The Effect of Adhesive Type on the Bond of NSM Tape to Concrete

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<u>Synopsis:</u> Near surface mounted (NSM) reinforcement is becoming a viable material for strengthening existing concrete structures in flexure and shear. As this method moves from the laboratory testing phase to implementation in the field, designers will need to be able to predict the capacity of the strengthening scheme. Bond of NSM reinforcement to concrete will likely be a key factor in determining the strengthened capacity. There are a number of parameters that affect bond between steel rebar and concrete, where only two different materials are present. In the case of bond of NSM reinforcement, a third material, adhesive, is present, further complicating the analytical description of bond of NSM reinforcement. This paper presents the results of two types of bond tests that were used to determine the effect of epoxy adhesive material properties on the bond of NSM tape to concrete. From the testing, it was found that even for epoxy adhesives with similar shear strengths, the bond strength and bond failure mechanisms differ significantly.

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INTRODUCTION

Several different types of fiber reinforced polymers (FRP) are available for use in strengthening applications. The most common are externally bonded sheets and plates. Near surface mounted (NSM) reinforcement is a recent development that has been gaining attention. Near surface mounted FRP is installed by first cutting a groove in the surface of the concrete. The groove is then filled with an appropriate adhesive, and the NSM reinforcement is placed in the groove. Round FRP rods have been studied by researchers for use as NSM reinforcement (De Lorenzis, Nanni, and La Tegola 2000; De Lorenzis and Nanni 2001, 2002; De Lorenzis, Lundgren and Rizzo 2004; Valerio and Ibell 2003). Rectangular FRP tape is emerging as an alternative NSM reinforcement, but is not yet widely available.

Externally bonded (EB) and NSM FRP each have their own advantages and drawbacks. Externally bonded FRP sheets can easily form to the shape of the structural member. This makes them more suitable for curved, I-shaped, T-shaped or otherwise oddly shaped members. A disadvantage of the EB FRP is the possibility of premature debonding. NSM FRP cannot usually form to the shape of a beam, but it can be anchored into flanges or adjacent members. The NSM FRP is much less sensitive to surface preparation than the EB FRP. NSM FRP also has more consistent quality because it is pre-cured and pultruded. It is also better protected after installation because it is embedded in the concrete.

Tensile bond tests conducted by Blaschko and Zilch (1999) indicated that applying FRP in slits greatly increased the ultimate load over applying FRP to the surface of the concrete. Hassan and Rizkalla (2002) compared the cost and effectiveness of rectangular NSM reinforcement to round NSM bars and EB sheets. Externally bonded sheets and rectangular NSM strips were found to be the most cost effective repair methods when cost of materials, equipment and labor were analyzed for a 30% increase in flexural strength of an existing bridge. Carolin, Nordin and Talisten (2001) conducted tests on seven beams strengthened in flexure with one or two square (10 x 10 mm [0.4 x 0.4in]) NSM reinforcement, and found that the strength of the beam was increased by 57% when one bar was added and between 93 and 141% when two bars were added, depending on the bonding material used.

De Lorenzis, Lundgren and Rizzo (2004) conducted a bond test on round NSM bars using groove filling material (epoxy paste and expansive cement) as a variable. It was found that tests with epoxy-filled grooves had higher strength than tests with expansive cement-filled grooves, attributed to the higher tensile strength of the epoxy. Carolin, Nordin and Talisten (2001) tested beams strengthened on the underside in flexure with square NSM rods and recommended using cement mortar instead of epoxy for improvement of health and environmental conditions on site.

Surface treatment of the bars was a variable in bond tests conducted by De Lorenzis Lundgren and Rizzo (2004). Both CFRP and GFRP bars were tested. Specimens containing bars with a spirally wound surface deformation pattern had higher bond strengths than specimens containing bars with a ribbed surface. De Lorenzis and Nanni (2002) found that deformed bars were more likely to cause a splitting failure of the surrounding material, while sand coated rods were more likely to pull out.

Surface preparation of the groove was also a variable in bond tests conducted by De Lorenzis, Lundgren and Rizzo (2004). The specimens with rougher grooves made by saw cutting achieved higher loads than specimens with smooth formed grooves.

Groove width was a variable in bond tests performed by De Lorenzis and Nanni (2001, 2002). They found that increasing the size of the groove increased the strength until the increase in groove width changed the mode of failure from splitting of the epoxy cover to longitudinal and inclined cracking of the surrounding concrete. De Lorenzis, Lundgren and Rizzo (2004) found that increasing the groove size increased the bond strength by delaying the splitting failure.

Several researchers investigated the effects of different bond lengths. Yan et al. (1999) using pullout tests, De Lorenzis and Nanni (2001) using a Rilem type hinged beam bond test and De Lorenzis, Lundgren and Rizzo (2004) using pullout tests with round No. 3 NSM FRP bars, found that increasing the bonded length of the NSM reinforcement over the range of $4d_b$ to $9d_b$ significantly increased the ultimate load, while a further increase in bonded length to $14d_b$ showed only modest increases in ultimate load. Hassan and Rizkalla (2003) conducted beam tests using rectangular NSM tape (25 x 1.2mm [1 x 0.05 in]) to strengthen beams in flexure, where the length of the NSM tape was a variable. They found that tape lengths of less than 500 mm (19.7 in) did not result in a significant load increase over the control beam with no FRP due to premature debonding of the tape. Tape lengths between 500 mm (19.7 in) and 1700 mm (66.9 in) resulted in a load increase of approximately 15 to 45% over the control beam with no NSM, but eventually failed by debonding of the FRP tape. Tape lengths greater than 1700 mm (66.9 in) had the highest loads, with a load increase of approximately 53% over the control beam, and failed by rupture of the strips. In contrast to the previously mentioned work on round NSM bars, Hassan and Rizkalla's work indicated that the development length for the rectangular NSM tape on the beams in the study was approximately 850 mm (33.5 in), the length of tape on either side of the central flexural crack. The large discrepancy in development length may be due to the significantly different types of testing and not necessarily due to the different cross-sectional shape.

