.

Characterization tests of connections made with 3.5-4.5 mm diameter and about 50 mm long pins embedded into the base material by means of a gunpowder charge can be found in Lamanna (2002) and Arora (2003). Testing was carried out on a variety of different types of fasteners, and on fasteners with and without pre-drilled holes. The connection test set-up was similar to that required in ASTM E 1190 (Fig. 15). Particular attention was paid to choose the type of material of the fastener depending on the strengths of concrete: zinc plated hardened steel fasteners with a ballistic tip for ease of penetration into higher strength concrete have been successfully driven into concrete with a compressive strength of up to 55 MPa. A neoprene-backed washer was found to be effective in limiting the damage caused to the FRP strip due to penetration of the fastener, and in preventing net-tension delamination failures. The washer also increased the bearing capacity of the FRP strip at the location of the hole by providing a clamping pressure and cleavage failures were avoided. Shallow 12 mm pre-drilled holes in the concrete also reduced any low level concrete failures, reducing the amount of initial cracking and spalling caused when driving a fastener into concrete, but decreasing the clamped bearing strength of the FRP strip and the scattering of the results. Thus it was possible to obtain a ductile failure mode at a load level of 4.4 kN. Experimentally it was also found that is appropriate to have a minimum value of the edge distance and fasteners spacing in the range between 50 and 75 mm, choosing the higher values for the higher strengths of concrete. More details can be found in Lamanna (2002) and Arora (2003).

Characterization tests of connections made with wedge bolts and anchors (Fig. 16) can be found in Rizzo (2005). The effects of the washer size and gap filler were analyzed and the results confirmed the expected qualitative behavior.

For 4.76 mm diameter wedge bolts, the mode of failure was bearing in the FRP material with bending and pull-out, or shear failure of the fasteners after very large deformation of the hole (Fig. 17). The average bearing load was 8.0 kN. Since no washer was used, it was possible to see the effect of the small ribs present under the integral washer of the fasteners in guaranteeing a mechanical grip of the strip. Since the high deformation of the fastener raises the risk of brittle failure of the connection due to the shear failure of the fastener, this type of connection was discarded.
For 9.525 mm diameter wedge bolts, the mode of failure was bearing in the FRP material for all the specimens having fasteners firmly attached to the concrete substrate. The pseudo-ductility of the connection strongly depended on how the connection was made. The following observations were made based on the tests performed:

- the length of the plateau corresponding to the maximum bearing load was limited when no washer was used. On the average, the load at failure was 159% higher than that one in unconstrained bearing conditions, while the use of epoxy as gap filler increased the ultimate bearing capacity of 67% with respect to the average ultimate load obtained specimens without gaps filler. The clamping affect the results since the bearing load depended on the mechanically gripping of the steel ribs under the head of the bolts: the coefficient of variation was 21.8%;
- larger washer can be not efficient if their stiffness is not properly increased. Fig. 18 shows a bearing failure with large deflection of the washer;
- a pseudo-ductile failure can be reached combining clamping, wider washer and epoxy as gaps filler (Fig. 19). The load at failure was, on the average, 181% higher (20.0 kN) than that one in unconstrained bearing conditions. For design purposes, the solution with an extra washer appears to be more efficient in terms of performance and reliability. It looks less sensitive to the clamping applied giving less scattering in the result (the coefficient of variation was 6.3%). In fact, the only integral washer provides different contribution to the capacity depending on the mechanical grip area: then, for example, if the hole is not straight or the bolt fit not properly in it, the grip will be localized only on a restricted arc of the hole with obvious detrimental effect.

