Federal Building and Fire Safety Investigation
of the World Trade Center Disaster

Strength and Impact Response of SFRM

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NIST

Disclaimer

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Effect of Impact on SFRM Protected Steel

- Estimate of extent of dislodged SFRM is needed for thermal-structural modeling
- Lack of available information on impact performance of members protected with SFRM

Overview

- In-place density and bond strength (Cafco BZ-II)
- Laboratory static strength properties (Cafco BZ-DC/F)
- Impact tests

Impact Damage

- SFRM was dislodged
  - Debris field
  - Localized accelerations and deformations
- Estimate extent of dislodged SFRM
  - Measure static adhesive and cohesive tensile strength
  - Develop “failure criteria”
  - Impact analysis and engineering judgment to estimate extent of dislodged SFRM

Laboratory Specimens

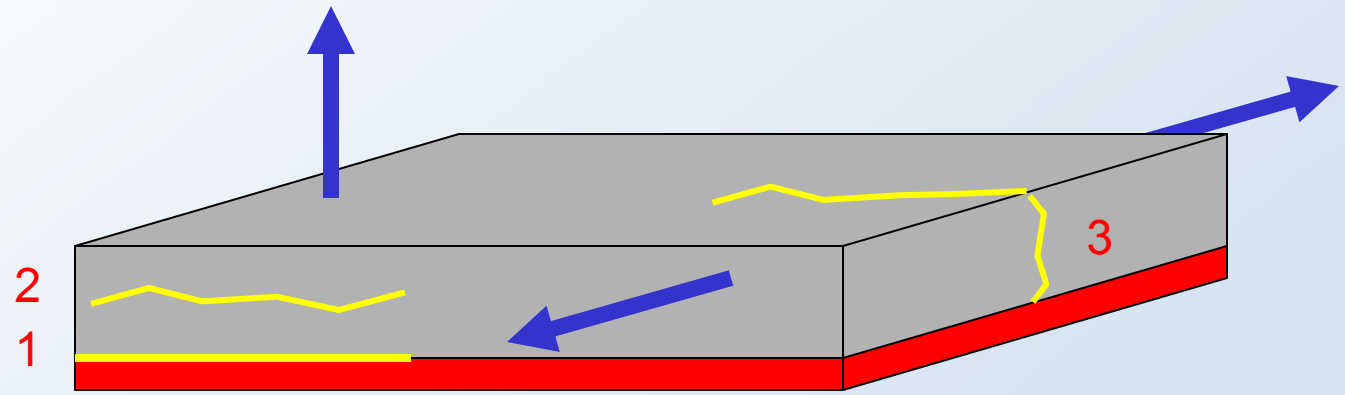
- 8 x 16 x ¼ in. plates
  - ¾ in. and 1-1/2 in. nominal thickness Cafco BZ CD/F
  - With and without primer (Tnemec 99 Red)
- 1 x 20 in. bars
  - ¾ in. and 1-1/2 in. nominal thickness Cafco BZ CD/F
  - With and without primer (Tnemec 99 Red)


March 25, 2004

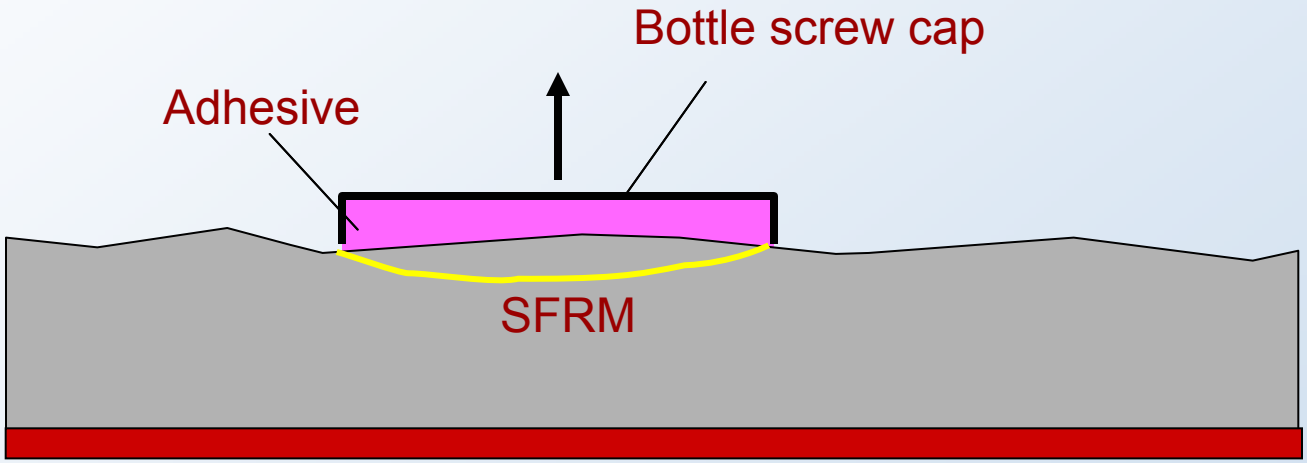

March 24-25, 2004

Tensile strength properties of fiber-based SFRM

1. Adhesion to steel
2. Cohesion normal to surface
3. Cohesion parallel to surface (in-plane)



ASTM E 736 – Cohesion/Adhesion of SFRM Applied to Structural Members (adopted 1980)



