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Flexural Strengthening of Reinforced Concrete Beams Using Fasteners and Fiber-Reinforced Polymer Strips

by Anthony J. Lamanna, Lawrence C. Bank, and David W. Scott

Current methods of flexural strengthening of reinforced concrete beams with fiber-reinforced polymer (FRP) strips require time-consuming and often difficult preparation to provide adequate bond strength between the FRP strip and the concrete substrate. This paper presents a feasibility study of an alternative method of attaching FRP strips to reinforced concrete beams. The method utilizes off-the-shelf powder-actuated fasteners to attach pultruded FRP strips to the concrete. Small-sized beams strengthened with this method were tested, and the results were compared with the results from beams strengthened with conventional bonding methods and to the results from control beams. Small-size beams strengthened using powder-actuated fasteners attained 65 to 70% of the increase in capacity of the beams strengthened using the conventional bonded method; however, the fastening method is extremely rapid and the failure modes of the beams strengthened by the fastening method were more ductile than those strengthened by the bonded method.

Keywords: beam; polymer; repair; strength; tests.

INTRODUCTION

In recent years, there has been an increase in the use of lightweight, nonmetallic, fiber-reinforced-composite materials to repair and strengthen concrete structures (Emmons et al. 1998a). A common repair method is to adhesively bond strips of thin composite laminates, also known as fiber-reinforced polymer (FRP) strips, to the surfaces of reinforced concrete beams or slabs to increase their capacity. Typically, these strips are attached to the soffits to increase the flexural capacity of the reinforced concrete element. The method used to strengthen concrete beams with composite strips is similar to one that has been used with some popularity since the mid 1970s, particularly in Europe, to repair concrete beams with steel plates (Swamy et al. 1987). In one popular method, the composite strip is bonded to the concrete surface with a room-temperature curing two-part epoxy adhesive (Sika 1999). The procedure for this method is time-consuming because it can take days per application to sandblast, clean, and smooth the concrete suitably for bonding. The two-part epoxy system must be mixed in a precisely controlled fashion and applied in a careful manner to produce a good bond line. Following the application of the adhesive, the composite strip "must not be disturbed for a minimum of 24 h" (Sika 1999), and often the adhesive will not reach design strength until 7 days (Masterbuilders 1998).

Other systems make use of preformed fiber fabrics and apply the epoxy resin system to the fabric and to the concrete substrate simultaneously (Masterbuilders 1998). These systems require the same time-consuming and careful preparation and curing as in the case of bonding a prefabricated composite strip to the concrete (Emmons et al. 1998b).

It has been claimed by a number of researchers (Spadea et al. 1998; Jones et al. 1988) that there may be a need to provide mechanical anchorage to the composite strip at its ends to prevent catastrophic brittle failure of the strengthened beam by strip detachment. The strip end anchorages have a greater effect in beams that are shorter (with a high ratio of shear force-to-bending moment) than in longer beams. It has been recommended that strip end anchorages be used for all loading conditions (Garden and Holloway 1998). This anchorage is usually provided in the form of anchor bolts or cover plates. Similar mechanical anchorages have been recommended for use with epoxy-bonded steel plates (Hussain et al. 1995). These mechanical anchorages are used to prevent peeling failures, and are not intended to be the primary load transfer mechanism between the concrete and the composite strip.

The use of an entirely mechanically attached composite strip appears to be the next logical step in the development of research in this area. As previously noted, a number of researchers feel that it is necessary to use some form of mechanical end anchorage for a bonded strip. Others feel it may be necessary to provide continuous anchorage to prevent bond slip. This study investigates whether or not a composite strip can be attached and anchored using multiple, small distributed fasteners without any bonding. Similar techniques for attaching composite material parts using small rivets or self-tapping screws are used in the aerospace and the automotive industries (Matthews 1987). The use of multiple small fasteners, as opposed to large diameter bolts, distributes the load evenly over the composite strip and does not cause premature failure due to excessive stress concentrations at the holes in the composite strip.

RESEARCH SIGNIFICANCE

As an alternative to the existing method of bonding composite strips to concrete structures, which requires excessive time and skilled labor, a commercial off-the-shelf powder-actuated fastening system was used to attach composite strips to concrete. Such tools are readily available, and do not require sophisticated training to operate. The tools are inexpensive, and a variety of fasteners are commercially available. Such a technique could meet requirements for rapid strengthening in situations where time is critical, as there is no need to prepare the surface or clamp the strip while the epoxy cures. There is only a need to hold the strip in place while the fasteners are driven into the concrete. This research provides an initial investigation into the feasibility of such a method.

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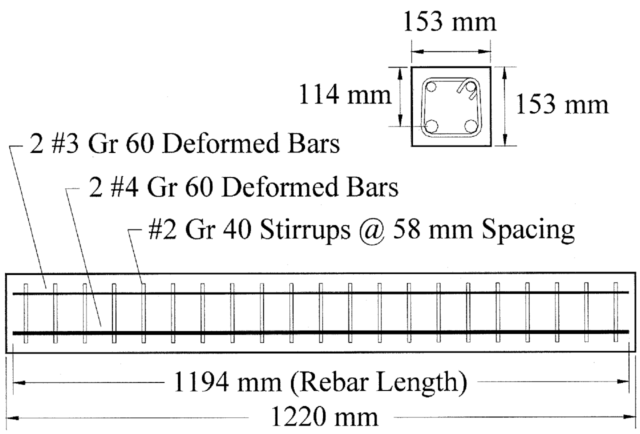

Fig. 1—Beam dimensions and reinforcement details.

RESEARCH OBJECTIVES

The objective of this study was to conduct a preliminary investigation into the feasibility of strengthening reinforced concrete beams in flexure using powder-actuated fasteners to rapidly attach composite material strips to the beams. Based on failure criteria for bonded systems, a goal of the study was to have the composite strip remain attached to the beam at least until the concrete failed in compression after the primary reinforcing steel had yielded, and to obtain a pseudoductile failure mode. A further objective was to compare experimental results with theoretical predictions.

