Fracture Energy of GFRP-Concrete Bonded Interface after Sustained Loading in Natural Environments

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Durability of externally bonded FRP sheets: What do we know?

- Water
  - Plasticization
  - Hydrolysis
- Elevated temp. (not fire)
  - Post cure
  - Creep
- Freeze/thaw
  - Micro-cracking of concrete
- Ultraviolet
  - Post cure
  - Chain shortening

What about…

- *natural outdoor environment?*
- *sustained loading?*

Objective

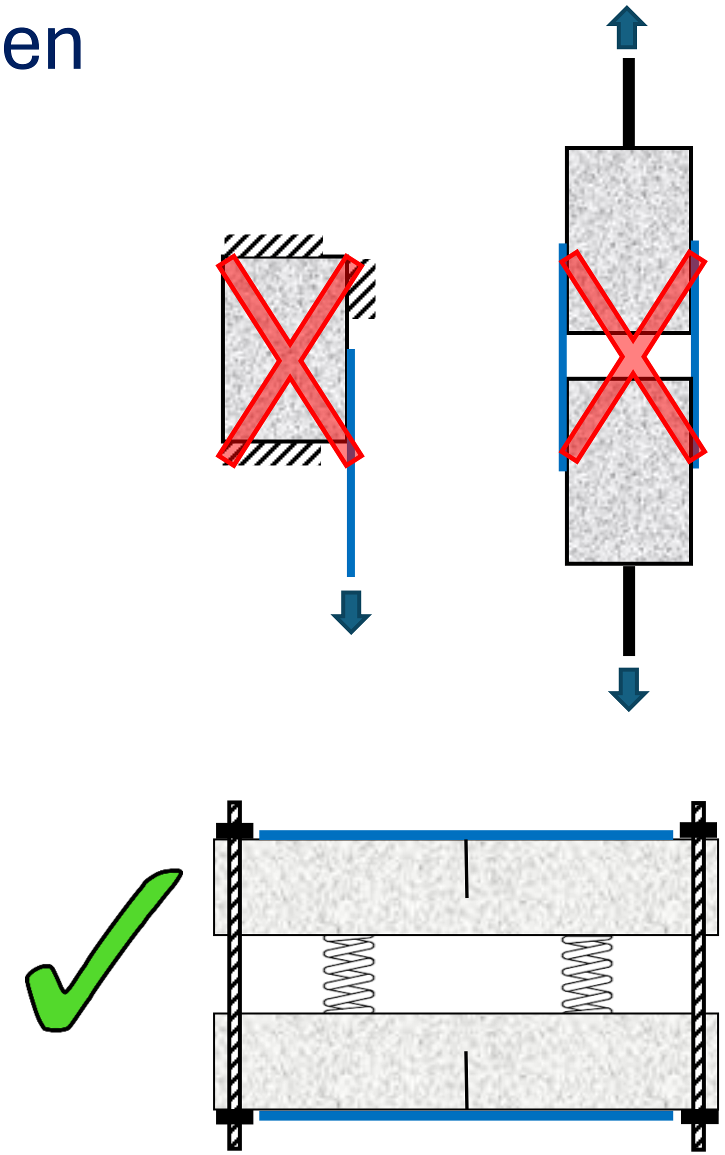
Evaluate effects of multi-year sustained loading and environmental exposure on Mode II interfacial fracture energy of GFRP/concrete bond

- Unconditioned beams: 0 time
- Conditioned beams: 6 and 13 years with sustained loading in indoor and outdoor environments

Selection of Bond Specimen

Simple FRP/concrete bond specimen that can be left unattended, **<u>under load</u>**, for many years

Aim to test specimens to failure at multi-year intervals



Materials

Glass fiber (uni-directional)

Aerial weight, g/m^2	900
Equivalent thickness, t_f, mm	0.353
Mean tensile modulus, E_f, MPa	72,400
Design[(a)] tensile strength, F_{fu}, MPa	1,520
Design[(a)] rupture strain, ε_{fu}, %	2.10