0.06 in. Galvanized Steel Sheet

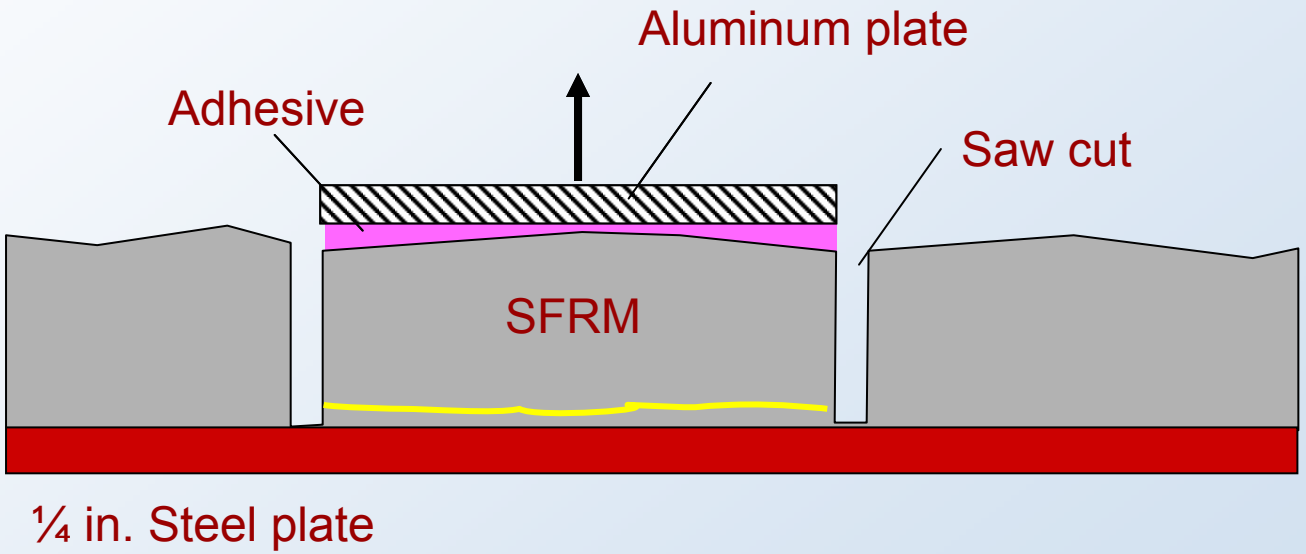

B7
2

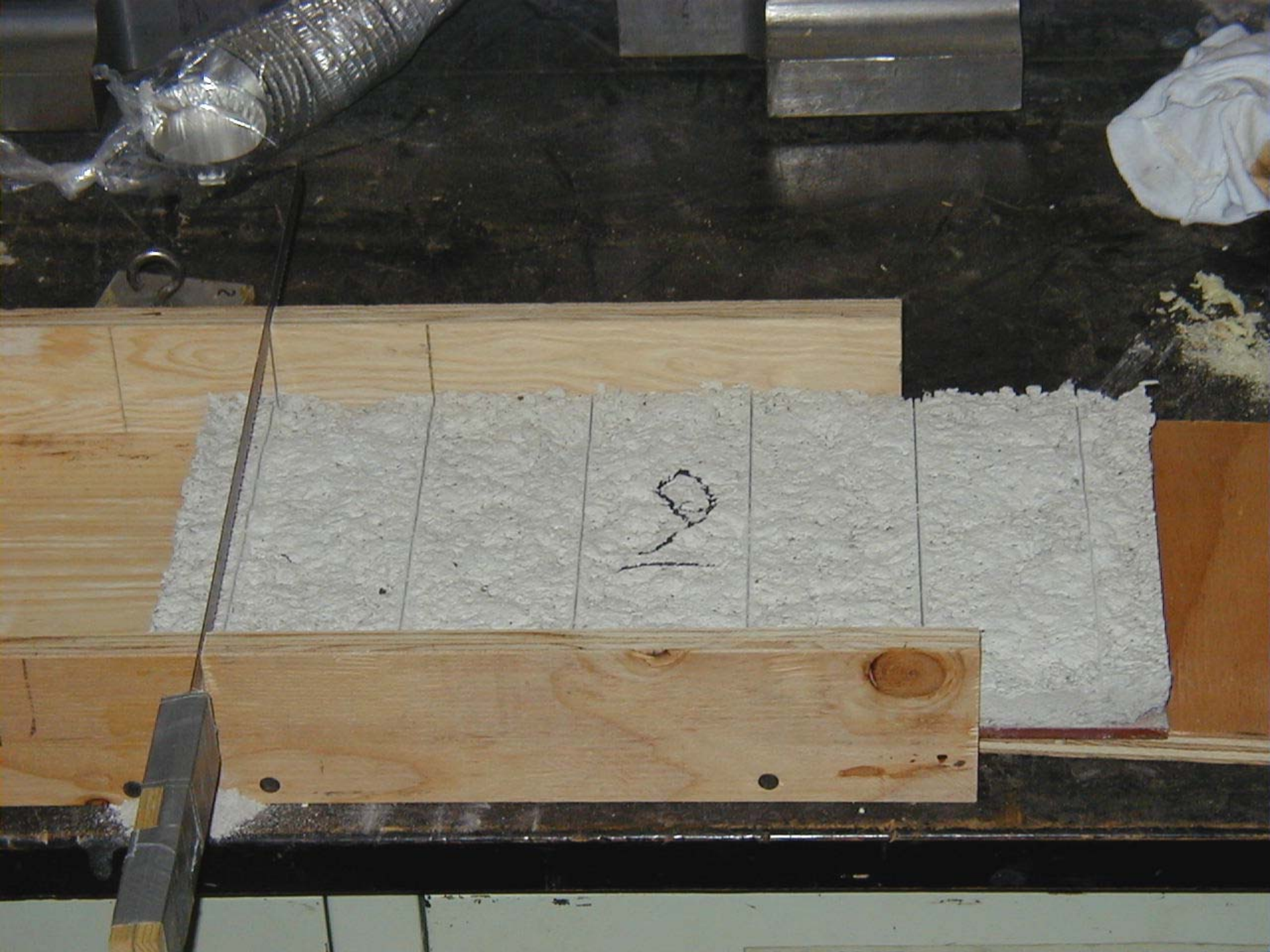
Limitations of ASTM Method

- Failure area not well defined
- Cannot measure both adhesive strength and cohesive strength
- No information on in-plane strength