For 9.525 mm diameter wedge anchors, the mode of failure was bearing in the FRP material for all the specimens with high rotation of the fasteners (Fig. 20). It was possible to observe pseudo-ductility of the connection after the maximum load was reached at a load 97% higher than the maximum load in unrestrained conditions. The use of epoxy as gap filler increased the ultimate bearing capacity of 15% and reduced the scattering in the results (the coefficient of variation reduced from 9.6% to 2.5%); slight increment of the stiffness but visible enlargement of the pseudo-ductile plateau were observed. In fact, the presence of the resin avoided the direct contact between the thread of the anchor shank and the FRP material diminishing the stress concentration and the damages induced by the sharpness of the thread. In addition, the filling of the hole with epoxy reduces the rotation of the fastener improving the washer efficiency and, therefore, the overall performance of the connection. For design purposes, the ultimate bearing capacity of this type of connection can be conservatively assumed as 14.0 kN.

Multi-bolted shear tests were performed in order to analyze the behavior of multi-connections between fastened FRP laminates and concrete members. The interest was focused on the load sharing between the fasteners and the type of failure. Thus, the goals were to demonstrate that it is possible to obtain a progressive bearing failure of multi-bolted FRP laminates and, consequently, that the maximum load at failure \( P_{bearing,m} \) is given multiplying the load at failure \( P_{bearing,c} \) of the single fastener for the number \( n_{fasteners} \) of fasteners. A preliminary study was conducted in order to properly choose the pattern of the fasteners (relative position and spacing of the fasteners). Thus, some FEM models for single row and staggered patterns were developed in order to support such conclusions. The fastening along a single row of bolts appears to do not be convenient since “shear lag” effects do not allow exploiting completely the capacity of the full laminate (experimental tests reported in Lamanna, 2002 confirm the numerical observations). In addition, since most of the load is concentrated in the middle of the strip, the connection can probably fail along the line joining the fasteners at loads smaller than the theoretical ones. The choice of the distance between the fasteners was less problematic since highly depending on technical issues. The minimum distance \( s_{min} \) has an inferior limit suggested by many fastener manufacturers as 5 to 10 \( dfastener \). For \( dfastener = 9.525 \) mm, it results \( s_{min} = 45 \) to 95 mm.

Therefore, the spacing of the fasteners was chosen small enough in order to contain the specimens length simulating, at the same time, critical situations that can be experienced in the shear span anchoring. The tests confirmed the expected results: the load can be redistributed between all the fasteners with an overall pseudo-ductile behavior of the connection. Fig. 21 depicts the bearing failure of a multi-bolted connection made with 9.525 mm diameter wedge bolts. For example, Fig. 22 plots load distribution factor \( \kappa \) for the four fasteners on one side of the specimens for different level of load. It is interesting to note how the load is differently distributed between the fasteners during the test. At the first stages, the closest fastener to the loaded side of the concrete block supported most of the applied load, while the contribution of the two farther fasteners was less than 10%. Increasing the load, the other fasteners started to contribute more strongly until a quite even distribution among all the fasteners was reached close to failure. At the end, fastener #4 was the one that contributed more underlining that the failure started in the fasteners close to the loaded side and propagated toward the farther side. Finally, it was possible to state that the best performance was obtained using wedge anchors: the smaller stiffness of the single connection allowed a better redistribution of the load with respect to the wedge bolts.

More details about single and multi-bolted shear tests can be found in Rizzo (2005).
Field Applications

Several field applications were made using MF-FRP systems as strengthening of flexural deficient bridges.

The use of a powder-actuated fastening system was found very efficient for low compressive strength concrete in lab (Borowicz, 2002, and Lamanna, 2002) and field (Arora, 2003) applications (Fig. 23). Nevertheless, during the installation of the FRP strengthening on the field it was found that occasionally, fasteners did not fully penetrate the concrete substrate due to the presence of obstructions (such as large aggregates), and pocket of poor consolidation and/or deteriorated concrete (factors that can be easily controlled in a lab environment) caused loosening of nails. On the other hand, in cases of compressive concrete strength higher than 17.2 MPa, the fastening method resulted in concrete spalling and cratering which were considered not acceptable for the full engagement of the laminate.