Hassan and Rizkalla also performed a parametric analytical study which indicated that development length increased with increasing internal steel reinforcement ratio.

It is difficult to directly compare the results of the tests on NSM FRP because several different types and shapes of bars were used in the tests, and there were very few test results available for rectangular NSM FRP tape. To further gain an understanding of the performance of NSM tape for strengthening, it was included in an investigation at the University of Minnesota regarding shear strengthening of bridge pier caps.

One of the first issues of importance discovered in the tests was the choice of adhesive to bond the NSM reinforcement to the concrete. To this end, a study was conducted to investigate the effect of adhesive on NSM bond using small-scale bond tests in which the concrete was highly confined. Larger scale bond tests were then used to better predict bond strength in field applications and to investigate parameters such as fiber orientation to crack and vibration during cure.

SMALL-SCALE ADHESIVE TESTS

Some NSM tapes are not commercially sold as a system. Consequently, appropriate choice of adhesive is a critical factor to the success of the system. As part of the research investigation, seven different adhesives were chosen for evaluation. Six specimens of each adhesive were tested. The adhesive that exhibited the best behavior along with one of the more popularly used adhesives were used for the larger scale NSM FRP bond tests.

Test set-up

The FRP system chosen was Aslan 500 CFRP tape manufactured by Hughes Brothers. Aslan 500 Tape was chosen because it was the most readily available rectangular near surface mounted tape in the US. The rectangular profile is desirable because it increases the bondable surface area for a given cross-sectional tape area. It was made from 4.8 GPa (700 ksi) carbon fiber, 60% by volume in a bisphenol epoxy vinyl ester resin matrix. The tape was rectangular with a 2 x 16 mm (0.079 x 0.63 in) cross section and area of 32 mm^2 (0.05 in^2). The manufacturer specified guaranteed tensile strength of the tape was 2.1 GPa (300 ksi) and the modulus was 130 GPa (19,000 ksi). The manufacturer specified ultimate strain of the tape was 1.7%. The measured tensile strength was determined in the laboratory to be 2.5 GPa (360ksi) with a coefficient of variation of 4.5% from an average of six tensile tests.

The adhesives chosen for testing were Sikadur Anchorfix-3, Master Builders/Chemrex Concresive 1420, 3M DP600NS, 3M DP460NS, Sonneborn Epofil, Sikadur 35 Hi-Mod LV, and Sikadur 32 Hi-Mod. Recommended cure time, viscosity, tensile strength, tensile modulus, elongation to failure, and shear strength of these adhesives are given in Table1. All information in the table was provided by each manufacturer except the elongation to failure for 3M DP460NS, which was determined in previous research at the University of Minnesota (Nozaka, 2002). A dash in the table indicates that the information was not available.

The small-scale bond test setup is shown in Figure 1. Concrete blocks measuring approximately 152 x 152 x 203 mm (6 x 6 x 8 in) were cast in modulus of rupture beam molds. Plywood spacers were set in the molds to divide the beams into three pieces approximately 203 mm (8 in) in length. The plywood spacers moved slightly during casting, causing the lengths of the blocks to vary between 150 and 250 mm (6 and 10 in). All of the blocks had a 152 x 152 mm (6 x 6 in) cross section which were the dimensions of importance to the test. Due to volume limitations of the mixer, the blocks were cast in two batches on consecutive days. Compressive strengths and split tensile strengths, measured as the average of three tests per ASTM C39 and ASTM C469 respectively using 102x203 mm (4 x 8 in) cylinders at the beginning of the adhesive tests, are shown in Table 2.

A 6.4 x 19 mm (0.25 x 0.75 in) groove was saw-cut into one of the 152 mm (6 in) high sides of the concrete blocks using a tuck pointing blade on a circular saw. The groove was cut perpendicular to the top side of the block. The grooves were then brushed clean and high pressure air was used to remove any remaining dust or debris. The FRP tape was cut to a length of 406 mm (16 in), then lightly sanded and wiped with acetone to remove any dust or grease from the surface.

The procedure for applying the adhesive differed depending on the consistency of the adhesive. Epofil, Sikadur 32, and Sikadur 35 were two-component liquid adhesives. To apply them to the specimens, the FRP tape was inserted into the center of the groove. Small pieces of tape, placed so as to not interfere with flow of the adhesive, were used as spacers at the top and bottom of the FRP to keep the FRP in the center of the groove and slightly forward of the back of the groove. The front of the groove was then sealed with duct tape, leaving the top of the groove open. For Sikadur 32 and Sikadur 35, the two components of the adhesive were measured and mixed thoroughly using a drill fitted with a mixing attachment. The adhesive was then transferred to a squeeze bottle and dispensed into the groove from one side of the top until the entire groove was full. After filling, the front of the tape was tapped to dislodge any trapped air. Post-test inspection did not reveal any voids in the adhesive. Epofil was a two-component cartridge that was mixed with a static mixing nozzle and dispensed into the top of the groove using a manual gun. Sikadur Anchorfix-3, Concresive 1420, 3M DP600NS and 3M DP460NS were non-sag two-component adhesives that were supplied in cartridges. They were mixed with static mixing nozzles and applied using manual guns. The grooves were not taped for application of the non-sag adhesives. The grooves were filled from the front with the adhesive. The FRP tape was then coated with the adhesive and inserted into the center of the groove. The surface of the adhesive was smoothed with a trowel.

After application of the adhesive, the FRP tape was clamped to a steel tube and angle seated on top of the block. The angle kept the FRP tape perpendicular to the top of the block while the adhesive cured.

Approximately 24 hours prior to testing, aluminum tabs were epoxied to the top end of the FRP tape. The 16 x 102 mm (0.625 x 4 in) tabs were cut from 3.2 mm (0.125 in) thick aluminum. They were lightly sanded and wiped with acetone before bonding them to the FRP tape with a fast-curing epoxy.

