University of Miami
College of Engineering
Structures and Materials Laboratory

ACCREDITED

# CERTIFIED TEST REPORT

## EVALUATION OF ANCHORING SOLUTION FOR EXTENALLY BONDED FIBER REINFORCED POLYMER (FRP) SYSTEMS

Report Number: R-5.10_161206_FSS
Date: December 16, 2016

**REPORT PREPARED FOR:**

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**Quality System:** The Structures and Materials Laboratory (SML) maintains a quality system in compliance with ISO 17025-2005, accredited under International Accreditation Service (IAS), testing laboratory, TL-478

**Procedures:** All tests and services are done in accordance with the SML Quality Manual (Version 2.4) revised August 31, 2015; relevant standard operating procedures (SOPs); and with the applicable requirements of the reference standard test methods.

**Test Data:** All the test results presented herein are linked through unbroken chain to the raw data files recorded on the day of the test. Analyzed data is obtained directly from the recorded raw data during testing, from which the test results are presented. This report contains analyzed tabulated data results of each test.

| **Controls:** | |
|---|---|
| Superseded Report | new |
| Reason for Revision | n/a |
| Effective Date | December 16, 2016 |

| **Test Report Approval Signatures:** | |
|---|---|
| Quality review Approval | I indicate that I have reviewed this Test Report and agree with the contents it presents, and find it meets all applicable laboratory requirements and policies. I approve for its release to the customer.<br>Name: Francisco De Caso<br>Signature:<br>Date: December 16, 2016 |
| Technical review Approval | I indicate that I have reviewed this Test Report and agree with the technical contents it presents, and find it meets all applicable laboratory requirements and policies. I approve for its release to the customer.<br>Name: Antonio Nanni<br>Signature:<br>Date: December 16, 2016 |

## EXECUTIVE SUMMARY

This certified test report, evaluates the performance of a unique anchor solution for externally bonded fiber reinforced polymer (FRP) systems on concrete substrate.

The anchor solution is a development composed of two components: i) a 'flat staple' composed of a pre-cured carbon FRP piece and; ii) a saturated fiber sheet piece that wraps around the flat staple anchor and is placed onto the externally bonded FRP sheet or laminate, here in referred to as anchor 'Type Z'.

Based on double shear load tests of FRP laminates bonded to concrete per the results reported here, the following can be concluded:

- When comparing type Z anchor system to an un-anchored FRP laminate bonded to concrete, under the same conditions it improves the load carrying capacity of the FRP laminate by 156%.
- When comparing type Z anchor system to an FRP laminate bonded to concrete anchored only with the 'flat staple' only component, under the same conditions it improves the load carrying capacity of the FRP laminate by over 115%.

The anchor type Z translates the failure to the concrete substrate, fully engaging the FRP laminate system bonded to the concrete. Neither laceration nor debonding of the FRP laminate occurs with anchor type Z, which are unwanted failure modes since they do not fully engage the FRP laminate.

In summary the anchor behaves as a single element (coupling both the staple and wrapped piece), and results in an effective anchoring solution as presented herein.

# 1. BACKGROUND

The use of externally bonded fiber reinforced polymer (FRP systems) is to date a widely used and accepted practice to strengthen, repair and upgrade structures, where the focus of this report is in concrete and masonry structural elements.

Strengthening with FRP can be classified in two application categories: contact- and bond-critical. When FRP systems are confining elements, e.g. columns, this are referred to as contact critical applications, where contact between the structural element (i.e. columns) and the FRP system is critical to ensure the effectiveness of the strengthening solution. Bond-critical refers to all other applications where the effectiveness of the FRP system depends on assuring adequate bond between the FRP laminate and the concrete substrate, e.g. flexural and shear strengthening of beams or walls. In bond-critical applications, premature debonding of the FRP system from the substrate is typically the failure more.

A proposed solution to counter debonding consists in proving anchorage to the FRP system (fiber sheet or laminate) to the substrate. The solution has proved to be feasible and to significantly improve the efficiency of the FRP strengthening system by allowing it to carry higher loads. A wide variety of anchoring methodologies have been developed and proposed in order to avoid the debonding problem, where the main two solutions are referred to as: U-wrapping or patch anchors and spike anchors.