Notwithstanding the speed of powder-actuated system, MF-FRP systems with concrete wedge anchors and bolts were used to strengthen four Missouri off-system bridges characterized by high compressive concrete strength and/or with large hard aggregates. The installation of wedge bolts resulted much easier and faster than the installation of wedge anchors since it only consists in driving them into predrilled holes. Unfortunately, where the aggregates present in the concrete consisted mostly by Meramec stones or chert, one of the most common rocks in Missouri, due to the hardness of the rock, the thread of driven bolts in it was heavily damaged: in those cases, the wedge anchor MF-FRP system were preferred (Fig. 24).

Design Recommendations and Conclusions

From basic geometrical considerations validated by means of the experimental work done using the particular pultruded FRP laminate, it can be stated that the ultimate bearing capacity \( P_{bearing,c} \) of the connection, in constrained condition can be calculated starting from the bearing stress \( \sigma_{bearing} \) at failure of the FRP material, found from unconstrained bearing tests, by means of an equivalent diameter \( \beta d_{fastener} \) as depicted in Fig. 25, where \( d_{fastener} \), \( d_{washer} \) and \( t_{FRP} \) are the diameter of the fastener, the outer diameter of the washer and the thickness of the FRP laminate, respectively. For common working conditions, \( \beta \) depends on the clamping, the stiffness of the washer and the presence of gap filler. To be noted that this is the maximum bearing load that can be reached only if the bearing in the FRP material controls the failure of the connection, and geometrical specifications are respected in order to avoid different modes of failure of the connection such as failure or pull-out of fastener, spalling of concrete, and net-tension, cleavage and shear-out in the FRP laminate. Fig. 26 reports the recommended MF-FRP connections validated based on laboratory and field applications. Where the environment is very aggressive, stainless fasteners will be used instead of the zinc plated ones. Fig. 27 lists the design loads of the connections suggested by the authors. The safety factor is different for the three types of connection configuration. It was chosen taking into account the coefficient of variation of the results, and the type of failure experienced during the tests (the pseudo-ductility is smaller for wedge bolts; a measure of the pseudo-ductility can be given by the length of the plateau corresponding to the maximum load).

The design of the MF-FRP strengthening can be computed according to the experimental results attained at the University of Wisconsin-Madison (Bank et al., 2002, and Lamanna, 2002) and at the University of Missouri-Rolla (Rizzo, 2005), and in compliance with ACI 440.2R-02, where applicable. Basically, the flexural capacity of the strengthened section can be estimated by means of the common assumptions used for externally bonded FRP systems for strengthening concrete structures. Unlike bonded FRP strengthening systems, particular attention must be paid in the anchoring of the laminate. The layout of the fasteners has to be checked at ultimate and service conditions. Depending on the position of the fasteners, it is possible to determine the factored moment capacity as function of the position \( z \) from the supports: \( \phi M_u = \phi M_u(z) \) (\( \phi \) is the strength reduction factor according to ACI 440.2R-02 Equation 9-5). Then, the element is well designed if for each section \( \phi M_u(z) \geq M_u(z) \). As an example, Fig. 28 reports the case of a simply supported beam with the positive factored moment \( M_u \). From a design point of view, in order to exploit all the capacity of the FRP laminate, the minimum number \( n_{fasteners, min} \) of fasteners to be installed can be computed with Fig. 29, assuming that the load carried by the laminate is evenly distributed among all the fasteners located in the anchorage-length/shear-span, assumption verified with the measurement made on beams tests (Lamanna, 2002, and Arora, 2003) and multi-bolted shear tests (Rizzo, 2005). The latter assumption is true only at ultimate conditions. Under service conditions, the load carried by each fastener is a function of the loading configuration as well as of the fasteners distribution. This implies that, if the pattern is not properly chosen, bearing of some of the fasteners can occur under service conditions jeopardizing the structural behavior of the strengthened element.