EXPERIMENTAL PROGRAM

The primary goal of this investigation was to demonstrate the feasibility of strengthening small-sized reinforced concrete beams with composite strips using a powder-actuated fastening system. Small-sized reinforced concrete beams were chosen for this feasibility study to provide future comparisons to the testing of similar sized beams in existing literature (Hussain et al. 1995). Beams were not preloaded, primarily for reasons of safety, because the effect of driving fasteners into loaded concrete beams was not known in advance. When a composite strip is attached to a beam with mechanical fasteners, cracks develop. The beams were not precracked. It was assumed that a beam precracked by loading would behave in the same manner as a beam initially cracked during fastening of the composite strip.

Test specimens

The test specimens were divided into two target concrete design strengths: 21 and 42 MPa (3000 and 6000 psi) concrete. The beams were 1220 mm (48 in.) long and had a cross section of 153 x 153 mm (6 x 6 in.) and were cast in the laboratory with concrete supplied by a local vendor. A pea gravel mixture was used due to the small cover and tight stirrup spacing. The concrete mixture proportions are given in Table 1. The actual concrete strengths at 28 days were 20.94 ± 0.31 MPa (3037 ± 45 psi) and 42.48 ± 1.19 MPa (6161 ± 173 psi) based on fourteen 153 mm (6 in.) diameter x 305 mm (12 in.) high cylinder tests per concrete mixture.

Table 1—Concrete mixture proportions

Material	21 MPa mixture, kg/m^3	42 MPa mixture, kg/m^3
Pea gravel	974	974
Sand	888	910
Type I cement	279	363
Water	189	168

Table 2—Hilti fasteners used in research

No.	Type	Intended use	Shank diameter, mm
1	X-ALH	High-strength concrete and high-grade steel	4.0 (≤ 22 mm length), 4.5 (≥ 27 mm length)
2	X-DNI	Concrete and steel	3.7
3	X-ZF	Concrete and steel	3.5

The beam size and steel reinforcement was the same for both concrete strengths. The beams were designed in accordance with ACI 318. Primary tension steel was provided by two No. 4 Grade 60 deformed bars. Two No. 3 Grade 60 deformed top bars were used to provide stability to the reinforcing bar cage during casting. The relative reinforcement ratios (ρ/ρ_{bal}) were 0.68 for the 21 MPa beams and 0.39 for the 41 MPa beams. Shear reinforcement was provided in the form of closed stirrups of No. 2 Grade 40 smooth bars. These stirrups were placed at 58 mm (2.25 in.) on center throughout the beam. This stirrup spacing was the maximum spacing (d/2) permitted by ACI. This stirrup spacing ensured that a shear failure in the strengthened beams would be avoided. Figure 1 shows the beam dimensions and the arrangement of the reinforcing steel.

Beams were identified by a numbering code, for example, F-21-S-102-2R. The first letter denotes how the beam was strengthened: F for a fastened strip, B for a bonded strip, and C for a control beam with no strip. The second term represents the concrete strength, either 21 or 42 MPa. The third letter is the type of composite strip used for strengthening: S for standard, D for double standard, H for high modulus, and F for fabric. The fourth term is the width of the composite strip in millimeters. The fifth term is the number of rows of fasteners, followed by an R if the test is a repeat of a previous test. Hence, the previous example is the second 21 MPa concrete beam strengthened with a standard composite strip 102 mm (4 in.) in width fastened to the soffit with two rows of fasteners. One beam has a fifth symbol, L, meaning larger diameter AL fasteners were used to attach the composite strip. The three different varieties of fasteners used in this study are detailed in Table 2.

A powder-actuated fastening system was used to attach the composite material strengthening strips. The system uses a 6.8 mm (0.27 in.) caliber short gunpowder booster. Listing the length in millimeters following the designation differentiates fasteners of the same type. All fasteners were used with 18 mm (0.71 in.) diameter neoprene backed steel washers that eliminate crushing damage in the composite by providing a flexible material between the steel part of the washer and the

Table 3—Characteristics and properties of composite strips

Type	Name	Layup	Thickness, mm	Longitudinal modulus E,* GPa	Longitudinal strength,* MPa
1	Standard	$m^{0.5}/R_8/m_2^{2.0}/R_8/m^{0.5}$	3.2	13.8	231.7
2	Double standard	$m_3^{0.5}/R_8/m_3^{2.0}/R_8/m_3^{0.5}$	6.4	15.5	204.5
3	High modulus	$m^{1.5}/R_{56}/m^{1.5}$	3.2	27.3	560.7
4	Fabric	(0/90)/(+45/–45)/(0/90)/(+45/–45)/(90/0)	3.2	17.0	351.0

*Average of five tests.

Note: R_n = no. n of 113 yield rovings R; m_y^x = no. y of continuous strand mats of x oz/ft^2; and (θ_1/θ_2) = 24 oz/yd^2 fabric with θ_1 and θ_2 layers.

composite strip. The washers also provide a clamping pressure that increases the bearing strength of the composite strip.

The main operating principle of powder-actuated fasteners is that concrete is compressed by the fastener as material is displaced as it penetrates the material. When the fastener is installed in the concrete, the surface of the fastener becomes deformed and generates friction with the surrounding material. The heat generated in this process causes sintering and creates a bond between the concrete and the fastener (CEB 1994). These two factors give the fastener its holding power.