After the tab epoxy had cured, the specimen was inserted into an MTS 900 kN (200 kip) test frame. The test setup is shown in Figure 1. Shims were used under the concrete block to position the top of the block tightly against the top plate. The top plate kept the block from rotating as the tensile force was applied eccentrically to the block through the FRP tape, which was located on one side of the block. The plate also put the concrete in a state of compression to promote an adhesive failure rather than a concrete failure to facilitate comparison of the different adhesives. The crosshead was lowered until the grips covered approximately 76 mm (3 in) of the tabs. The hydraulic grips were closed and the testing began. The loading was displacement-controlled at a rate of 0.25mm/min (0.01 in/min). Testing continued until the load dropped suddenly due to failure of bond between the tape and the adhesive, failure of the concrete, failure of the adhesive, or fracture of the FRP tape. If the FRP tape had not broken, it was pulled out of the concrete block before both parts were removed from the test frame.

Some of the blocks were re-used for a second round of testing. A groove was cut in the face opposite the first groove. The same procedure was followed for preparation and testing.

Small-scale adhesive test results

There were several different types of failures observed in the adhesive tests. Most of the adhesive tests using Anchorfix-3, Concresive 1420, Sikadur 32, Sikadur 35, and Epofil failed by a loss of bond between the FRP tape and the adhesive. This usually occurred in a very sudden fashion. In some of these tests, shock from the abrupt loss of bond immediately caused the FRP tape to break. In these cases, the FRP broke off cleanly with no fraying of the fibers. The tests using 3M DP600NS all failed by loss of bond between the adhesive and the concrete. The tests using 3M DP460 NS failed in various ways including loss of bond between the tape and the adhesive, failure in the adhesive, failure in the concrete, and fracture of the FRP tape. When failure occurred by fracture of the FRP tape, it was not a clean break. The fibers began to fray and break off individually until the tape completely deteriorated. Figure 2 shows a photograph of a typical failure for each adhesive type.

Table 3 shows the maximum loads reached in each of the tests, as well as the age of adhesive cure at the time of testing. A dash in the table indicates that the test was not valid because of a failure due to the gripping method. Figure 3 shows a graph comparing the average and highest load of the six tests conducted for each of the seven adhesives. The tests using Sika Anchorfix-3 had the lowest ultimate strengths with an average load of 30 kN (6.8 kips) and a maximum load of 34 kN (7.7 kips). The tests using 3M DP460NS had the highest ultimate strengths with an average load of 73 kN (16.5 kips) and a maximum load of 81 kN (18.3 kips). The other adhesives all performed comparably, with maximum loads between 50 and 60 kN (11.3 and 13.6 kips).

No strong correlation between any of the manufacturer provided adhesive properties and the results of the small-scale bond tests was observed. Adhesive tensile strength and shear strength correlated the least well (r^2 values of approximately 0.07 and 0.02 respectively), with tension modulus and elongation at failure correlating better (r^2 values of 0.53 and 0.42). Clearly the results of these tests indicate that picking an adhesive

solely based on the manufacturer provided shear strength will not lead to the best system. Nozaka (2002) found that the bond strength between FRP and steel was strongly dependent on the ductility of the adhesive. Long lengths of adhesive are required to yield in shear to build up enough force through redistribution to fracture the FRP. It is possible that the development length of NSM tape in highly confined concrete is also highly dependent on the ability of the adhesive to deform and yield in shear, which cannot typically be determined from the manufacturer provided data.

LARGE-SCALE BOND TESTS

Large-scale bond tests that more typically represent the state-of-stress of concrete in NSM applications were also conducted. The test setup is shown in Figure 4. Two concrete blocks were placed adjacent to each other to simulate a crack between them, with two strips of FRP NSM tape connecting the two blocks on each side of every specimen. The blocks were loaded in a direction perpendicular to the crack to simulate crack opening. An advantage of this test setup was the ability to test the FRP without gripping it directly, which eliminated a possible stress concentration due to mechanical grips. This test setup also allowed tensile load to be applied to FRP on both sides of the block at one time while keeping the moment in the tape strips to a minimum.

Parameters

Variables addressed in this part of the study are summarized in Table 4 and included tape orientation, adhesive type, and vibration during cure of the adhesive, through the use of six specimen. For each adhesive type, two repeats were performed with the tape oriented at 90 degrees to the simulated crack. Tape orientation was a variable for the NSM tape because it was anticipated that NSM tape may be used for shear as well as flexural strengthening. In shear strengthening applications, it is quite possible that the tape would not be placed at 90 degrees to the crack, so a worst case scenario, with the tape strips placed at 45 degrees to the crack was investigated. Specimen naming convention consisted of the manufacturer-strip orientation-repetition number (e.g. Specimen Sika-90-2 was the second test [repeat] using Sika Anchorfix-3 with the tape oriented 90 degrees to the simulated crack.

Although adhesive 3M DP460NS performed best in the small-scale adhesive tests, it was among the most expensive adhesives and had very little reported data in the literature regarding its use between FRP and concrete. On the other hand, Sika Anchorfix-3 was a commonly used adhesive to bond FRP to concrete. Therefore both 3M DP460NS and Sika Anchorfix-3 were chosen for study in the large-scale specimen to represent a promising adhesive and a more typically used adhesive.

One specimen with NSM FRP was loaded with a small amplitude cyclic load while the adhesive was curing. This was done to investigate possible effects of service load vibrations occurring during cure of the adhesive. If it is to be applied in the field under traffic loading, the effect of cyclic loading on bond strength may be important.

Specimen Design and Construction

Each half specimen was a rectangular shape, 610 x 305 x 305 mm (2 x 1 x 1 ft). The two halves joined together to form a square shape 610 x 610 x 305 mm (2 x 2 x 1 ft). Specimen drawings can be found in Figure 5. A square shape was chosen to allow investigation of different tape orientations.