The checking of the structure under service loads is generally very complex. By means of convenient assumptions, an iterative procedure can be used to solve the problem. Common commercial math programs might help the designers in the calculation.

Considering in Fig. 30 the portion of the beam included by the section A-A and B-B and containing the fastener \( i \), it is possible to solve the problem in a discrete fashion using the procedure presented herein. For each portion of the beam between two successive fasteners, it
is possible to build the tri-linear curve $M-\phi$ with the values of the moments $M_i$, at cracking, $M_f$ at yielding and $M_a$ at failure and the relative curvatures $\phi_i$, $\phi_f$ and $\phi_a$. Consequently, it is possible to build a similar curve also for the neutral axis $c$, simplifying in such way its calculation. Therefore, it is possible to calculate the strains in the FRP material in the lengths $i-1-i$ and $i+i+1$, and consequently the stress at the location of the fastener $i$. Iterating the procedure for all the fastener, it is possible to obtain the stresses at the fasteners locations. Such stresses must be less than the capacity of the connection $P_{bearing}$. In the cases in which the stresses are higher than the capacity, more fasteners should be added checking again the new fasteners layout with the previously described procedure.

It can be noted that the stress in the FRP will increase with the gradient of the moment between two successive fasteners. This basically implies that the checking of the fasteners at service condition should be performed considering the single load conditions producing the maximum demand for each fastener instead of the envelope for moving loads (such as in the design of the strengthening for bridges). In fact, since the envelope curve is generally flat, its use would lead to a non conservative design procedure.

Fig. 31 summarized the recommended MF-FRP systems depending on the compressive strength of the concrete.

If time is very critical, the PA system appears more convenient being more rapid and allowing the complete exploitation of the FRP strengthening right after its application, since the load transfer mechanism relies just on the mechanical anchoring of the pins. A minimum embedment of 25 $mm$ beyond the pre-drilled hole is recommended. Based on the results of the studies conducted, 45 to 50 $mm$ long fasteners are recommended for use with 3.2 $mm$ thick FRP strips. The expansion anchors are typically used just at the ends of each strip to prevent end-delamination.

On the other hand, from the previous theoretical and experimental analysis, it appears that the use of anchor systems is preferable to powder-actuated systems when the substrate consists of high strength concrete and the shear span available to anchor the MF-FRP laminate is too short. The drilling operation can prevent major concrete damages of the concrete around the holes, while the use of gap fillers improves the performance of the connection in terms of strength and stiffness. The epoxy should be injected in half an hole, or even more if necessary, in order to be spread over a small area of concrete around the hole, the FRP material and the fasteners accessories, thus to fill all the existing gaps of any type (tolerance in the holes, spalling of concrete, and so on). From a theoretical point of view, fasteners having 9.525 $mm$ diameter seem to be suitable for a wide range of strength of concrete allowing the reaching of the pseudo ductile bearing failure in the MF-FRP laminate side. In addition, using wedge anchor it is also possible to adjust the embedment length of the fastener depending on the layout of the steel reinforcement of the particular structure. It is important to note that the load at failure of the fastener anchored in the concrete depends on the embedment length. The minimum embedment length must be chosen in order to have a load at failure of the fastener enough high to allow the reaching of the bearing failure in the FRP laminate.

To be noted that, since the connection fails at higher loads than those found in unrestrained conditions, higher free edge distances should be used: based on the tests performed, the minimum value recommended is 65 $mm$.

Finally, it is important to underline that, for practical issues, the spacing of the fasteners in the moment span cannot be higher than a certain value in order to avoid loosing length of laminate mostly when it is fastened underneath the structure as in field applications. Therefore, an upper limit of 300 $mm$ is recommended.

References

ACI Committee 440.2R-02 (2002). “Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures.” American Concrete Institute, MI, USA.