[(a)] Mean minus 3 standard deviations

Concrete

28-Day Target Strengths: 21, 41 MPa

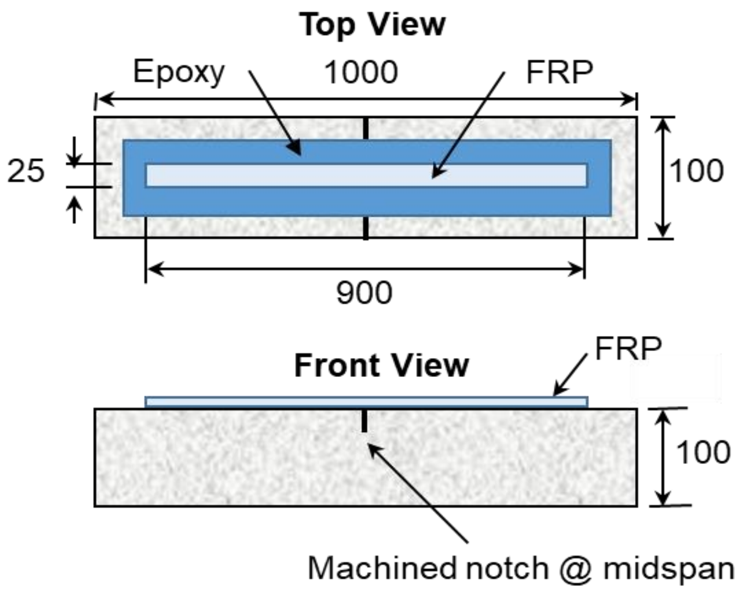
Course & fine aggregates

No air entrainment admixture

Epoxy

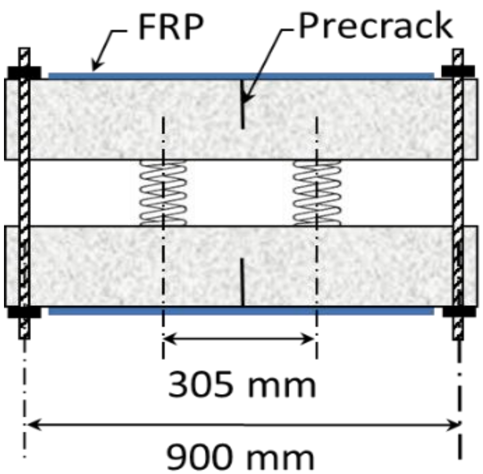
	Primer	Putty	Saturant
Mean tensile modulus, E_m, MPa	720	1,800	3,000
Mean tensile strength, F_m, MPa	17	15	55

FRP Strengthened Prisms



- Designed to fail by debonding
- A 6-mm-deep starter notch was saw-cut
- The notch was filled with foam
- The soffit was ground and cleaned
- Over a 3-day period:
  2 coats of primer
  2 coats of putty
  1st coat of saturant
  1 layer of dry unidirectional fibers
  2nd coat of saturant
  (No UV protection)
- Notch extended to a "pre-crack" by 3-pt. bending

Sustained Loading



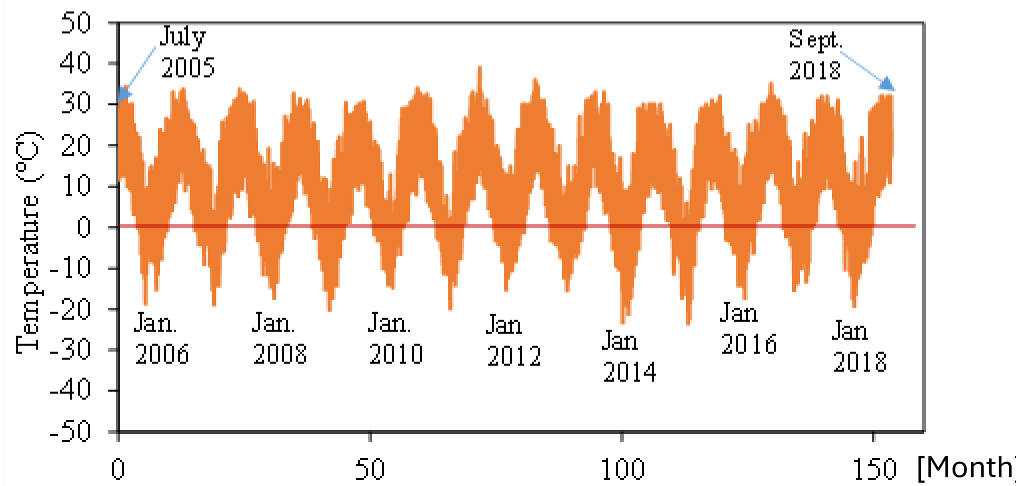
- Beams placed in 4-pt bending rigs with springs
- Sustained fiber strain ~ 13% of the guaranteed rupture strain (2730 μm/m)

Indoor condition (21-23°C)