Tensile Pull-off Test for Adhesion and Cohesion

Adaptation of technique used to test overlays applied to concrete (ASTM C 1583)

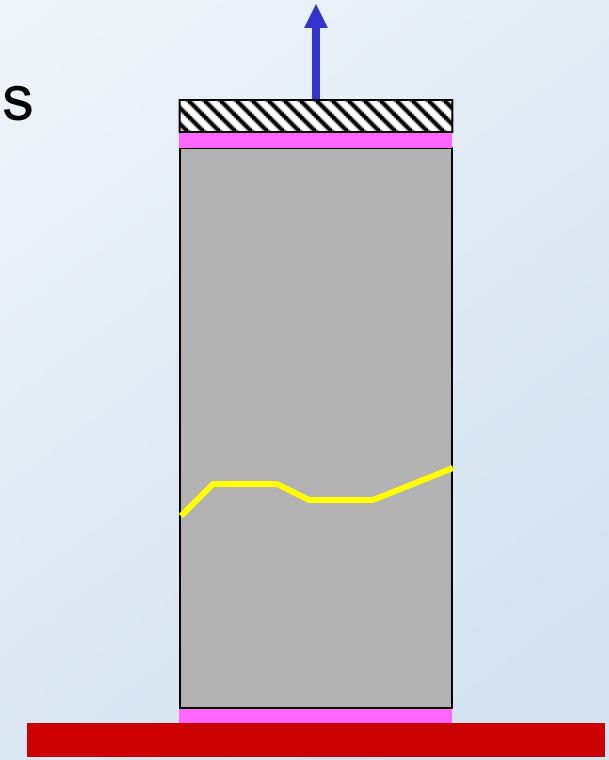





Specimens for density and in-plane cohesive strength
C
B
A
16
Specimens for adhesive/cohesive (N) strength

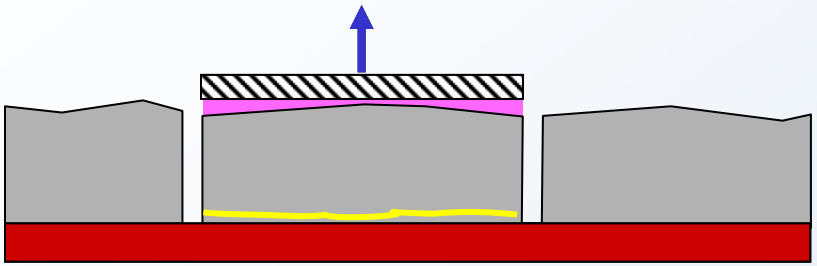
In-Plane Tensile Strength

- Prepare prism by sanding
- Measure mass and dimensions
- Compute density
- Measure tensile strength



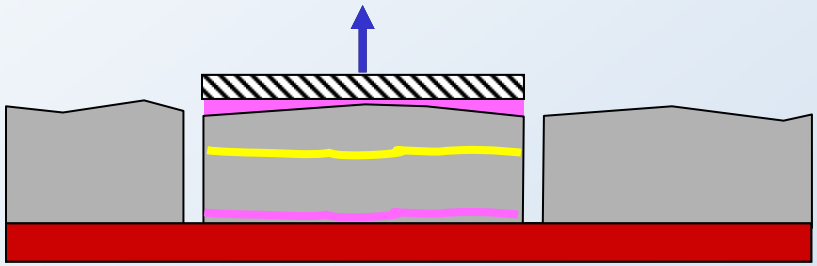
Tensile Pull-off Test for Adhesion and Cohesion