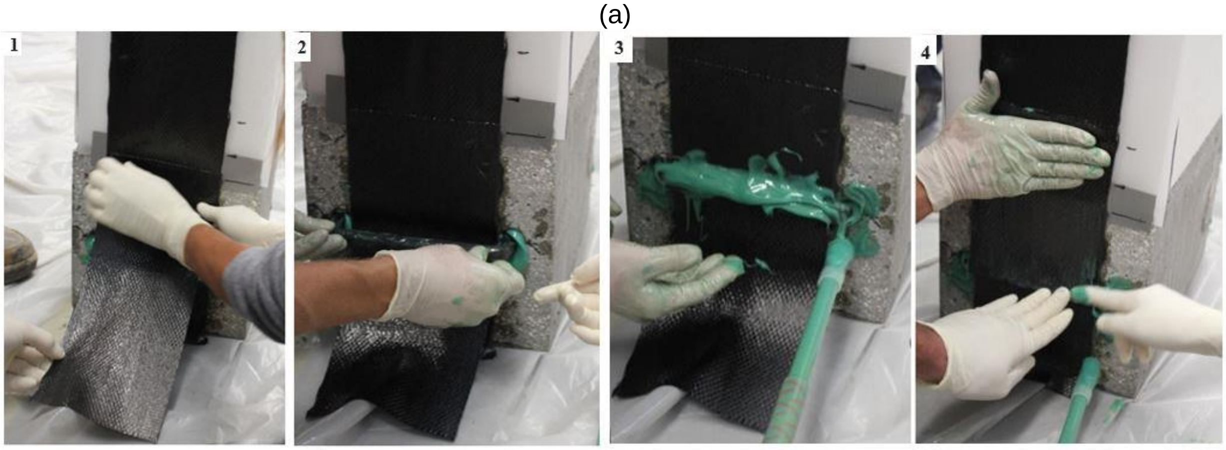
This reports presents a unique anchoring solution for FRP systems consisting of a ‘staple’ type of anchorage in combination with a piece that wraps around the staple anchor and is placed onto the FRP sheet or laminate, as descried in the next sections.

# 2. PRODUCT DESCRIPTION

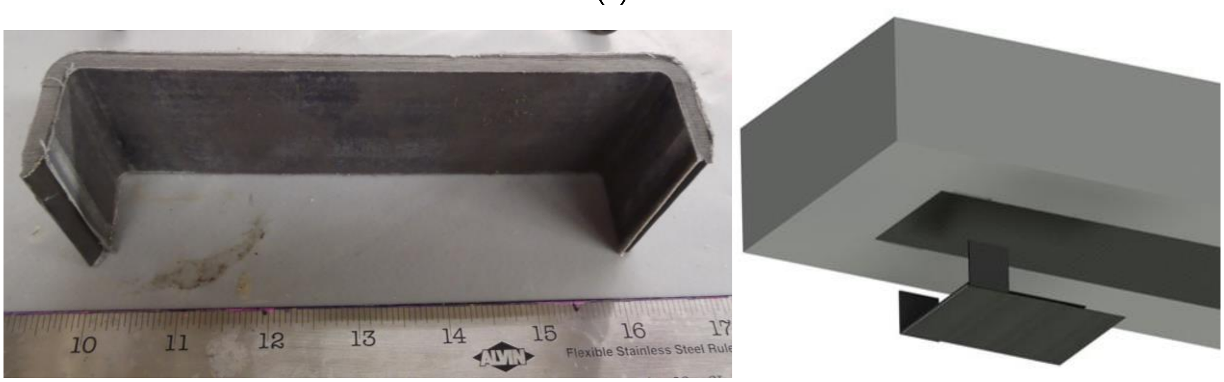
The anchoring solution for FRP systems under evaluation presented herein, is an evolution which combines two elements: i) the ‘flat staple’ composed of a pre-cured carbon FRP piece which transfers loads into the substrate by embedding the ‘legs’ of the staple into the substrate via cut slits or grooves and; ii) a saturated fiber sheet piece that wraps around the flat staple anchor and is placed onto the FRP sheet or laminate, increasing the contact area to transfer loads from the FRP sheet or laminate to the staple. Refer to Figure 1 for a schematic of the anchoring system as well as the installation on concrete substrate.