For this study, the capacity of single fasteners was determined in a similar manner to ASTM E 488. The load capacity per fastened connection was determined by testing a piece of FRP composite material strengthening strip fastened to a concrete substrate with a powder-actuated fastener. Testing was carried out on a variety of different types of fasteners, strips, and fastener layouts. The capacity of the connection was found to be a function of the depth of fastener embedment in the concrete, the bearing strength and edge distances of the strengthening strip, and the strength and aggregate properties of the concrete.

Beams were strengthened using a variety of pultruded glass vinylester FRP composite material strips. The majority of strips were cut from off-the-shelf composite plates, and the rest were manufactured specially for research purposes. The types of strips, listed in Table 3, used in this study were as follows:

- Type 1—A standard strip cut from a 3.2 mm (1/8 in.) thick standard pultruded plate consisting of sixteen 113 yield E-glass rovings, two layers of 2967 g/m^2 (2.0 oz/ft^2) continuous strand mat, and two layers of 742 g/m^2 (0.5 oz/ft^2) continuous strand mat. A 113 yield roving denotes there are 113 yd per lb, or 227.5 m per kg;
- Type 2—A double standard strip cut from a 6.35 mm (1/4 in.) thick plate with sixteen 113 yield E-glass rovings, three layers of 2967 g/m^2 (2.0 oz/ft^2) continuous strand mat, and six layers of 742 g/m^2 (0.5 oz/ft^2) continuous strand mat;
- Type 3—A high modulus specialty strip containing fifty-six 113 yield E-glass rovings and two 2225 g/m^2 (1.5 oz/ ft^2) continuous strand mats; and
- Type 4—A fabric specialty strip containing five layers of 3959 g/m^2 (24 oz/yd^2) multidirectional E-glass stitched fabrics.

Longitudinal tensile tests according to ASTM D 3039 were conducted on all strips to determine elastic modulus and tensile strength. Burnout tests were conducted in accordance with ASTM D 2584 to determine fiber architecture. Dimensions and mechanical properties of the strengthening strips used are also reported in Table 3.

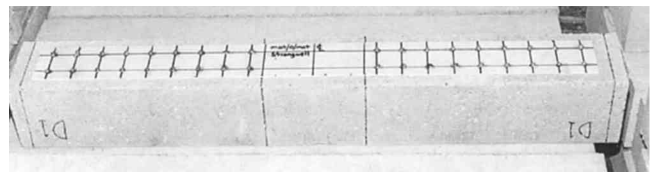

Fig. 2—Composite strip attached to concrete beam using two rows of fasteners and 50.8 mm (2 in.) spacing between fasteners.

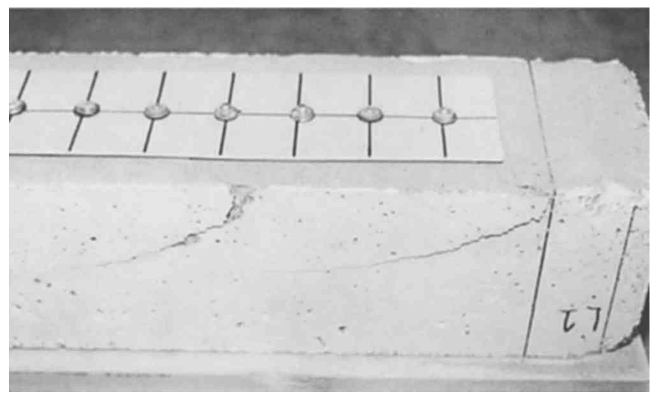

Fig. 3—Initial cracks in F-42-S-102-(L) due to fastening.

In all tests, the composite strips were terminated 25.4 mm (1 in.) from the beam supports. The composite strips were cut to the required length, and the fastener locations were marked. For the sake of convenience, the beam was placed upside down, and the fasteners were inserted from the centerline of the beam progressing outward to one end of the beam. Then the fasteners were inserted from the centerline to the other end of the beam. A 50.8 mm (2 in.) spacing was used between fasteners along the length of the beam, as well as between rows in beams with two rows of fasteners. This spacing distance was determined from separate tests on small concrete blocks. Attaching the composite strip with the powder-actuated fasteners took about 10 min per beam. Table 4 and 5 show the strip attachment information for the 21 and 42 MPa beams. Figure 2 shows a picture of a beam with a composite strip attached with fasteners. A closeup picture of the fasteners is shown in Fig. 3.

Composite strengthening strips were attached to Beams B-42-S-102, B-21-S-102, and B-21-S-51 using the M-Brace primer, putty, and saturant. These beams were tested for comparison purposes. Preparation of these beams took roughly 4 h. The epoxy adhesive was allowed to cure for the recommended 7 days before the beams were tested (Master-

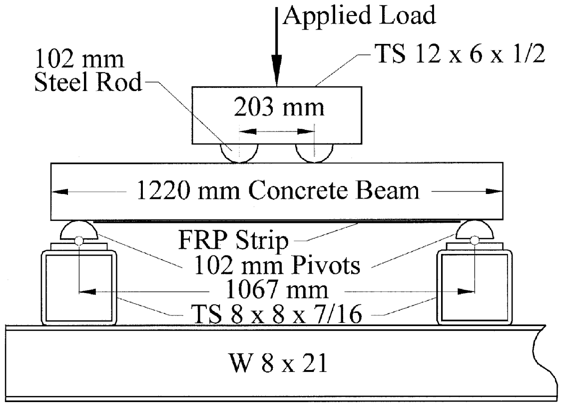

Fig. 4—Schematic of beam test setup.

Table 4—Strip attachment information for 21 MPa beams

Beam	Strip type	Fastener type	Fastener length, mm	No. of rows	Strip width, mm
C-21	Control				
F-21-S-102-1	1	2	32	1	102
F-21-F-102-1	4	2	32	1	102
F-21-D-102-1	2	2	37†	1	102
F-21-H-102-1	3	2	32	1	102
F-21-S-102-2	1	3	27	2	102
F-21-S-102-2R*	1	3	27	2	102
F-21-S-51-1	1	2	32	1	51
B-21-S-102	1	Bonded			102
B-21-S-51	1	Bonded			51

*Minor initial cracking upon attaching strip.
†Additional 5 mm length to account for extra thickness of strip.

builders 1998). The beams with bonded strips did not have any form of mechanical anchorage at the strip ends.