First Test

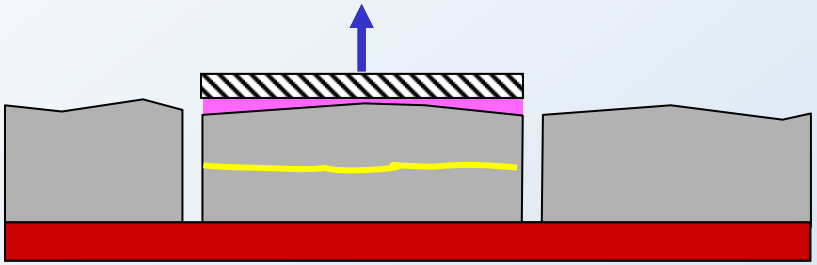


Adhesive failure

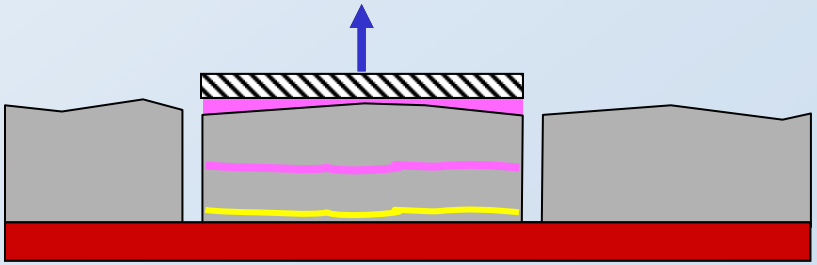
Re-Test



Cohesive failure



Cohesive failure



Adhesive failure

Test 1- Adhesive failure

Test 2- Cohesive failure

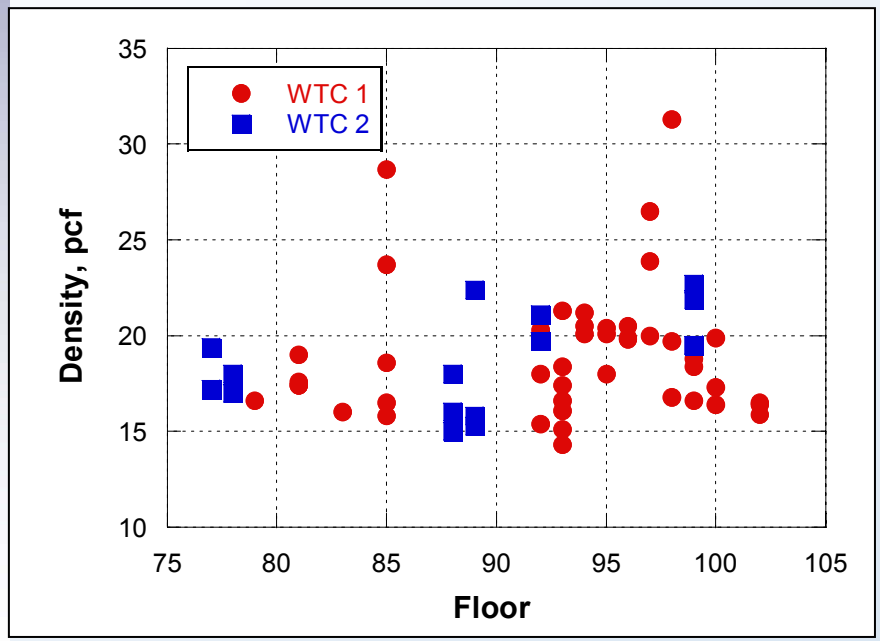
Results

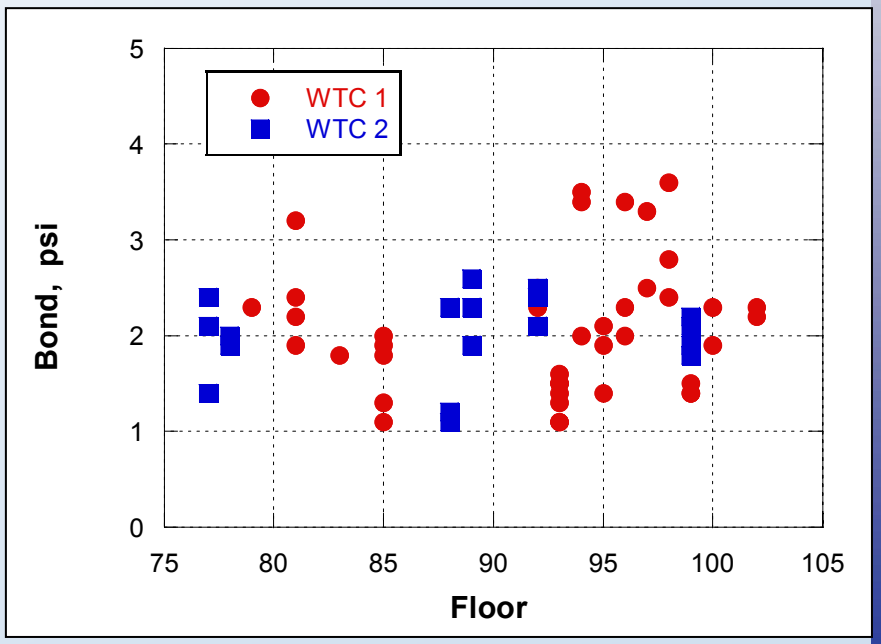
- Tenant Alteration Audit reports for BZ-Type II (1997-1999):
  - ASTM E 736 adhesive/cohesive strength
  - ASTM E 605 density
- Laboratory tests (BZ DC/F)
  - Density
  - Adhesive strength
  - Cohesive strength normal to surface
  - Cohesive strength parallel to surface