Characterization tests of the staple anchor alone have been also conducted (without the saturated fiber sheet piece that wraps around the flat staple anchor) to demonstrate the significant effectives of the combined approach. Combining the saturated fiber sheet piece that wraps around the flat staple anchor is only possible due to the geometry and unique layout of the flat staple. No laceration nor debonding of the wrapped piece, or other partial failure modes occur, since the anchoring solution performs as a single element coupling of both the staple and wrapped piece, and results in an effective anchoring solution as presented in this report.

(a)




(b)




(c)

Figure 1 – Anchor solution under evaluation: a) schematic of installation;
b) installation steps on concrete substrate; and c) staple anchor (left) and schematic of installation for flexural strengthening on concrete slab element (right)

# 3. SCOPE OF WORK

The scope of work presented herein aims to evaluate the performance of the aforementioned flat staple anchor solution for externally bonded FRP systems, by testing and comparing the load carrying capacity results of three type of specimens:

i) **Benchmark Specimen (TYPE B)**: This is the reference specimen, establishing the specimen layout for all tests consisting of a six-inch (6 in.) wide strip of unidirectional carbon FRP sheet is bonded to a concrete block. No anchoring solution is used in this type of specimen.

ii) **Staple Only Specimen (TYPE S)**: Using the same established layout in the benchmark specimen, the bonded FRP sheet is anchored with the flat staple of geometry equivalent to six-inch (6 in.) long, two-inch (2 in.) wide and one-inch deep legs embedded in the concrete.

iii) **Staple and Wrapped Piece Specimen (TYPE Z)**: Using the same established layout in the benchmark specimen, and flat staple geometry in the staple only specimen; the bonded FRP sheet is anchored with the flat staple a saturated fiber sheet piece that wraps around the flat staple anchor and is placed onto the FRP sheet or laminate

# 4. TEST METHODOLOGY

Currently, no standard test criterion has been developed to characterize the performance of FRP anchor systems. Nevertheless, there are well-established test methodologies that have been adopted in numerous research studies and published in peer-reviewed papers.

The methodology adopted to evaluate the performance of the FRP anchor solution is based on a double shear bond test methodology, where two bonded areas are engaged in shear. To this end, an FRP laminate is bonded to two opposing sides of a concrete block. In the test side the anchor is installed on the FRP sheet, while on the other the FRP sheet is extended and wrapped around the concrete block to provide additional bonded length and anchored to ensure failure is on the test side of the block. The test layout provides a closed loop system, where by a hydraulic jack is inserted in between the concrete block and the opposite end of the FRP laminate. A steel fixture is used to ensure tensile load is distributed evenly on to the FRP laminate, avoiding stress concentration that might result in premature or invalid failure modes. Refer to Figure 2 for a description of the test setup and layout, and Figure 3 where an illustration of the anchor and specimen payout is provided.