Testing procedures

A test fixture was designed to test the beams in four-point bending. A span of 1067 mm (42 in.) was used with a moment span of 203 mm (8 in.). The beams were tested using a 244.6 kN (55 kip) servohydraulic MTS actuator controlled with a MTS Teststar controller. A schematic of the test setup is shown in Fig. 4. All beams were tested in displacement control at a rate of 0.5 to 0.8 mm/min (0.02 to 0.03 in./min). Beams were tested to displacements well beyond the ultimate load to gain an understanding of the modes of failure and ductility.

ANALYSIS OF EXPERIMENTAL DATA

Displacement at the load point δ and load P were recorded in all tests and the moment in the center of the span was calculated to compare with theoretical predictions. The ductility ratio

$$DR = \frac{\delta_u}{\delta_y} \tag{1}$$

was calculated to evaluate the ductility of the beam.

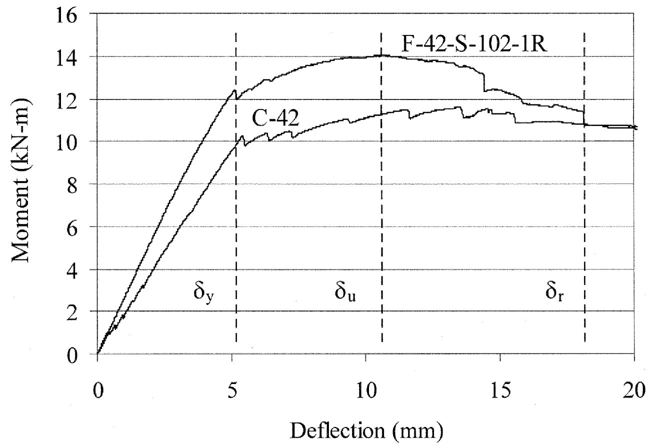

Fig. 5—Moment versus deflection curves for Beams C-42 and F-42-S-102-1R.

Table 5—Strip attachment information for 42 MPa beams

Beam	Strip type	Fastener type	Fastener length, mm	No. of rows	Strip width, mm
C-42	Control				
F-42-S-102-(L)*	1	1	32	1	102
F-42-S-102-1*	1	2	32	1	102
F-42-S-102-1R†	1	2	32	1	102
F-42-S-102-1RR*	1	2	32	1	102
B-42-S-102	1	Bonded			102

*Major initial cracking upon attaching strip.
†Minor initial cracking upon attaching strip.

Figure 5 shows moment versus deflection curves for a 42 MPa control beam, C-42, and a strengthened beam, F-42-S-102-1R. Yield is defined as the point at which the moment versus deflection curve ceases to be linear. Ultimate is defined as the highest point on the moment versus deflection curve. Return is defined when the curve of the strengthened beam touches or crosses over the curve of the control beam. This signifies that the strengthening is no longer effective, and the beam acts as the unstrengthened control beam once the composite strip has detached.

To determine the theoretical strength, the following assumptions were made: 1) a linear strain distribution was assumed over a cracked concrete section; 2) the tensile steel has yielded and the strain is much greater than 0.00207; 3) the Whitney stress block was used to model the stress in the concrete compressive zone at the ultimate strength, when the concrete crushed; 4) uniform strain and stress was assumed through the depth of the composite strip; 5) the effect of the top steel was ignored; 6) the composite strip was assumed to have no effect on the shear capacity of the beam, either by increasing the shear capacity through dowel action, or by decreasing the shear capacity through the formation of cracks from fastener embedment; and 7) even though they were attached at discreet points, strain compatibility between the entire composite strip and concrete was assumed. This last assumption implies that there was no slip allowed between the strip and concrete, either at yield or at ultimate moment, and there was no rotation of the fasteners in the concrete substrate. A further implication of this assumption was that there was no local damage to the composite strip at the fastener

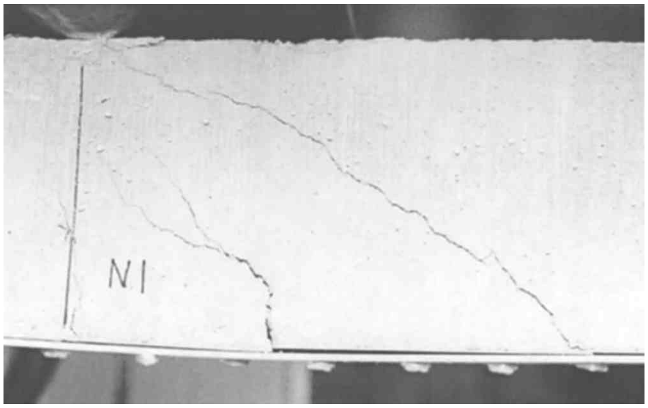

Fig. 6—Composite strip remained attached at concrete crushing in presence of shear cracks in F-21-F-102-1.

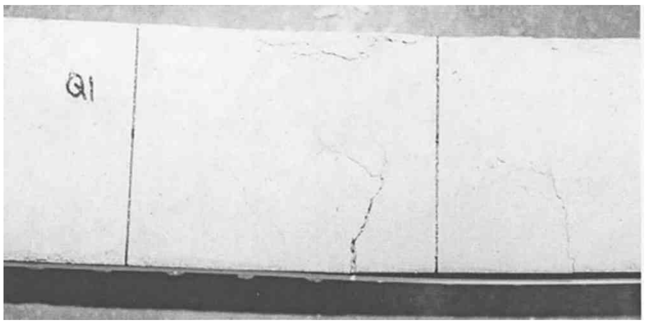

Fig. 7—Composite strip remained attached after testing well past concrete crushing (d » 76 mm) in presence of flexural cracks in F-21-H-102-1.

locations due to bearing stresses. It is recognized that these assumptions idealize the behavior of the strengthened beams.