Outdoor condition (during winter)

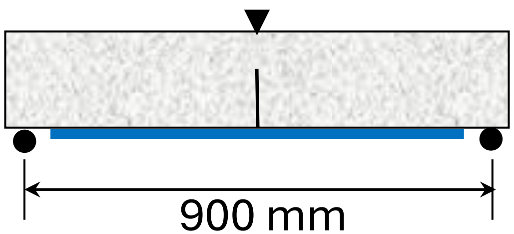
Outdoor condition (during summer)

Outdoor Weather in Central Pennyslvania



- "Warm-summer humid continental" climate -- Group Dfb according to the Köppen-Gieger climate classification system
- ~65 freeze/thaw cycles per year (~840 over 13 years)

Bond Testing and Concrete Testing After Bond Testing

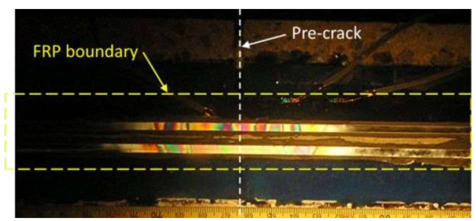


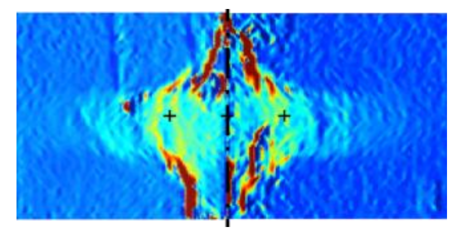
3-point bend test

- Servo-hydraulic or screw-driven load frame in stroke control

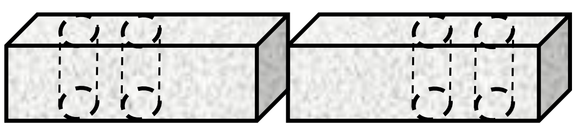
Strain measurement on GFRP

- Photoelastic coatings (0 yr)
- Digital image correlation (6, 13 yrs)