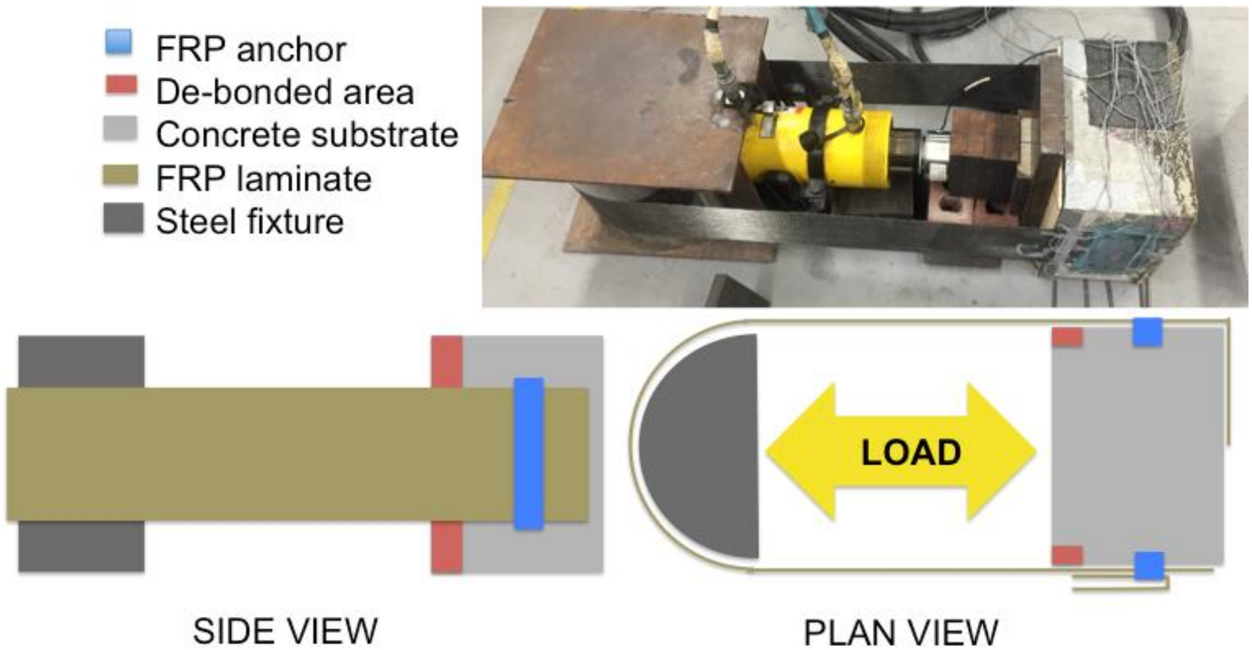
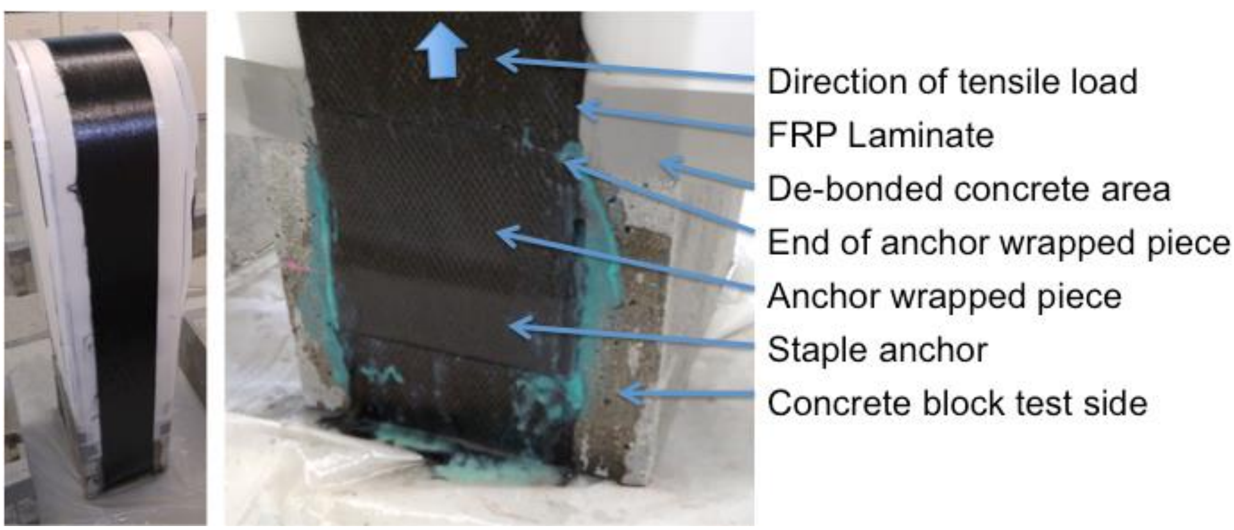



Figure 2 – FRP anchor double shear test setup and layout




(a) (b)

Figure 3 – Specimen type Z layout: (a) entire specimen with FRP sheet; (b) close up of bonded end to concrete showing staple and wrapped piece.