TEST RESULTS

The beams with fastened strips failed by concrete crushing. After the concrete began to crush, the strip began to detach as the fasteners pulled out of the concrete. This resulted in a gradual decrease in moment after the ultimate moment was reached, providing a large amount of ductility before the strengthening lost its effectiveness. The beams with bonded strips failed in a sudden manner.

Results for 21 MPa beams

In all beams that utilized mechanical fasteners, failure occurred in the compression zone. At the point of concrete crushing, large flexural and shear cracks existed in the beams. The composite strips remained attached in the presence of these cracks. Figure 6 shows the composite strip still attached to Beam F-21-F-102-1 in the presence of shear cracks after concrete crushing. Figure 7 shows the composite strip beginning to detach from Beam F-21-H-102-1 in the presence of flexural cracks well after concrete crushing ($\delta \approx 76$ mm). This ability of the strip to remain attached in the presence of cracks was seen in all tests with fastened strips.

In Beams F-21-S-102-2 and F-21-S-102-2R, two rows of fasteners were used to attach the composite strip. To reduce initial cracking, smaller diameter ZF fasteners were used. Both beams failed in concrete crushing. Initial cracking during fastening occurred in Beam F-21-S-102-2R due to a small edge distance, similar to the initial cracking that occurred in Beam F-42-S-102-(L), as previously seen in Fig. 3.

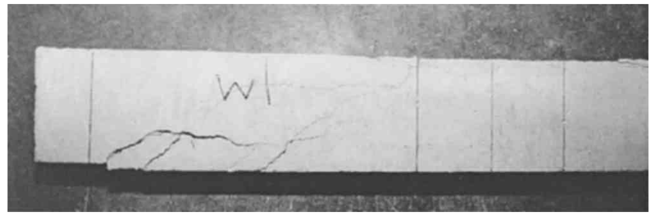

Fig. 8—Failure of B-21-S-102 by debonding of layer along reinforcing bar.

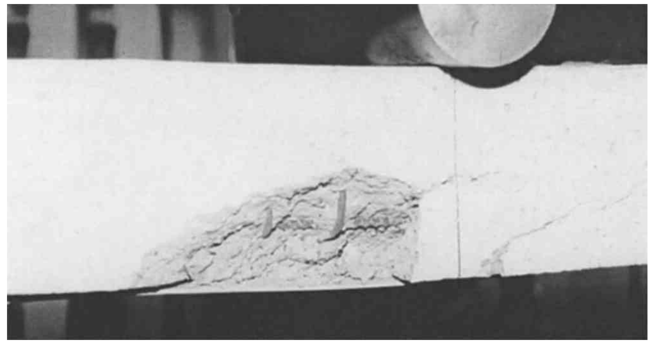

Fig. 9—Spalling in F-42-S-102-(L) during testing caused by initial cracks.

Beams that were strengthened by bonding the composite strip (B-21-S-102 and B-21-S-51) failed by debonding of the concrete layer along the reinforcing bar. These beams with bonded strips contained no end anchorage. Figure 8 shows the failure of B-21-S-102, which has been declared as a shear-tension failure in the concrete leading to debonding along the reinforcing bar (Buyukozturk and Hearing 1998). The strip remained bonded to the concrete surface.

Results for 42 MPa beams

Beam F-42-S-102-(L) had a several large initial cracks caused during the fastening of the strip, seen in Fig. 3, which led to spalling of large chunks of concrete, as shown in Fig. 9. This beam had a limited increase in yield moment, but the strip quickly became ineffective after yield with no increase in ultimate moment.

To try to reduce the amount of initial cracking from attaching the strip, DNI fasteners were used for Beam F-42-S-102-1. As seen in Table 2, DNI fasteners have a smaller diameter than the ALH fasteners used on Beam F-42-S-102-(L). ZF fasteners were not used, as the smaller diameter fasteners bent when trying to shoot them into the higher-strength concrete. Although some initial cracking occurred with the DNI fasteners, the cracking was much less severe than in Beam F-42-S-102-(L). Beam F-42-S-102-1 failed due to concrete crushing while developing a good ductility and a postpeak response that was a gradual reduction in strength rather than a sudden drop in strength. Beam F-42-S-102-1 is shown in Fig. 10. While some initial cracking occurred on the right side, after concrete crushing the strip began to debond from the left side, showing that the initial cracking on the right side did not seem to affect the failure mechanism in this test. Based on the success of Test F-42-S-102-1, two repeats F-42-S-102-1R and F-42-S-102-1RR were conducted to confirm the behavior. While both tests were successful, initial cracking occurred in both tests.

The initial cracking observed in the 42 MPa beams results from the fact that the concrete is stiffer than the concrete of

Table 6—Strength results for 21 MPa beams

Beam series	Yield moment, kN-m	% increase yield	Ultimate moment, kN-m	% increase in ultimate moment	Calculated ultimate moment, kN-m	% difference from experimental
C-21	9.51	—	10.2	—	10.1	–1.2
F-21-S-102-1	11.3	+19.2	11.9	+15.9	12.7	+6.8
F-21-F-102-1	12.3	+28.9	12.4	+21.2	13.1	+5.4
F-21-D-102-1	12.0	+26.0	12.1	+18.2	13.0	+7.4
F-21-H-102-1	13.0	+36.8	13.3	+30.2	14.2	+6.8
F-21-S-102-2	12.2	+28.6	13.3	+29.8	12.7	–4.7
F-21-S-102-2R	12.1	+27.0	12.7	+24.6	12.7	–0.7
F-21-S-51-1	11.4	+20.2	11.9	+16.4	11.6	–2.8
B-21-S-102	12.3	+29.3	14.0	+37.0	12.7	–9.7
B-21-S-51	10.9	+14.8	12.9	+26.5	11.6	–10.6

$$\%\text{ difference from experimental} = \frac{\text{calculated ultimate moment} - \text{ultimate moment}}{\text{ultimate moment}} \times 100\%$$