PANYNJ Tenant Alteration Audit Reports

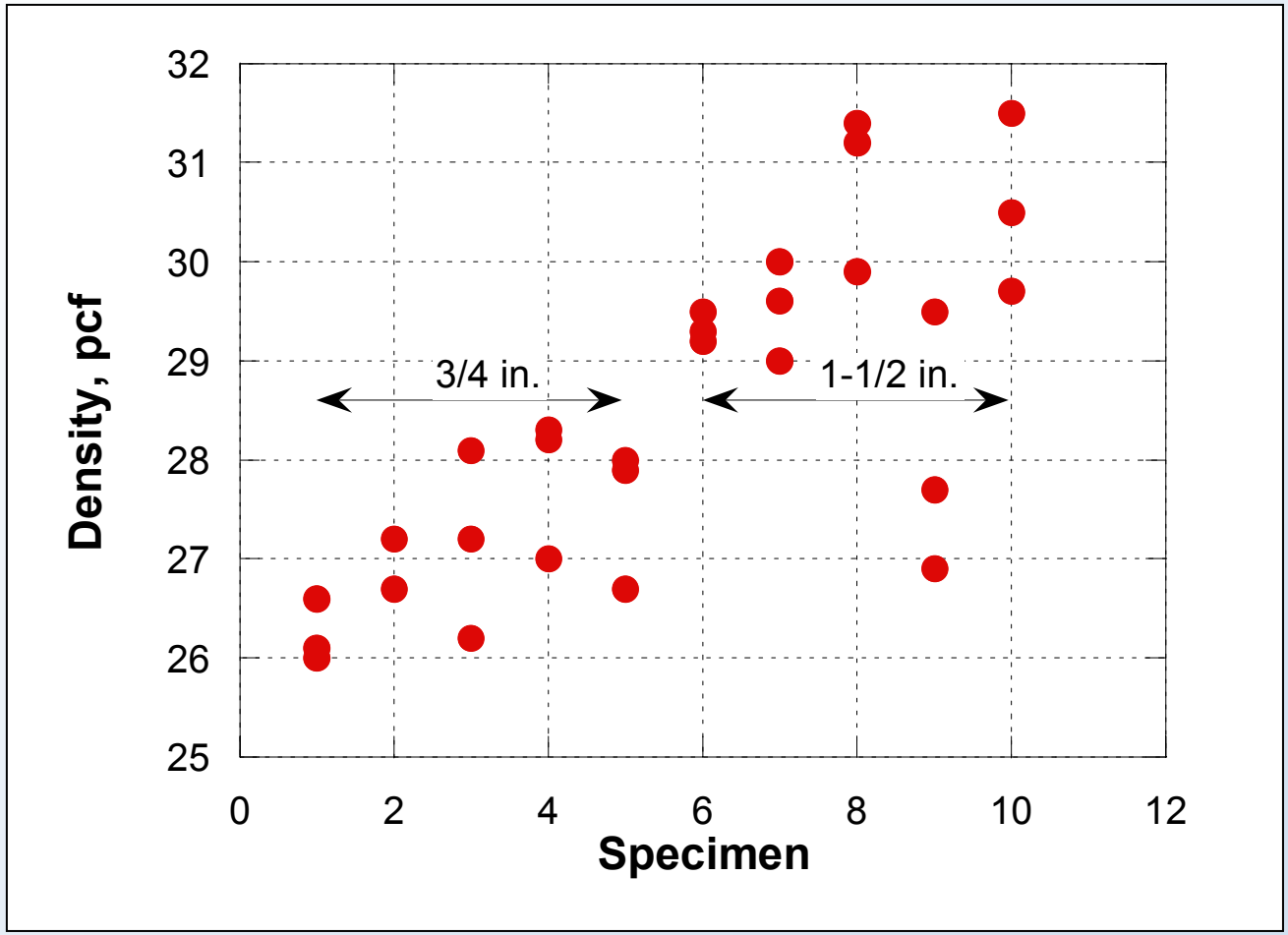
- Average density: 18.9 pcf (sd = 3.2 pcf; COV = 0.16)
- Average bond strength: 2.1 psi (sd = 0.6 psi; COV = 0.30)

- UL Design No. G805: Min. avg. = 13 pcf; min. ind. = 11 pcf
- Isolatek literature: Avg. bond strength ≈ 1 psi (150 psf)





Laboratory Density (BZ DC/F)



Laboratory Density (BZ DC/F)

Thickness	Average	Stand. Dev.	CoV
¾ in.	27.2 pcf	0.8 pcf	0.03
1 ½ in.	29.7 pcf	1.3 pcf	0.04