- 3 resistance strain gages near notch



Concrete compression strength test after removal of GFRP

- Three or four 70×112 mm cylinders

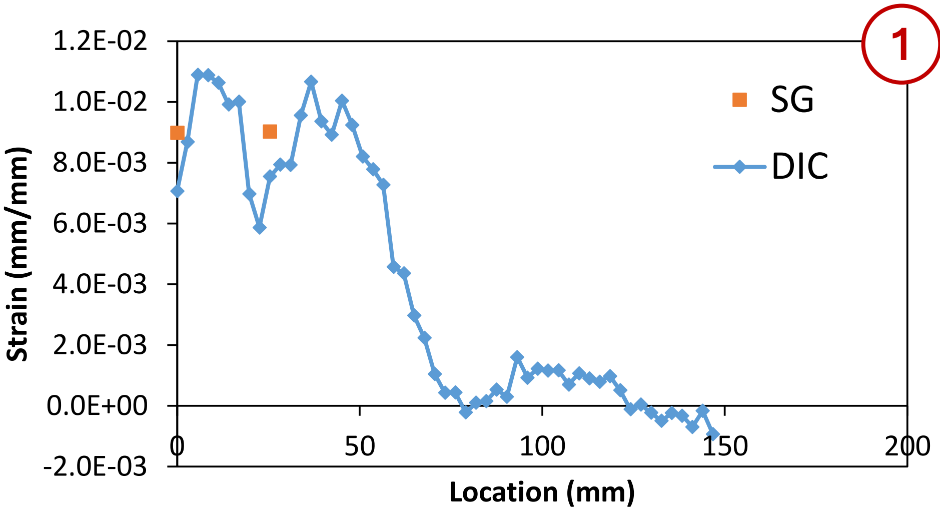
Typical Failure Mode

Debonding, followed by GFRP rupture @ notch or secondary crack

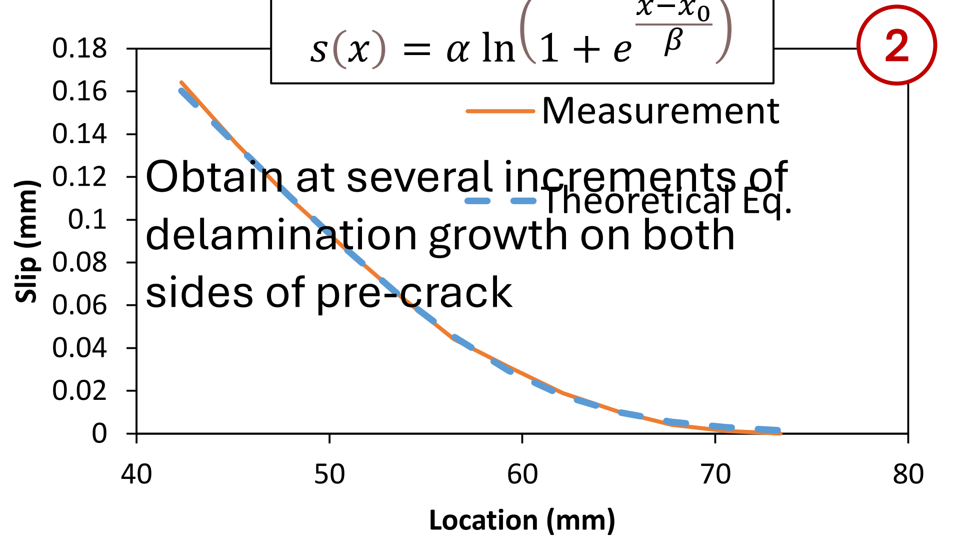
Mix of adhesive failure and concrete-cohesive failure

Note: In this paper, our focus is on the onset and early part of bebonding process

Fracture Energy Measurement Method

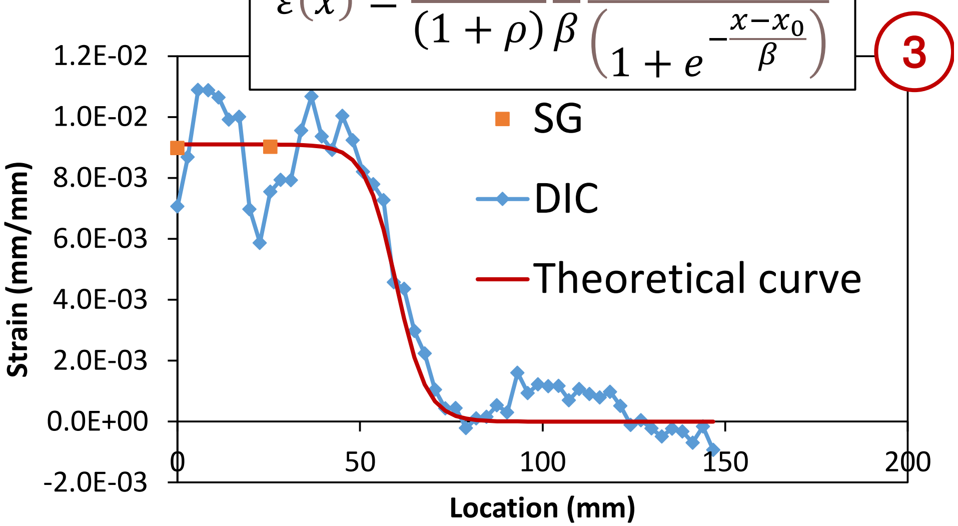


$$s(x) = \alpha \ln\left(1 + e^{\frac{x - x_0}{\beta}}\right)$$

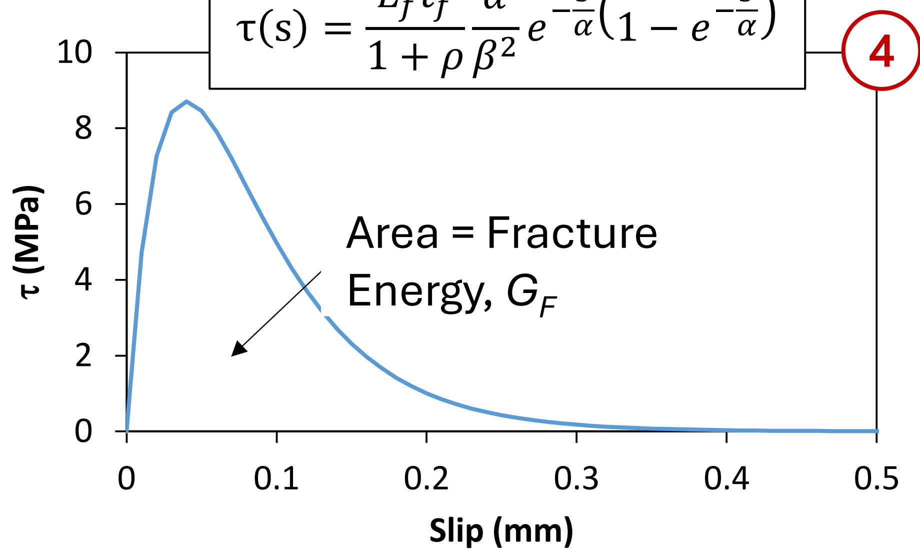


Obtain at several increments of delamination growth on both sides of pre-crack

$$\varepsilon(x) = \frac{1}{(1+\rho)} \frac{\alpha}{\beta} \frac{1}{\left(1 + e^{-\frac{x - x_0}{\beta}}\right)}$$