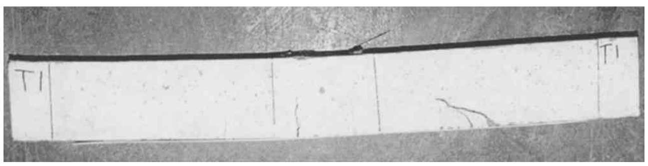

Fig. 10—Composite strip detached from left side of F-42-S-102-1 well after reaching ultimate moment (d » 76 mm). Initial cracking marked on right side.

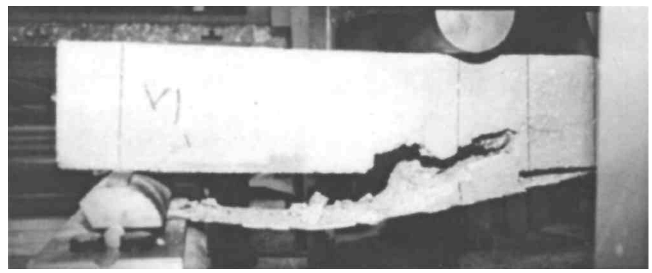

Fig. 11—Plate debonding of composite strip from concrete surface in B-42-S-102.

the 21 MPa beams. Because the main principle of powder-actuated fasteners is to displace the base material, the stronger, and therefore stiffer, concrete is more likely than the lower-strength concrete to be damaged by the introduction of the fastener. Hard aggregates struck at certain angles can cause the fastener to bend, reducing capacity of the fasteners and causing damage to the concrete (CEB 1994).

The bonded Beam B-42-S-102 failed by debonding of the composite strip from the concrete. The failure occurred within a few millimeters of the surface of the concrete, not in the adhesive layer. A large chunk of concrete bounded by flexural cracks detached from the beam in the moment span. Figure 11 shows the failure of Beam B-42-S-102. This beam did not have any end anchorage. It is thought that the higher strength of the concrete used in Beam B-42-S-102 helped prevent the debonding along the reinforcing bar layer that occurred in Beams B-21-S-102 and B-21-S-51.

DISCUSSION

The beams exhibited initial cracking during fastening if too high a charge or too large a fastener were used to attach the composite strip. This issue is related to edge distance, which will increase in larger beams. Hilti recommends a 50.8 mm (2 in.) edge distance and a 76.2 mm (3 in.) fastener spacing (Hilti 2001), while Ramset recommends a 76.2 mm (3 in.) edge spacing and a 76.2 mm (3 in.) fastener spacing (Ramset 1999). In the small 153 mm (6 in.) wide beams tested in this study, the severity of cracking was due to using the minimum edge distance on both sides of each fastener. It is thought that the 50.8 mm (2 in.) minimum edge distance recommended by Hilti is inadequate, and that the edge distance of 76.2 mm (3 in.) provided by Ramset is more appropriate for this application. The microcracking caused by the fasteners is in the cracked portion of the cross section and is thought to not greatly effect the flexural capacity of the beam.

Discussion of 21 MPa beams

Beams strengthened using mechanical fasteners exhibited increases in yield moment over the control beam ranging from 19 to 37%, and increases in ultimate moment ranging from 16 to 30%. Ductility ratios ranged from 1.16 to 1.73, while the ductility ratio of the control beam was 1.75. The calculated ultimate moment, using the Whitney's stress block, varied from underpredicting the experimental value of the strengthened beams by 11% to overpredicting by 7%. Strength results are given in Table 6 and ductility results are given in Table 7.

Beams F-21-S-102-1, F-21-F-102-1, and F-21-H-102-1 were strengthened with composite strips with moduli of 13.8, 17.2, and 27.6 GPa (2 million, 2.5 million, and 4 million psi). The yield moments were increased 19, 29, and 39% over the control beam, and the ultimate moments were increased 16, 21, and 30% over the control beam. The ultimate moments were not increased as much as the yield moments due to slight rotation of the fasteners in the concrete caused by local crushing of the concrete, and due to possible bearing damage in the composite strip at the fastener locations. This bearing damage was minimized by the clamping pressure produced by the neoprene-backed washers. A combination of this imperfect bond between the composite strip and the concrete beam and bearing damage in the composite strip are possible reasons the calculated moments are greater than the experimental values. The higher the strip modulus, the greater the amount of strengthening, and the larger the difference between experimental and calculated values.

Table 7—Ductility results for 21 MPa beams

Beam series	δ_y, mm	δ_u, mm	δ_r, mm	*DR*
C-21	6.77	11.82	—	1.75
F-21-S-102-1	7.55	9.15	15.7	1.21
F-21-F-102-1	6.71	7.77	24.6	1.16
F-21-D-102-1	7.78	9.21	18.8	1.18
F-21-H-102-1	6.73	7.89	18.0	1.17
F-21-S-102-2	7.23	12.53	20.6	1.73
F-21-S-102-2R	8.91	11.29	20.6	1.27
F-21-S-51-1	7.24	10.39	23.6	1.43
B-21-S-102	8.04	13.40	15.2	1.67
B-21-S-51	7.33	14.32	18.5	1.95

Beams F-21-S-102-1, F-21-F-102-1, and F-21-H-102-1 had ductility ratios of 1.21, 1.16, and 1.17, respectively. This means that the ultimate moment occurred at a lower deflection after yield than the control beam, which had a ductility ratio of 1.75. As expected, the strengthening decreased the ductility of the beams.