Isolatek literature: Average minimum density = 13 pcf

Adhesive Strength

Poor adhesion to primed plates

¾ in. Thickness

1 ½ in. Thickness

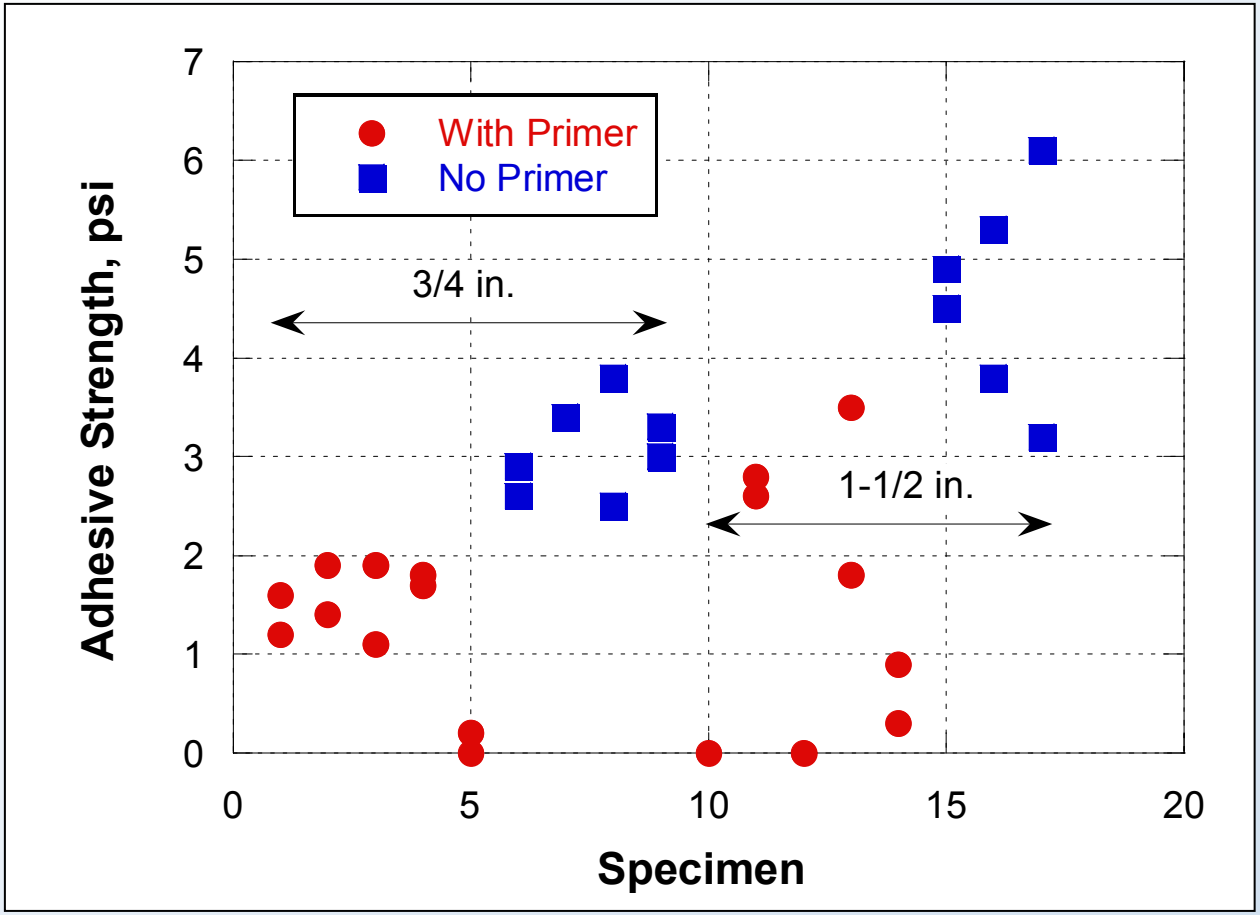
Adhesive Strength

Good adhesion to bare steel

¾ in. Thickness

1 ½ in. Thickness

Laboratory Adhesive Strength



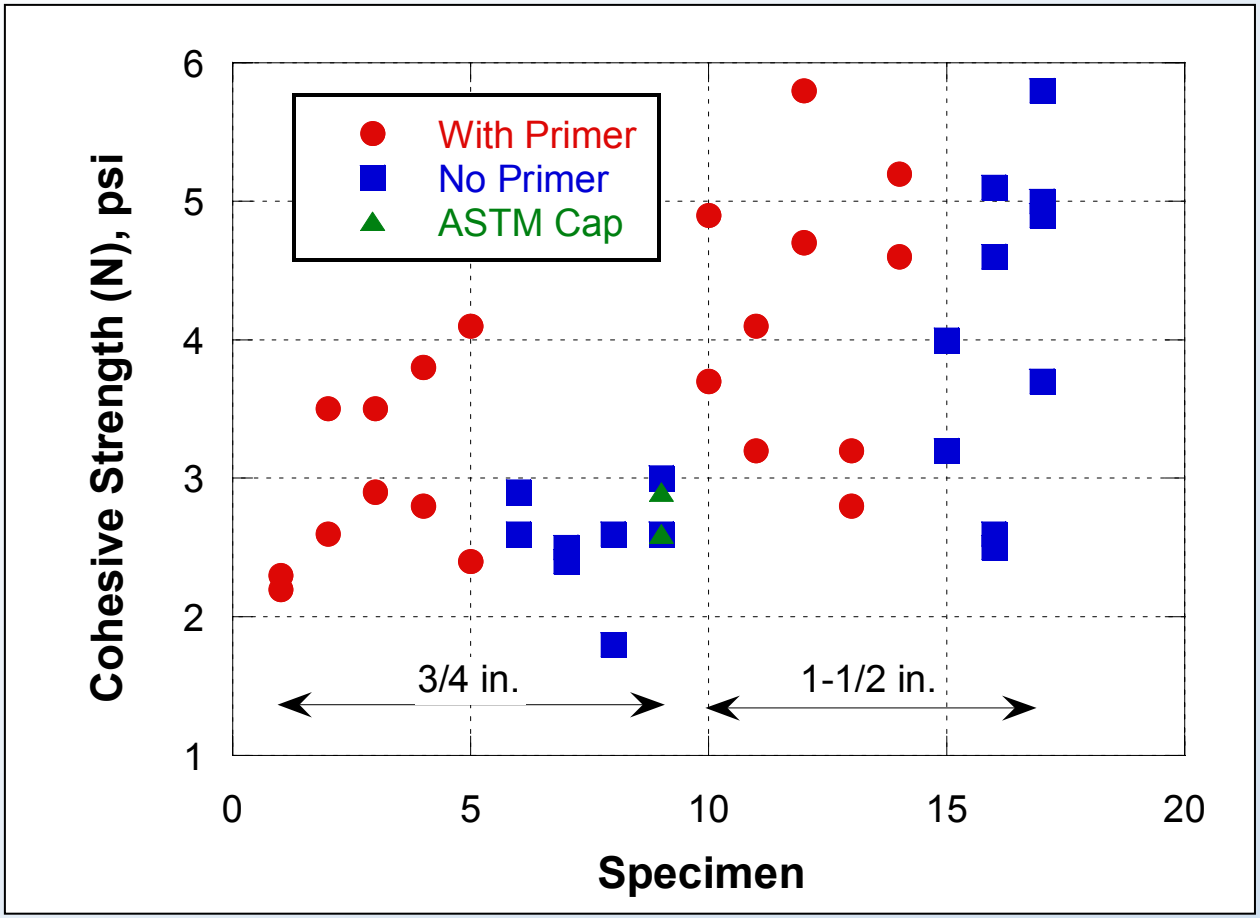
Laboratory Adhesive Strength

Isolatek literature: Minimum bond strength for BZ CD/F (ASTM E 736) with uncoated or galvanized steel = 0.7 psi (100 psf)