Sufficient Grade 60 reinforcement was used in each specimen half to prevent cracks from occurring elsewhere in the specimen. Four Grade B7 threaded rods embedded into the specimen attached the specimen to the loading frame. There was not enough room inside the half specimen to anchor the rods through bond, so a nut was placed in the middle of the half specimen to serve as mechanical anchorage.

Two unbonded 32 mm (1.25 in) diameter steel rods extended through snug-tight greased PVC sleeves in both halves of the specimen. This system acted similarly to a linear bearing to ensure that the crack opened evenly with no rotation of the blocks.

The concrete was delivered from a ready-mix plant. The mix design specified normal weight concrete with a compressive strength of 28 MPa (4000 psi) at 28 days. Compressive strengths measured per ASTM C39 at the beginning and end of the large-scale tests with 102x203 mm (4x8 in) cylinders and split tensile strengths measured per ASTM C496, along with their coefficients of variation and the concrete age at the time of testing are given in Table 5.

Instrumentation and Data Acquisition

A computer data acquisition system was used to record time, displacement, and load from every test. Data was taken at a rate of 1 Hz. All of the tests were displacement-controlled to allow data to be collected for FRP on both sides of the specimen (i.e., as each strip failed, the test was continued in a controlled manner until all of the strips had failed). In every test, four linear variable differential transformers (LVDTs) located near the corners were used to measure the crack opening on each corner of the block to ensure that the blocks were mainly translating and not rotating as the test progressed.

Procedure

The specimen was placed into the load frame and adjusted so that the top half of the specimen could slide freely on the steel rods running between the two specimen as the crosshead was raised and lowered. Once the top and bottom halves were sufficiently aligned with each other and with the steel beams, the blocks were grouted to the steel beams. Nuts were then placed on the threaded rods and fully torqued.

Two 6.4 x 19 mm (0.25 x 0.75 in) grooves 76 mm (3 in) on either side of center were cut into the full length of the specimens on each side with a diamond tuck pointing blade on a circular saw. The grooves were then brushed and blown out with pressurized air to remove any dust or debris. A layer of petroleum jelly was placed on the horizontal surfaces between the two blocks to ensure the two blocks would not be bonded together by adhesive that might migrate into the interface.

The adhesives used came in two-part cartridges that were mixed using a static mixing nozzle and dispensed with a manual or pneumatic gun. A small amount of adhesive was discarded at the beginning of each cartridge to ensure that only well-mixed adhesive was applied. The FRP tape was cut to 610 mm (24 in) and one piece of tape was coated with adhesive. Prior to filling, the edges of the grooves were masked with tape to prevent excess adhesive on the surface of the concrete. One groove was then filled with adhesive and the tape was inserted so that it was centered in the groove. Any remaining voids were filled with adhesive and the excess adhesive was removed with a trowel. The surface was smoothed, and the masking tape was removed. The same procedure was then followed for the other three grooves.

The hydraulics were turned on and the load was set to 4.5 kN (1 kip) in compression in order to maintain a constant position while the FRP cured. The load was held for at least 48 hours until testing began. Keeping the load constant was more successful than keeping the displacement constant, possibly due to shrinkage in the grout.

One specimen had cyclic loading applied while the adhesive was curing. For that specimen, the load was set to cycle between 4.5 and 22 kN in compression at a frequency of 1 Hz. This load range was determined from an analysis of overhang of the pier cap of MN Bridge 19855/56 with the bridge loaded with passenger cars.   The maximum flexural stress on the face of the pier cap overhang, assuming uncracked sections was calculated.   The 17.5 kN load applied to the large-scale test specimen resulted in this same stress, The stress was then applied to the bond test specimen in compression. It was not possible to apply any tension to the specimen while the adhesive was curing because there was nothing to resist tension holding the two halves of the specimen together. The loading began as soon as the FRP had been applied to the specimen, and continued for 3 days until the specimen was tested.

Testing of the six specimens was conducted approximately 48 hours after bonding, with the exception of Specimen Sika-90-1 which was tested approximately 24 hours after bonding, and Specimen 3M-90-3V, which was tested approximately 72 hours after bonding to accommodate the cyclic loading during cure. In all cases, full cure should have been reached after 24 hours (Table 1). The tests were monotonic with a crosshead loading rate of 0.00127 mm/sec (0.00005 in/sec). The tests continued until failure (loss of load carrying capability) or a crosshead displacement of 1.25 mm (0.5 in).

Large-Scale Bond Test Results

Table 4 gives the results of the tests for the six large-scale specimen, including, maximum load reached in the test, load drops associated with the failure of each individual tape strips and the order of strip failure (the superscripts on the failure loads). A superscript "*s*" indicates that two or more different tape locations failed simultaneously and the total load was divided equally among the tape strips.

For each of the specimens using Sika Anchorfix-3, the failure began with cracking of the adhesive that extended into the surrounding concrete, followed by a shear failure in the concrete near the interface between the two blocks, often resulting in the loss of a large piece of concrete from the block as shown in Figure 6a. Ultimately the specimen

using Sika Anchorfix-3 lost bond between the FRP tape and the adhesive, with the tape pulling out of the adhesive. During this phase, load carrying capacity was provided by friction between the tape and the adhesive. All of the FRP tapes that had been bonded using Sika Anchorfix-3 showed little to no concrete attached to the surface and significant damage to the matrix during post-test inspection as shown in Figure 7a. The variability in bond between the first two tests using Sika Anchorfix-3 was high. The tests were identical with the exception of cure time, but Specimen Sika-90-1showed indications of poorly cured adhesive in two locations upon post test inspection, even though the manufacturer recommended installation procedure was followed.   It was unclear why these two locations showed poor cure, while the rest of the adhesive had cured well. The second test, Sika-90-2, was a repeat of the first test with an ultimate load of 169 kN (38.1 kips), and was taken as more predictive of a well cured bond between FRP and concrete using Sika Anchorfix-3.