Beam F-21-D-102-1 was strengthened with a composite strip that had a modulus similar to that of the strip of F-21-S-102-1, but it was twice as thick, providing a total axial stiffness *AE* similar to that of the strip of F-21-H-102-1. This thicker composite strip was used to attempt to demonstrate that increasing the area, not just the modulus of the composite strip, can readily increase the strengthening effect. The ultimate strengthening with this strip was 12% less than F-21-H-102-1. A possible reason for this difference is the force resultant on each fastener was farther from the concrete surface that caused the fasteners to rotate more than in the case of the thinner strip. This increased rotation caused more slip, reducing the effectiveness of the strengthening.

Beams F-21-S-102-2 and F-21-S-102-2R were strengthened using the same composite strip as F-21-S-102-1; however, two rows of fasteners were used instead of only one. This increased the strengthening effect by approximately 10%, and the experimental and calculated ultimate moments matched, as compared with the 7% difference for Beam F-21-S-102-1. This is a result of using twice as many fasteners, which halves the load per fastener and thus reduces the amount of slip between the composite strip and concrete. Changing to two rows of fasteners decreased the edge distance to 50.8 mm (2 in.) from 76.2 mm (3 in.), which increased the amount of cracking in the beam when the composite strip was attached. The second row of fasteners also provided a higher ductility ratio in Beam F-21-S-102-2, but the initial cracking present in Beam F-21-S-102-2R reduced the increase in ductility ratio.

Beam F-21-S-51-1 was tested with a composite strip of the same type as F-21-S-102-1, except that the strip was 50.8 mm (2 in.) wide instead of 101.6 mm (4 in.) wide. The ultimate moment of Beam F-21-S-51-1 was the same as F-21-S-102-1. Because the same amount of strengthening was achieved with the thinner strip as with the wider strip, the entire width of the 101.6 mm (4 in.) wide composite strip is not mobilized when attached with a single row of fasteners. The forces are transferred into the composite strip through the small-diameter fasteners. Beams F-21-S-51-1 and F-21-S-102-1 demonstrate that there should be a row of fasteners for every 50.8 mm (2 in.) width of composite strip. The calculated moment was only 3% lower than the experimental value, as compared with the 7% difference for Beam F-21-S-102-1.

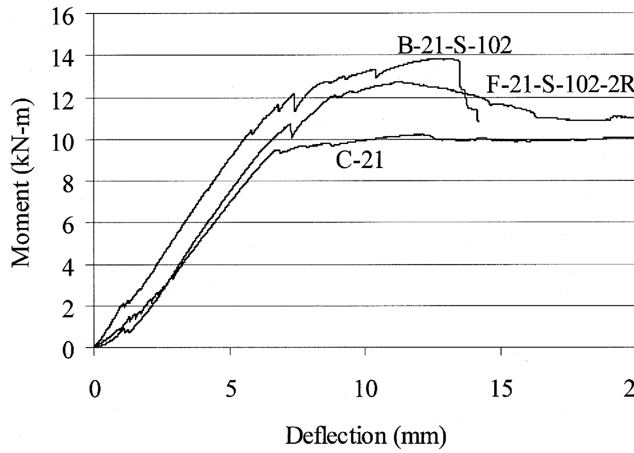

Fig. 12—Comparison of bonded to fastened for selected 21 MPa beams.

Moment versus deflection curves for Beam B-21-S-102, which had a bonded composite strip 102 mm (4 in.) wide, Beam F-21-S-102-2R, and control Beam C-21 are shown in Fig. 12. The curves show similar slopes in the elastic region for B-21-S-102 and F-21-S-102-2R. The sudden drops in the curves occur when shear cracks form in the shear span, but they do not appear to affect the overall behavior of the beams. The bonded Beam B-21-S-102 had an increase in ultimate moment of 37%, while the fastened Beam F-21-S-102-2R had an increase of 25%, showing that the bonded method is more effective in achieving a greater strengthening; however, once Beam F-21-S-102-2R reached its ultimate moment it gradually lost strength, while Beam B-21-S-102 failed suddenly upon reaching its ultimate moment. Comparing Beams F-21-S-102-2R and B-21-S-102, the fastened method is approximately 30% less effective than the bonded method. Beam B-21-S-51 was similar to Beam F-21-S-51-1, except that the composite strip was bonded in the former and was fastened in the latter. Herein, the fastened method was approximately 35% less effective than the bonded method.

Discussion of 42 MPa beams

Beams strengthened using mechanical fasteners exhibited increases in yield moment ranging from 8 to 18%, and increases in ultimate moment ranging from 10 to 20% over the control beam. Ductility ratios ranged from 1.98 to 2.62, while the ductility ratio of the control beam was 1.99. The calculated theoretical ultimate moment, using the Whitney's stress block, underpredicted the experimental value of the control beam by 7% and overpredicted the value of the beams strengthened with fasteners by 17 to 40%. The theoretical moment underpredicted the strength of the bonded beam B-42-S-102 by 11%. Strength results are given in Table 8, and ductility results are given in Table 9.

Beam F-42-S-102-(L) had a 10% increase in yield moment and no increase in the ultimate moment. The ductility ratio of 2.41 was greater than the ductility ratio of control Beam C-42. The calculated moment overpredicted the ultimate moment by 40%. Spalling that occurred due to initial cracking made the fasteners lose their anchorage, and the composite strip had no effect shortly after yield was reached.