## 5. TEST INFORMATION

| | |
|---|---|
| Specimen preparation: | All specimens were prepared by Structures and Materials Laboratory personnel, following manufactures instructions. All concrete blocks used in testing were cast in a single batch conforming to ASTM C192/C192M-13a, to ensure validity on the comparison of the test results. Concrete substrate surface was prepared via sandblasted to ensure a minimum surface roughness of CPS 3, as defined by ICRI was achieved. The FRP laminate and anchors were installed on the substrate simultaneously. |
| Specimen geometry: | Geometry of test area is provided in Figure 4. All geometry was kept consistent to ensure validity on the comparison of the test results. |
| Test Location: | Structures and Materials Laboratory, SML, University of Miami, 1251 Memorial Dr., MEB108 Coral Gables, FL, 33146 |
| Test setup: | Load was applied via hydraulic jack manually to a quasi-constant rate. All load measurements were recorded with a load cell conforming to ASTM E4-16. |
| Specimen Conditioning: | After installation of the FRP laminate and anchor on the concrete substrate, the specimens were left to cure for a minimum period of 5 days. Following that, specimens were brought into the laboratory to become temperature balanced for a minimum period of 24 hours at 23 ± 1°C (73 ± 3°F) and 60 ± 5% RH. |
| Specimen ID: | Specimens are labeled and uniquely identified for quality and traceability using the format T_XX, where T is the specimen type (B for benchmark, S for staple only, and Z for staple and wrapped piece specimen) product, and X is the sample number. |