The specimens using 3M DP460NS exhibited progressive cracking in the concrete directly surrounding the groove, ultimately failing when large pieces of concrete were broken off between the two blocks as shown in Figure 6b. None of the tapes fractured during the test. There was no failure between the FRP and adhesive or in the adhesive as shown by the large amount of concrete remaining bonded to the tape after the conclusion of the test in Figure 7b. The two identical tests of the specimen using the 3M DP460-NS (Specimens 3M-90-1 and 3M-90-2) did not exhibit high variability.

Effect of Adhesive Type for NSM FRP --   The specimens using 3M DP460NS exhibited much higher loads than those using Sika Anchorfix-3 even though the manufacturer's reported shear strengths of both adhesives were similar, with Sika Anchorfix-3 having a slightly larger value (Table1).   The maximum load for the 90 degree specimen with Sika Anchorfix-3 was 169 kN (38.1 kips). The average maximum load for the three 90 degree specimens with 3M DP460-NS was 246 kN (55.3 kips), with a coefficient of variation of 2.0%. The specimen using 3M DP460NS had an increase in ultimate load of 45% over the specimen using Sika Anchorfix-3, simply by changing the adhesive type with all other parameters kept constant.

Although these differences in strength were quite large, they were not as large as those observed between these two adhesives in the highly confined small-scale tests (143%). The difference in strength in the large-scale tests was mainly attributable to the difference in failure modes due to the different adhesive types. Specimens using 3M DP460NS had higher strengths because they were able to take better advantage of the strength of the FRP tape. The maximum loads recorded for the specimens made with 3M DP460NS were close to the load expected to fracture the four tapes when using the manufacturer's guaranteed strength for the Aslan 500 tape (266 kN [59.7 kips] based on a guaranteed strength of 2.1 GPa [300 ksi]). According to Table 1, 3M DP460NS had a larger elongation to failure, perhaps indicating that it was a more ductile adhesive in shear. From the results of the large-scale tests, it appeared that a tougher, less brittle adhesive may be more effective in bonding the dissimilar substrates of FRP and concrete. The failure surfaces for typical NSM specimens with both adhesives are shown in Figures 6a and 6b.

Effect of Fiber Orientation for NSM FRP -- Tape orientation was taken as a variable to examine potential shear strengthening cases. In a shear crack, the crack opens as well as slides. As a consequence, it may be desirable to place the reinforcement at a 45 degree angle to the crack. For this investigation, it was also of interest to see if this orientation could demonstrate good ductility while still carrying a considerable amount of load. Thus, the third test using Sika Anchorfix-3 (Specimen Sika-45-1) was conducted with the NSM reinforcement oriented 45 degrees to the crack.

As expected, this specimen had a much lower ultimate load than the specimen using Sika Anchorfix-3 with the reinforcement oriented 90 degrees to the crack (Specimen Sika-90-2). The 45 degree test reached a load of 99 kN (22.3 kips), 59% of the strength of the 90 degree specimen. This configuration was less stiff than the tests with fibers oriented 90 degrees to the crack, and had a larger displacement at peak load. The 45 degree specimen had approximately twice the displacement of the 90 degree specimen with the same adhesive at peak load (6.1 mm [0.24 in] for Sika-45-1, 3.0 mm [0.12 in] for Sika-90-2) The load vs. displacement plot for the 45 degree Sika Anchorfix-3 specimen (Sika-45-3), one of the 90 degree specimens using Sika Anchorfix-3 (Sika-90-2) and one of the 90 degree specimens using 3M DP460NS (3M-90-2), are shown in Figure 8.

Failure of Specimen Sika-45-1 began with progressive cracking of the concrete and epoxy on the surface, followed by shear failure of the concrete near the crack and a loss of bond between the FRP tape and the adhesive. The failure surface of the 45 degree specimen, shown in Figure 6c, lost much less concrete than the 90 degree specimen. The FRP tape did not fracture at the crack, but its flexibility allowed it to bend as the crack opened. There was significant damage at failure in the matrix of the tape near the crack.

Effect of Vibrations During Cure of Adhesive on NSM FRP -- The test of the specimen (3M-90-3V) that was cyclically loaded during curing of the 3M DP460NS adhesive had a maximum capacity of 242 kN (54.5 kips). The average of the tests using the same parameters, but no cyclic loading during cure (3M-90-1 and 3M-90-2) was 246 kN (55.3 kips). This shows that there was an insignificant change in strength when cyclic loading was applied to the specimen while the adhesive was curing. The failure surface of the specimen subject to vibrations was similar to that of the control specimens with the 3M adhesive. The failure surfaces are shown in Figure 6d.

CONCLUSIONS AND RECOMMENDATIONS

Bond strength of the NSM tape was highly dependent on both the adhesive as well as the state of stress in the concrete surrounding the tape. The dependence did not correlate to the manufacturer supplied shear strength of the adhesive. For most adhesives, even in the small scale tests with highly confined concrete, the failure was in the concrete or adhesive. Only the specimens using 3M DP460NS were able to achieve strengths large enough to break the NSM. In the more realistic large-scale tests neither adhesive could develop enough bond to break the NSM tape, with a maximum force of 98% of the strip strength using 3M DP460NS. The improvement in ultimate strength for the specimens using 3M DP460NS was likely attributable to the larger ductility of this adhesive.

However, there was no good correlation between any manufacturer provided adhesive material properties and the strength and ductility of the test specimen. Indicating that other material properties such as ultimate shear strain and shear modulus of the adhesives may play an important role in determining the amount of bond that can be developed. The limited scope of the work reported herein should be expanded to determine the role of concrete strength, NSM tape type, other forms of adhesives, and the effect of flexure in the tape,   with the long term goal to develop a design equation for bond of NSM that accounts for all the important physical parameters.

REFERENCES

Blaschko, M., and Zilch, K., 1999, "Rehabilitation of Concrete Structures with Strips Glued into Slits," *Proceedings of the Twelfth International Conference on Composite Materials*, Paris, France, July 5-9.

Carolin, A., Nordin, M., and Taljsten, B., 2001, "Concrete Beams Strengthened with Near Surface Mounted Reinforcement of CFRP," *Proceedings of the International Conference on FRP Composites in Civil Engineering*, pp. 1059-1066.