	Average	Stand. Dev.	CoV
¾ in. P	1.3 psi	0.7 psi	0.53
¾ in. NP	3.1 psi	0.4 psi	0.14
1 ½ in. P	1.2 psi*	1.4 psi	1.15
1 ½ in. NP	4.6 psi	1.0 psi	0.22

*For selected specimens; 2/3 of specimens had 0 bond strength

Laboratory Cohesive Strength Normal to Surface



Laboratory Cohesive Strength Normal to Surface

	Average	Stand. Dev.	CoV
¾ in. P	3.0 psi	0.7 psi	0.22
¾ in. NP	2.6 psi	0.4 psi	0.14
1 ½ in. P	4.2 psi	1.0 psi	0.23
1 ½ in. NP	4.1 psi	1.1 psi	0.27

As expected, primer had no effect.

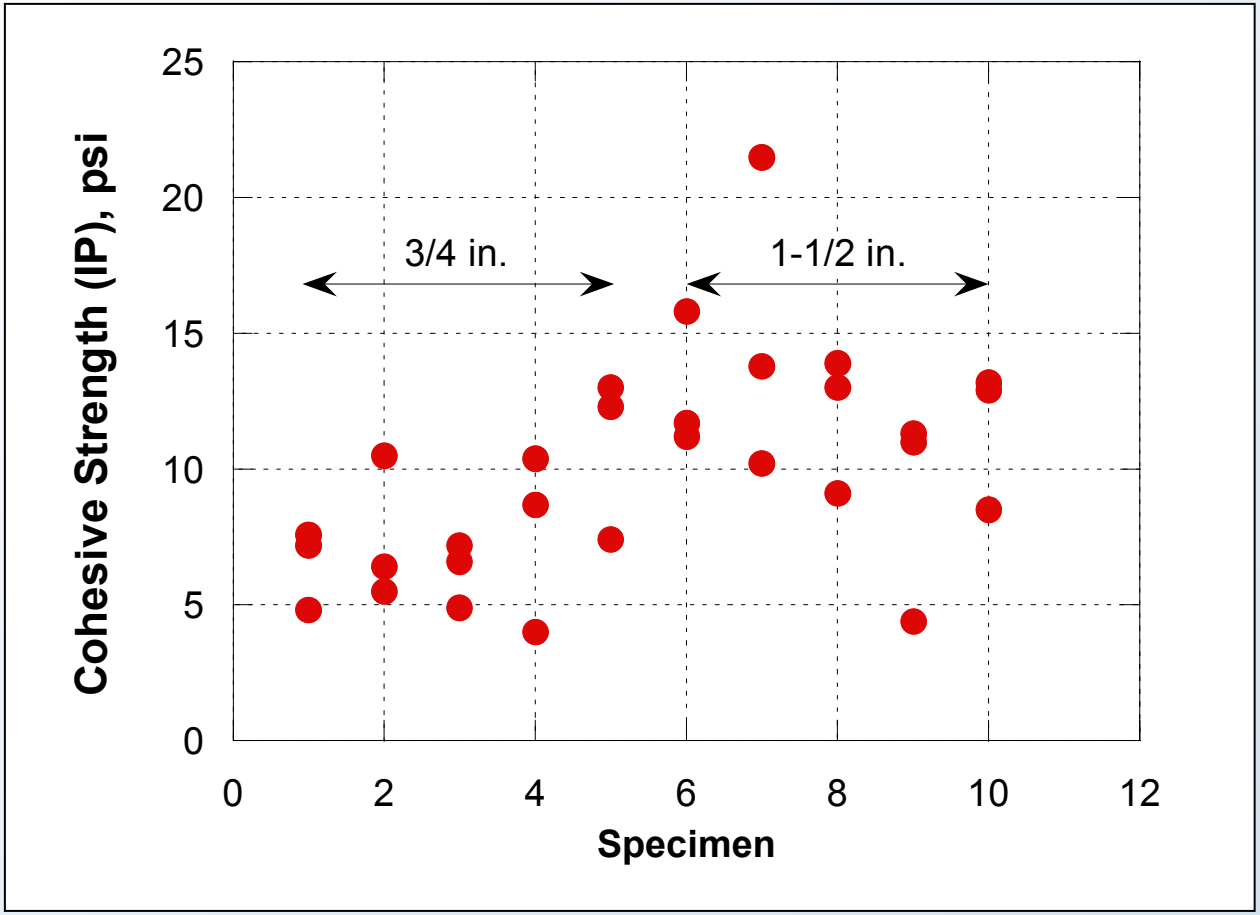
Comparison of Cohesive (N) and Adhesive Strength for Unprimed Steel

	Average	Stand. Dev.
¾ in. Cohesive	2.6 psi	0.4 psi
¾ in. Adhesive	3.1 psi	0.4 psi
1 ½ in. Cohesive	4.1 psi	1.1 psi
1 ½ in. Adhesive	4.6 psi	1.0 psi

2.8 psi
4.3 psi

No difference between adhesive and cohesive (N) strength ($p = 0.08$)

Laboratory Cohesive Strength Parallel to Surface



Laboratory Cohesive Strength Parallel to Surface

No reference values

Thickness*	Average	Stand. Dev.	CoV
¾ in.	7.8 psi	2.7 psi	0.35
1 ½ in.	12.1 psi	3.8 psi	0.31