Figure – 1 Pultruded FRP Laminate Used in the Mechanically Fastened FRP Systems

Figure – 2 Fasteners Used to Anchor the MF-FRP Laminates

Figure – 3 Cases of Major Concrete Deterioration

Figure – 4 Bearing Failure for Load Applied in the Longitudinal and Transverse Direction

\[ P_{FRP} = \sigma_{bearing}d_{FRP} \]

Figure – 5 Load corresponding to Bearing Failure in the MF-FRP Laminate

\[
\begin{align*}
P_{concrete_{-s}} &= \phi_c A_h \sqrt{E_c f_c'} \text{ lbf} = \phi_c \frac{\pi}{4} \sqrt{E_c f_c' d^2} \text{ lbf} \\
E_c &\approx 57000 \sqrt{f_c'} \text{ psi} \quad \text{with} \quad [f_c'] = [\text{psi}]
\end{align*}
\]

Figure – 6 Load corresponding to Spalling Failure in the Concrete Substrate

\[
P_{concrete_{-b}} = \min \left( 2\phi \frac{f_c'}{\text{psi}} \left( \frac{a}{\text{in}} \right)^2 \text{ lbf}, 1.4 \sqrt{\frac{d}{\text{mm}}} \sqrt{f_c'} \left( \frac{a}{\text{mm}} \right)^{1.5} \chi_h N \right)
\]

for \( d \leq 25 \text{ mm}; \quad \frac{l_d}{d} \in [4, 6] \)

with \( \phi = 0.85 \) and \( \chi_h = \frac{t}{1.4a} \leq 1 \)

Figure – 7 Load corresponding to Blow Out Cones in the Concrete Substrate

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\[ P_{\text{fastener}} = k_s \left( \frac{\pi d^2 f_y}{4} \right) \text{ for } k_s = [0.6, 0.7] \]

**Figure – 8** Load corresponding to Steel Fastener Failure

**Concrete Compressive Strength**

- □ 13.8 MPa
- ○ 20.7 MPa
- △ 27.6 MPa
- ◊ 34.5 MPa
- – 41.4 MPa

\[ P_{\text{fastener}} = 0.6(\pi d^2/4)f_y \]
\[ f_y = 400 \text{ MPa} \]

\[ P_{\text{concrete}} = 0.5(\pi d^2/4)(E_c f_y')^{0.5} \]

\[ P_{\text{FRP}} = d_{\text{FRP}} \sigma_{\text{bearing}} \]
\[ \sigma_{\text{bearing}} = 235 \text{ MPa} \]

**Figure – 9** Load at Failure of the Connection Components Depending on Fastener Size

\[ \sigma_{\text{eq}} = \sqrt{\sigma_{\text{axial}, z}^2 + 3\tau^2} = \]
\[ = \left[ \frac{N_z}{A_y} + \frac{64M_z}{\pi d^4} y \right]^2 + 3 \left( \frac{32 T_y}{3 \pi d^3} \frac{d}{2} - y^2 \right) \]

\[ M_x = T_y \left( 0.5t_{\text{FRP}} + t_{\text{GAP}} \right) \]

**Figure – 10** Equivalent Stress in the Fastener

**Figure – 11** Scheme for the Calculus of Stresses in the Fastener

**Figure – 12** Service Reduction Factor for Steel Fasteners

**Figure – 13** Fastener Working Conditions
Figure – 14 Fastener at Sintering Zone

Figure – 15 PA System Shear Test

Figure – 16 Anchor System Shear Test

Figure – 17 Failure Mode for Small Size Wedge Bolt

Figure – 18 Failure Mode for Wedge Bolt and Large Thin Washer

Figure – 19 Failure Mode for Wedge Bolt with Extra Washer and Gap Filler

Figure – 20 Failure Mode for Anchor Bolt
Figure – 21 Failure Mode for a Multi-Connection Made with the Wedge Bolts System