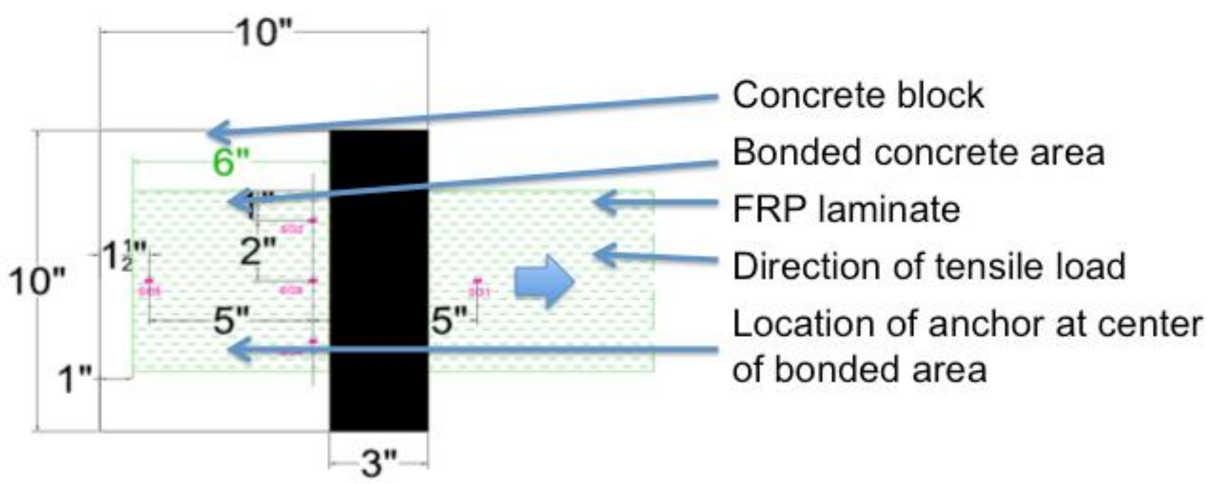



Figure 4 – Specimen test area geometry

# 6. TEST RESULTS

Table 1- Test Results for FRP Staple Anchor Solution

| SPECIMEN ID | Total peak load ($P_{max}$) | | Total load sustained by anchor ($P_{max}/2$) | | Increase in performance | Failure Mode |
|---|---|---|---|---|---|---|
| | lbf | kips | lbf | kips | % | |
| B_01 | 13041 | 13.04 | 6521 | 6.52 | -19.7 | FRP de-bonding |
| B_02 | 17034 | 17.03 | 8517 | 8.52 | 4.9 | FRP de-bonding |
| B_03 | 18635 | 18.63 | 9317 | 9.32 | 14.8 | FRP de-bonding |
| **Average** | **16237** | **16.24** | **8118** | **8.12** | | |
| Stand. Dev. | 2352 | 2.35 | 1176 | 1.18 | **0.0** | |
| Coef. of Var. (%) | 14.5 | 14.5 | 14.5 | 14.5 | | |
| S_01 | 24628 | 24.63 | 12314 | 12.31 | 51.7 | FRP de-bonding and slippage beneath the anchor |
| S_02 | 30118 | 30.12 | 15059 | 15.06 | 85.5 | FRP de-bonding and slippage beneath the anchor/FRP rupture |
| S_03 | 29170 | 29.17 | 14585 | 14.58 | 79.7 | FRP de-bonding and slippage beneath the anchor/FRP rupture |
| **Average** | **27972** | **27.97** | **13986** | **13.99** | | |
| Stand. Dev. | 2396 | 2.40 | 1198 | 1.20 | **72.3** | |
| Coef. of Var. (%) | 8.6 | 8.6 | 8.6 | 8.6 | | |
| Z_01 | 34480 | 34.48 | 17240 | 17.24 | 112.4 | Failure in concrete substrate |
| Z_02 | 43131 | 43.13 | 21566 | 21.57 | 165.6 | Anchor failure and FRP de-bonding |
| Z_03 | 45927 | 45.93 | 22964 | 22.96 | 182.9 | Failure in concrete substrate |
| Z_04 | 41412 | 41.41 | 20706 | 20.71 | 155.1 | Failure in concrete substrate |
| Z_05 | 42833 | 42.83 | 21417 | 21.42 | | Anchor failure and FRP de-bonding |
| **Average** | **41556** | **41.56** | **20778** | **20.78** | | |
| Stand. Dev. | 3829 | 3.83 | 1915 | 1.91 | **155.9** | |
| Coef. of Var. (%) | 9.2 | 9.2 | 9.2 | 9.2 | | |

(a) (b)

Figure 5 – Specimen representative failure modes: a) Failure in concrete substrate FRP de-bonding; and b) slippage beneath the anchor

## 7. CONCLUSIONS

This certified test report, evaluates the performance of an anchor solution for externally bonded fiber reinforced polymer (FRP) systems on concrete substrate. The anchor solution is a development composed of two elements: a) a 'flat staple' composed of a pre-cured carbon FRP piece and; b) a saturated fiber sheet piece that wraps around the flat staple anchor and is placed onto the externally bonded FRP sheet or laminate.

To this end, the experimental comparison of three test specimen types was undertaken including: i) benchmark specimen only with the FRP laminate bonded to concrete (no anchoring); ii) a specimen with the FRP laminate anchored only with the staple anchor to concrete; and iii) a specimen with the laminate anchored with the staple anchor and wrapped piece.

Characterization tests using a double shear methodology to apply tensile load on the FRP laminate to evaluate the capacity of anchored FRP system. The results are provided in Table 1 and demonstrate the improved effectiveness at anchoring the FRP laminate on to the concrete, where a 72% increase in load carrying capacity is measured for the anchor alone, and 156% for the anchor when wrapped piece, when compared to no anchor provided.

Furthermore, the improved performance of anchor type Z, compared to type S, which couples the anchor with the wrapped piece, provides over 100% increase in load carrying capacity. Combining the saturated fiber sheet piece that wraps around the flat staple anchor is only possible due to the geometry and unique layout of the flat staple. Neither laceration nor debonding of the FRP laminate occurs with anchor type Z, this is not the case for anchor type S, as reported in Table 1, which are unwanted failure modes since they do not fully engage the FRP laminate. The anchor type Z translates the failure to the concrete substrate, fully engaging the FRP laminate systems bonded to the concrete, showing that anchor type Z behaves as a single element (coupling both the staple and wrapped piece), and results in an effective anchoring solution as presented in this report.

The tests presented herein are true representations of the anchor solutions and FRP systems, where the coefficient of variance are in the range normal to the type of experimental testes undertaken. All results are traceable to NIST values.

**♦ END OF TEST REPORT ♦**