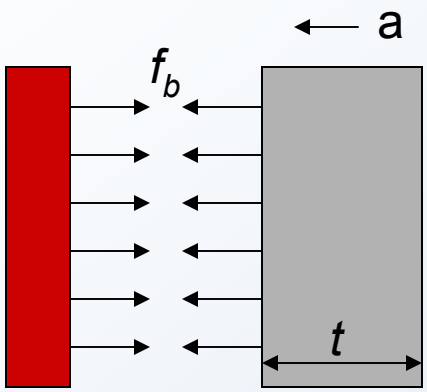
*Only specimens with primer

Impact Failure

- SFRM will dislodge when inertial tensile stresses exceed strength
- Planar elements
  - Controlled by adhesive or cohesive strength, whichever is smaller
- Bar
  - Controlled by cohesive strength parallel to surface

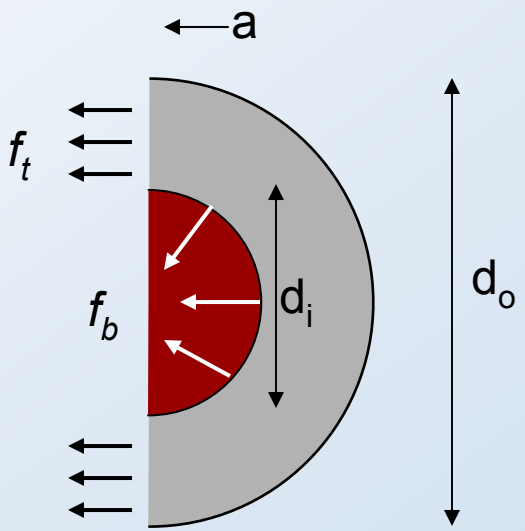
Simple Models

Planar Substrate



$$a = \frac{f_b}{\rho\, t}$$

Encased Bar

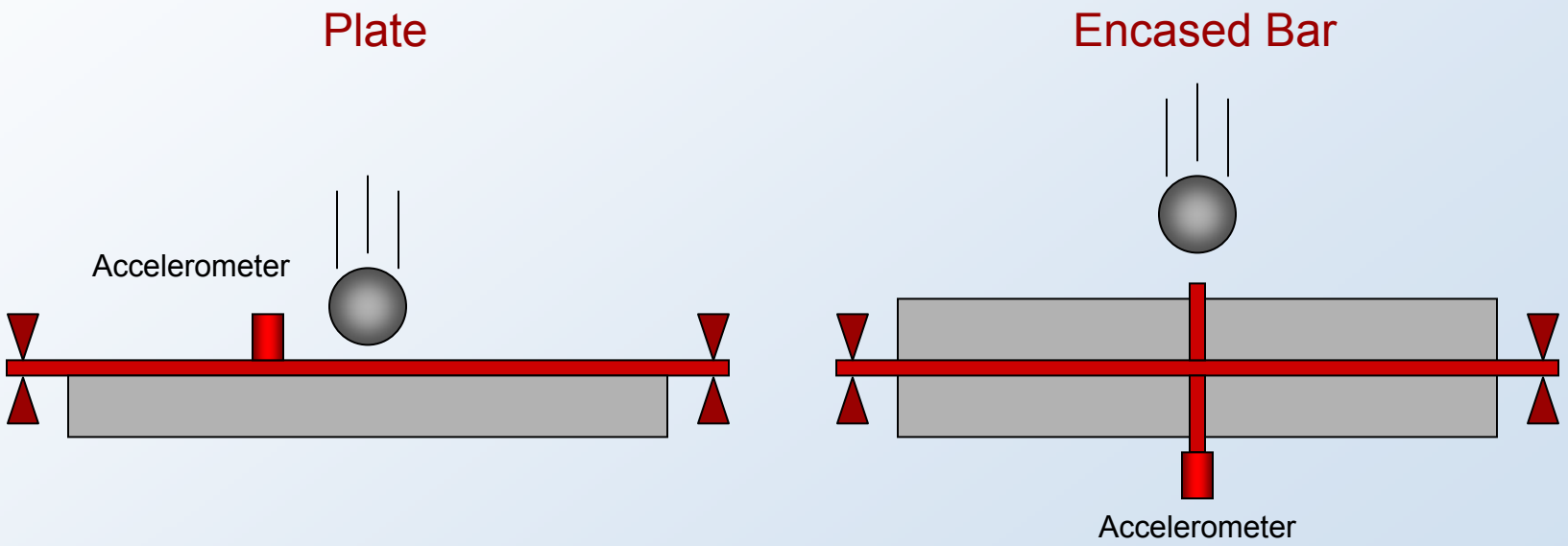


$$\alpha = \frac{f_b}{f_t}$$

$$a = \frac{4\, f_t (d_o + (\alpha - 1)\, d_i}{(d_o^2 - d_i^2)\, \rho\pi}$$

Impact Tests

- Determine acceleration to dislodge SFRM
- Correlate with static properties




CAUTION - DO NOT ENTER
Steel Plate
Dislodged SFRM

Summary

- In-place density for BZ DC/F in laboratory tests is higher than for BZ Type II from TAA reports
- Laboratory cohesive (N) strength for BZ DC/F is greater than in-place bond strength (ASTM E 736) for BZ Type II from TAA reports
- Laboratory static strength tests
  - Primer reduces adhesive strength, especially with thicker SFRM
  - In-plane cohesive strength greater than cohesive strength normal (N) to surface. *(Dislodgment from planar surfaces more likely than from encased bars.)*
  - For unprimed specimens, cohesive strength (N) is similar to adhesive strength.