Figure – 22 Share Load for a Multi-Connection Made with the Wedge Bolts System

Figure – 23 Application of MF-FRP Strengthening PA System Beneath Bridge Deck

Figure – 24 Application of MF-FRP Strengthening Anchor System Beneath Bridge Deck and Girders

\[
P_{\text{bearing}} = \sigma_{\text{bearing}} \cdot \beta \cdot d_{\text{fastener}}
\]

\[
\beta = \begin{cases} 
1 & \text{for uncostrined connections} \\
\frac{d_{\text{washer}}}{d_{\text{fastener}}} & \text{for perfectly costrained connections}
\end{cases}
\]

Figure – 25 Load corresponding to Bearing Failure in the FRP Laminates of a Connection

<table>
<thead>
<tr>
<th>System</th>
<th>Fastener</th>
<th>Washer</th>
<th>Gaps Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(^1)</td>
<td>Hardened Galvanized Steel Fasteners Diameter: 4.0 Length: 45 to 50</td>
<td>Neoprene Backed Steel Washers Outer Diameter: 12.0 Thickness: 2.0</td>
<td>None</td>
</tr>
<tr>
<td>B(^2)</td>
<td>Wedge Bolt Diameter: 9.525 Length: as Needed</td>
<td>Steel Washer Outer Diameter: 25.4 Thickness: (\geq 2.38)</td>
<td>Epoxy</td>
</tr>
<tr>
<td>C(^2)</td>
<td>Wedge Anchor Diameter: 9.525 Length: as Needed</td>
<td>Steel Washer Outer Diameter: 20.6 Thickness: (\geq 1.59)</td>
<td>Epoxy</td>
</tr>
</tbody>
</table>

\(^1\) PA Fastening System
\(^2\) Anchor Fastening System

Figure – 26 Recommended Validated MF-FRP Systems

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<table>
<thead>
<tr>
<th>System</th>
<th>Bearing Load at Failure, ( P_{MF-\text{FRP}} ) [kN]</th>
<th>Safety Factor, ( \gamma_{MF-\text{FRP}} )</th>
<th>Design Bearing Load, ( P_{MF-\text{FRP},d} = \frac{P_{MF-\text{FRP}}}{\gamma_{MF-\text{FRP}}} ) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.8</td>
<td>1.30</td>
<td>4.4</td>
</tr>
<tr>
<td>B</td>
<td>20.0</td>
<td>1.80</td>
<td>11.1</td>
</tr>
<tr>
<td>C</td>
<td>14.0</td>
<td>1.25</td>
<td>11.1</td>
</tr>
</tbody>
</table>

**Figure – 27** Design Loads of the Single Connection Made with the Recommended MF-FRP Systems.

**Figure – 28** Moment Distribution in a Simple Supported Beam

\[
n_{\text{fasteners, min}} = \frac{F_{\text{FRP}}}{P_{\text{bearing,c}}}
\]

**Figure – 29** Minimum Number of Fasteners to Anchor the MF-FRP Laminate in the Shear Span

\[
\varepsilon_{\text{FRP,A}} = \phi_A \left( d_{\text{FRP}} - c_A \right)
\]
\[
\varepsilon_{\text{FRP,B}} = \phi_B \left( d_{\text{FRP}} - c_B \right)
\]
**Figure – 30** Proposed Method to Check the Layout of the Fasteners in Service Load Conditions

<table>
<thead>
<tr>
<th>Concrete Compressive Strength [MPa]</th>
<th>MF-FRP Systems(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absence of Hard Aggregate</td>
<td>Presence Hard of Aggregate</td>
</tr>
<tr>
<td>13+27</td>
<td>PA System Wedge Anchors Wedge Bolts</td>
</tr>
<tr>
<td>27+41</td>
<td>Wedge Anchors Wedge Bolts</td>
</tr>
</tbody>
</table>

\(^1\) Trial tests of the fastening system to be used are recommended on critical and representative parts of the structures.

**Figure – 31** Recommended MF-FRP Systems Depending on the Compressive Strength of the Concrete

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