De Lorenzis, L., Lundgren, K., and Rizzo, A., 2004, "Anchorage Length of Near-Surface Mounted Fiber-Reinforced Polymer Bars for Concrete Strengthening-Experimental Investigation and Numerical Modeling," *ACI Structural Journal*, March-Apr, V. 101, No. 2, pp. 269-278.

De Lorenzis, L., and Nanni, A., 2001, "Characterization of FRP Rods as Near-Surface Mounted Reinforcement," *ASCE Journal of Composites for Construction*, May, V. 5, No. 2, pp. 114-121.

De Lorenzis, L., and Nanni, A., 2002, "Bond between Near-Surface Mounted Fiber-Reinforced Polymer Rods and Concrete in Structural Strengthening," *ACI Structural Journal*, Mar/Apr, V. 99, No. 2, pp. 123-132.

De Lorenzis, L., Nanni A., and La Tegola, A., 2000, "Flexural and Shear Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods," *Proceedings of the Third International Conference on Advanced Composite Materials in Bridges and Structures*, Aug, pp. 521-528.

Hassan, T., and Rizkalla, S., 2002, "Flexural Strengthening of Post-Tensioned Bridge Slabs with FRP Systems," *PCI Journal*, V. 47, N. 1, pp. 76-93.

Hassan, T., and Rizkalla, S., 2003, "Investigation of Bond in Concrete Structures Strengthened with Near Surface Mounted CFRP Strips," *ASCE Journal of Composites for Construction*, V. 7, N. 3, pp. 248-257.

Nozaka, K., 2002, "Repair of Fatigued Steel Bridge Girders with Carbon Fiber Strips," PhD Thesis, Department of Civil Engineering, University of Minnesota, 174 pp.

Valerio, P. and Ibell, T. J., 2003, "Shear Strengthening of Existing Concrete Bridges," *Structures and Buildings*, Feb, V. 156, No. 1, pp. 75-84.

Yan, X., Miller, B., Nanni, A., and Bakis, C., 1999, "Characterization of CFRP Rods Used as Near-Surface Mounted Reinforcement," *Proceedings of the Eighth International Structural Faults and Repair Conference,* M. D. Forde Editor., Engineering Technics Press, Edinburgh, CD-ROM version.

Table 1 Properties of Adhesives

Adhesive	Recommended Cure Time	Viscosity	Tensile Strength (MPa)	Tensile Modulus (MPa)	Elongation to Failure (%)	Shear Strength (MPa)
3M DP600NS	1 hour	Non-sag	-	-	-	24.7
Sikadur Anchorfix-3	24 hours	Non-sag	32.4	830	1.2	33.8
MBT/Chemrex Concresive 1420	24 hours	Non-sag	27.6	-	1.0	-
Sikadur 32 Hi Mod	7 days	2800 cps	35.2	2200	1.8	40.7
Sikadur 35 Hi Mod LV	> 7 days	375 cps	61.4	2800	5.4	35.2
Sonneborn Epofil	> 7 days	750 cps	50.3	3100	8.0	60.7
3M DP460NS	24 hours	Non-sag	35.2	2500	2.1	31.0

Table 2 Concrete Strengths for Adhesive Tests

Specimen Set (age of concrete)	Compressive Strength (MPa)	COV (%)	Split Tensile Strength (MPa)	COV (%)
Set 1 (58 days)	55.7	6.8	4.21	8.6
Set 2 (59 days)	64.5	6.3	4.55	5.0

Table 3 Maximum Loads for Adhesive Tests

Adhesive	Cure Time (days)	Test 1 Load (kN)	Test 2 Load (kN)	Test 3 Load (kN)	Test 4 Load (kN)	Test 5 Load (kN)	Test 6 Load (kN)	Ave. Load (kN)	Max. Load (kN)
Anchorfix-3	4	29.8	34.2	30.2	26.7	29.4	30.2	30.2	34.2
Concresive 1420	3	42.3	37.8	50.3	42.7	34.2	37.8	40.9	50.3
Epofil	18	58.7	-	52.9	53.8	59.2	59.2	56.9	59.2
Sikadur 35	17	-	-	52.5	53.8	49.8	53.4	52.5	53.8
Sikadur 32	16	53.4	53.4	55.2	-	60.5	56.5	55.6	60.5
DP600NS	4	43.6	54.3	50.7	41.8	48.0	48.0	47.6	54.3
DP460NS	4	76.1	62.7	81.4	76.1	79.6	65.4	73.4	81.4

Table 4 Large Scale Bond Tests

Test	Adhesive	Fiber Orientation to Crack (deg)	Date of test	Peak Load (kN)	Load Drops[a] East (kN)	Load Drops[a] West (kN)
Sika-90-1	Sika	90	11/13/03	123	N 35[1] S NA	N NA S NA
Sika-90-2	Sika	90	11/20/03	169	N 44[3] S 18[4]	N 13[1] S 32[2]
Sika-45-1	Sika	45	11/23/03	99	N 21[1s] S 21[1s]	N 34[2s] S 34[2s]
3M-90-1	3M	90	5/30/04	242	N 81[3] S 60[2]	N 59[1s] S 59[1s]
3M-90-2	3M	90	6/3/04	250	N 64[4] S 64[1]	N 59[3] S 59[2]
3M-90-3V	3M	90	6/7/04	242	N 51[3] S 68[4]	N 67[2] S 67[1]