Table 8—Strength results for 42 MPa beams

Beam series	Yield moment, kN-m	% increase yield	Ultimate moment, kN-m	% increase in ultimate moment	Calculated ultimate moment, kN-m	% difference from experimental
C-42	10.8	—	12.0	—	11.2	–7.2
F-42-S-102-(L)	11.9	+10.1	12.0	0.0	16.8	+39.9
F-42-S-102-1	12.0	+11.1	13.4	+11.4	16.8	+25.5
F-42-S-102-1R	12.7	+17.6	14.4	+19.5	16.8	+17.0
F-42-S-102-1RR	11.7	+8.2	13.2	+9.5	16.8	+27.7
B-42-S-102	14.5	+34.1	19.0	+57.7	16.8	–11.4

$$\text{\% difference from experimental} = \frac{\text{calculated ultimate moment} - \text{ultimate moment}}{\text{ultimate moment}} \times 100\%$$

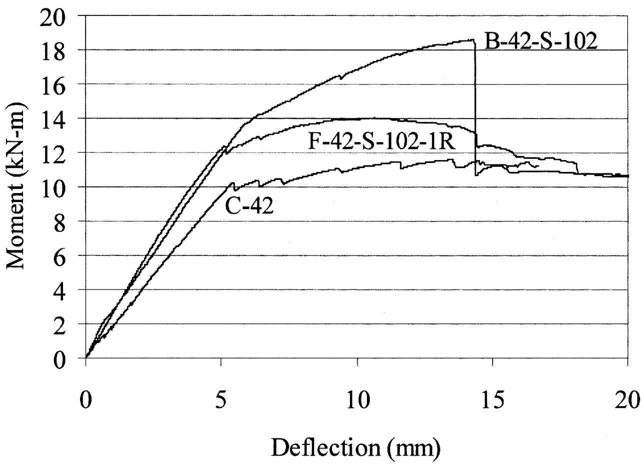

Fig. 13—Comparison of bonded to fastened for selected 42 MPa beams.

Beams F-42-S-102-1, F-42-S-102-1R, and F-42-S-102-1RR had increases in yield moment of 11, 18, and 10% and increases in ultimate moment of 11, 20, and 10% over the control beam. The 42 MPa beams had greater increases in the ultimate moment than the yield moment. Beam F-42-S-102-1RR did not perform as well as F-42-S-102-1 and F-42-S-102-1R because of severe initial cracking caused during attachment of the composite strip. The calculated ultimate moments overpredicted the experimental moments by approximately 23% in these beams.

Bonded beam B-42-S-102 showed a 34% increase in yield moment and a 58% increase in ultimate moment. The bonded Beam B-42-S-102 also showed a higher flexural stiffness after yielding than Beam F-42-S-102-1R. The moment versus deflection curves for Beams B-42-S-102, F-42-S-102-1R, and C-42 are shown in Fig. 13. The calculated ultimate moment underpredicted the experimental ultimate moment by 11%. The experimental ultimate moments of Beams F-42-S-102-1, F-42-S-102-1R, and F-42-S-102-1RR were much lower than the calculated ultimate moments. This discrepancy shows that slip occurs in the beams strengthened with mechanically fastened strips. This slip is likely to be greater in concrete beams that exhibit significant cracking from the attachment of the composite strip.

CONCLUSION

Tests of small-sized concrete beams have demonstrated that attaching composite strips with powder-actuated fasteners may be feasible for rapid strengthening applications. Cracks develop in the concrete due to the penetration of the fastener. This cracking is a function of the fastener type and diameter, along with the edge and spacing distances. Initial cracking from fastener penetration was observed in almost all tests, due to the maximum available edge distance of 76.2 mm (3 in.) in the beams tested. This cracking may prevent the strengthened beam from reaching the increased ultimate moment that would be achieved if the strip were adhesively bonded; however, a strengthening effect is still achieved. Based on these preliminary tests of small beams, it appears that to utilize this method of repair, a lower level of strengthening will be reached in reinforced concrete beams with high-strength concretes and minimum edge distances. This cracking is expected to be reduced in larger beams that can provide larger edge distances.

Table 9—Ductility results for 42 MPa beams

Beam series	δ_y, mm	δ_u, mm	δ_r, mm	*DR*
C-42	7.14	14.23	—	1.99
F-42-S-102-(L)	5.88	14.14	14.2	2.41
F-42-S-102-1	5.31	12.87	16.3	2.42
F-42-S-102-1R	5.63	11.15	18.8	1.98
F-42-S-102-1RR	5.73	15.04	18.8	2.62
B-42-S-102	6.65	14.69	14.7	2.21

At ultimate load, large deformations and concrete cracking appear to decrease the efficiency of this method; however, all strengthened beams except F-42-S-102-(L) showed a satisfactory increase in capacity from yield to ultimate load. The presence of a shear lag effect from the inability of a single row of fasteners to distribute the load throughout the entire width of a 101.6 mm (4 in.) composite strip also appears to decrease the efficiency of this method. To remedy this, a row of fasteners should be used for every 50.8 mm (2 in.) width of strip.

Strengthening beams with composite strips and powder-actuated fasteners is a viable option for instances where speed of installation is a major factor. An additional benefit of a mechanically fastened composite strip is gradual failure after the ultimate state is reached; however, the speed of installation appears to come with the price of a lower strengthening compared with a bonded composite strip.

This preliminary study demonstrates feasibility of flexurally strengthening reinforced concrete beams by attaching a composite strip entirely with small mechanical fasteners. Further work needs to be completed before design recommendations can be developed for this method.

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NOTATION

a	=	shear span
A	=	cross-sectional area of composite strip
AE	=	axial stiffness
DR	=	ductility ratio
E	=	longitudinal modulus of elasticity
M	=	bending moment ($M = P \times a$)
P	=	applied load at each load point
δ	=	load point deflection
δ_r	=	load point deflection at return
δ_u	=	load point deflection at ultimate
δ_y	=	load point deflection at yield
ρ	=	reinforcement ratio
ρ_{bal}	=	balanced reinforcement ratio

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