[a] Superscripts on loads indicate the order of failure

Table 5 Concrete Strengths for Bond Tests

Test Date (age of concrete)	Compressive Strength (MPa)	COV (%)	Tensile Strength (MPa)	COV (%)
11/20/03 (224 days)	54.1	2.3	4.41	10.0
6/20/04 (437 days)	60.0	3.1	4.55	7.3
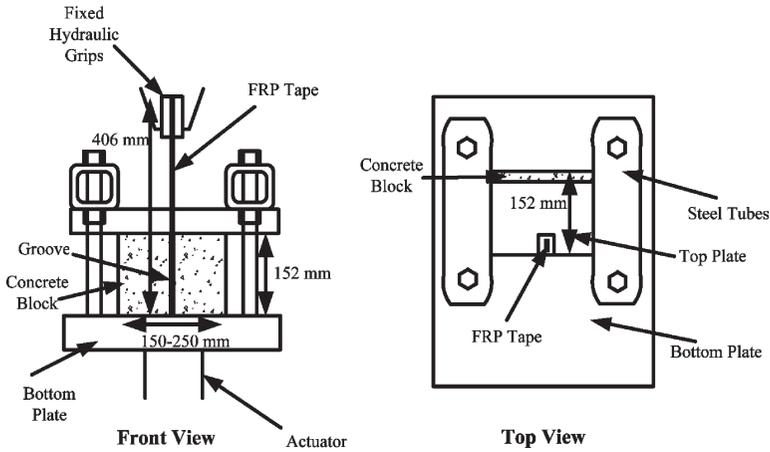
Figure 1 Adhesive Test Setup

a) Sika Anchorfix-3

b) Concresive 1420

c) Sikadur 35

d) Sikadur 32

e) 3M DP 600 NS

f) 3M DP 460 NS

g) Epofil
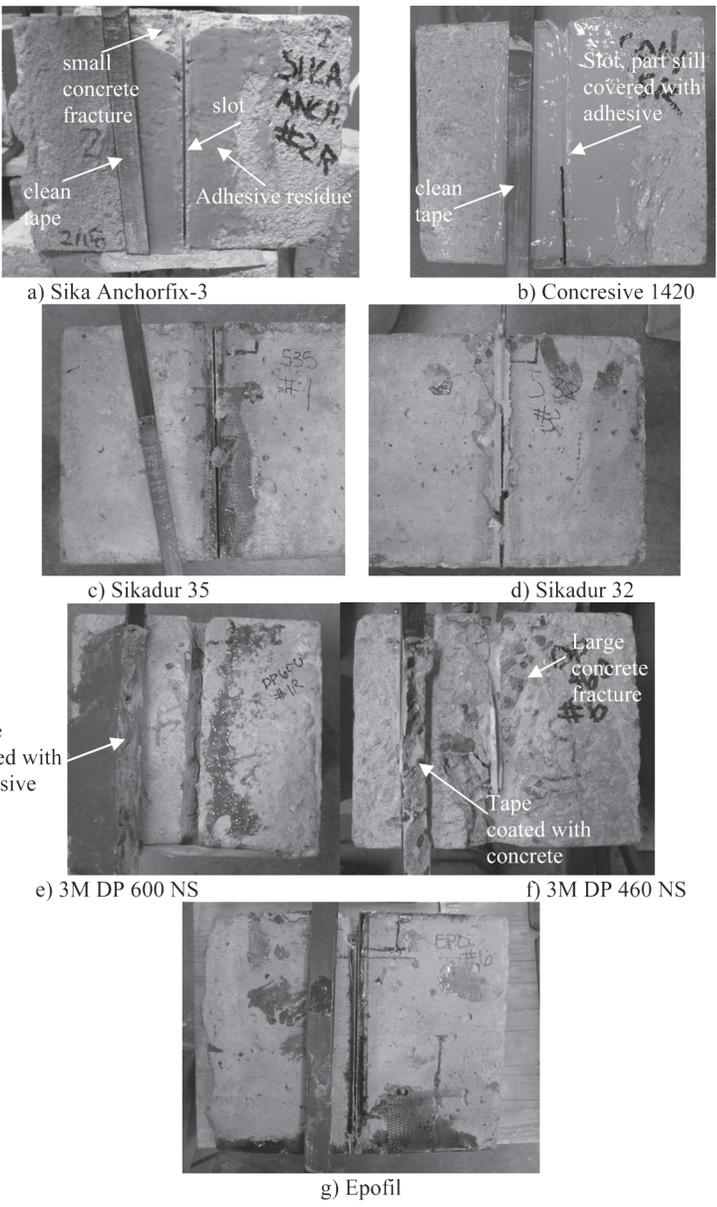
Figure 2 Adhesive Test Specimens after Failure
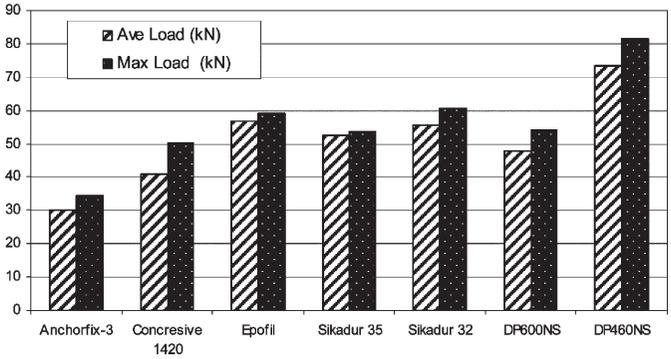
Figure 3 Adhesive Test Load Comparison Graph
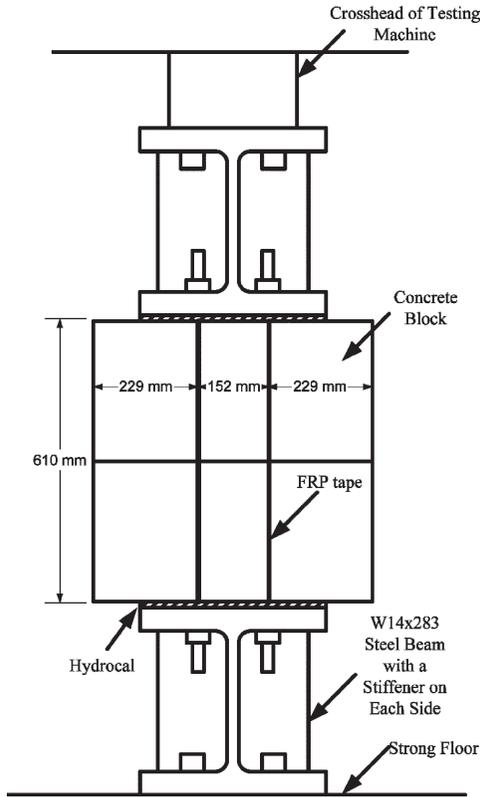
Figure 4 Large-ScaleTest Setup for 90 Degree Tests
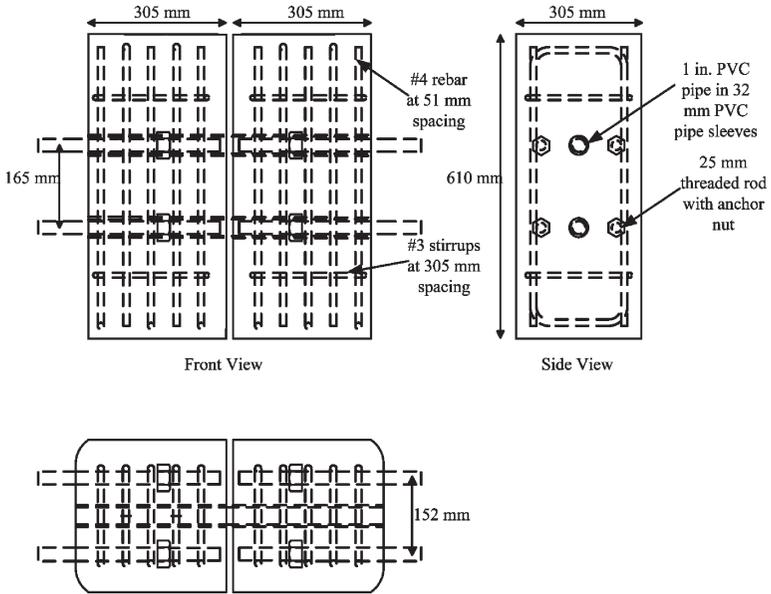
Figure 5 Bond Test Specimen Drawings

a) Specimen Sika-90-2   b) Specimen 3M-90-2

c) Specimen Sika-45-1   d) Specimen 3M-90-3V
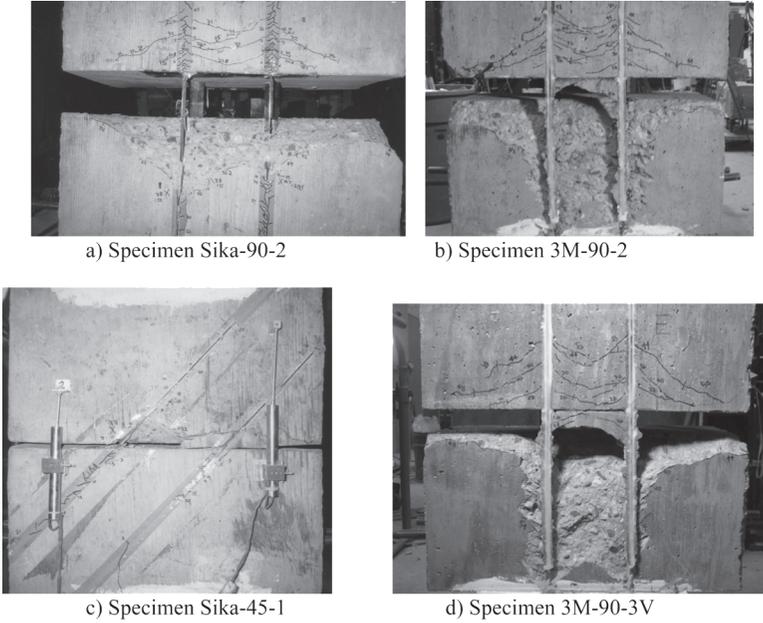
Figure 6 Comparison of NSM Failure Surfaces

a) Tape Using Sika Adhesive   b) Tape Using 3M adhesive
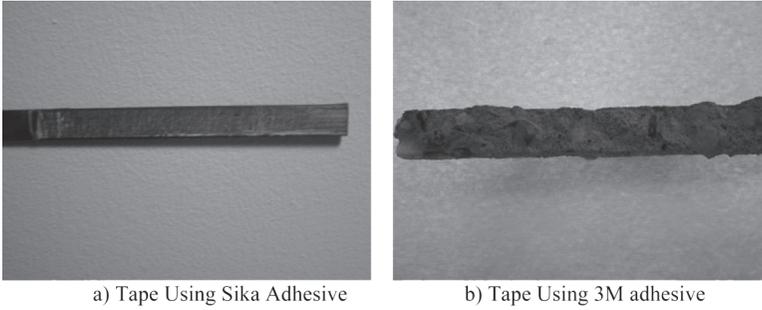
Figure 7 Comparison of Tapes after Failure
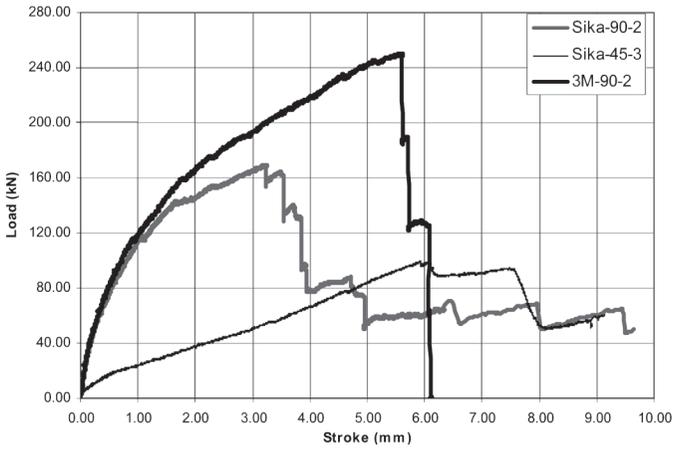
Figure 8 Load vs Deflection Plots