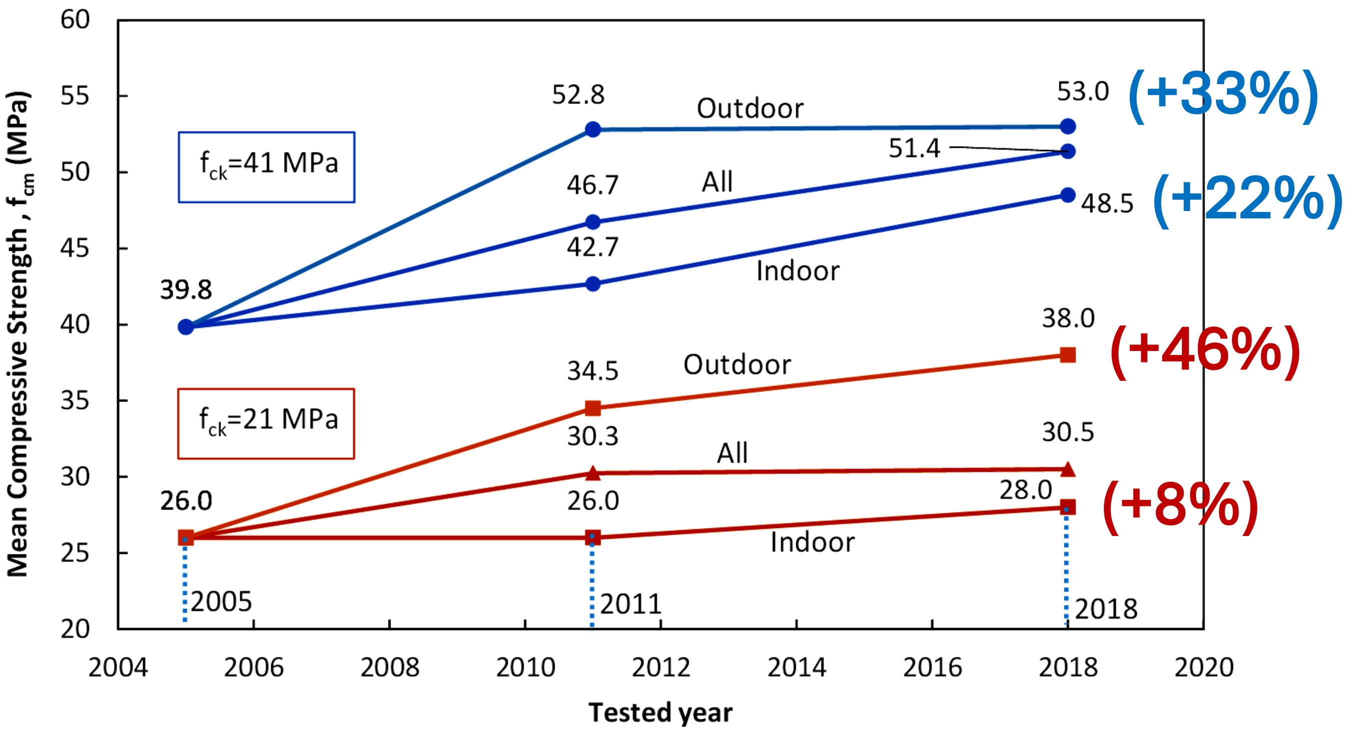


$$\tau(s) = \frac{E_f t_f}{1 + \rho} \frac{\alpha}{\beta^2} e^{-\frac{s}{\alpha}}\left(1 - e^{-\frac{s}{\alpha}}\right)$$



Zhou Y., Wu Y., and Yun, Y. (2010). Analytical modeling of the bond-slip relationship at FRP-concrete interfaces for adhesively-bonded joints, *Composites: Part B*, **41**(6), 423-433.

Results of Concrete Cylinder Testing



Outdoor beams exposed to more moisture

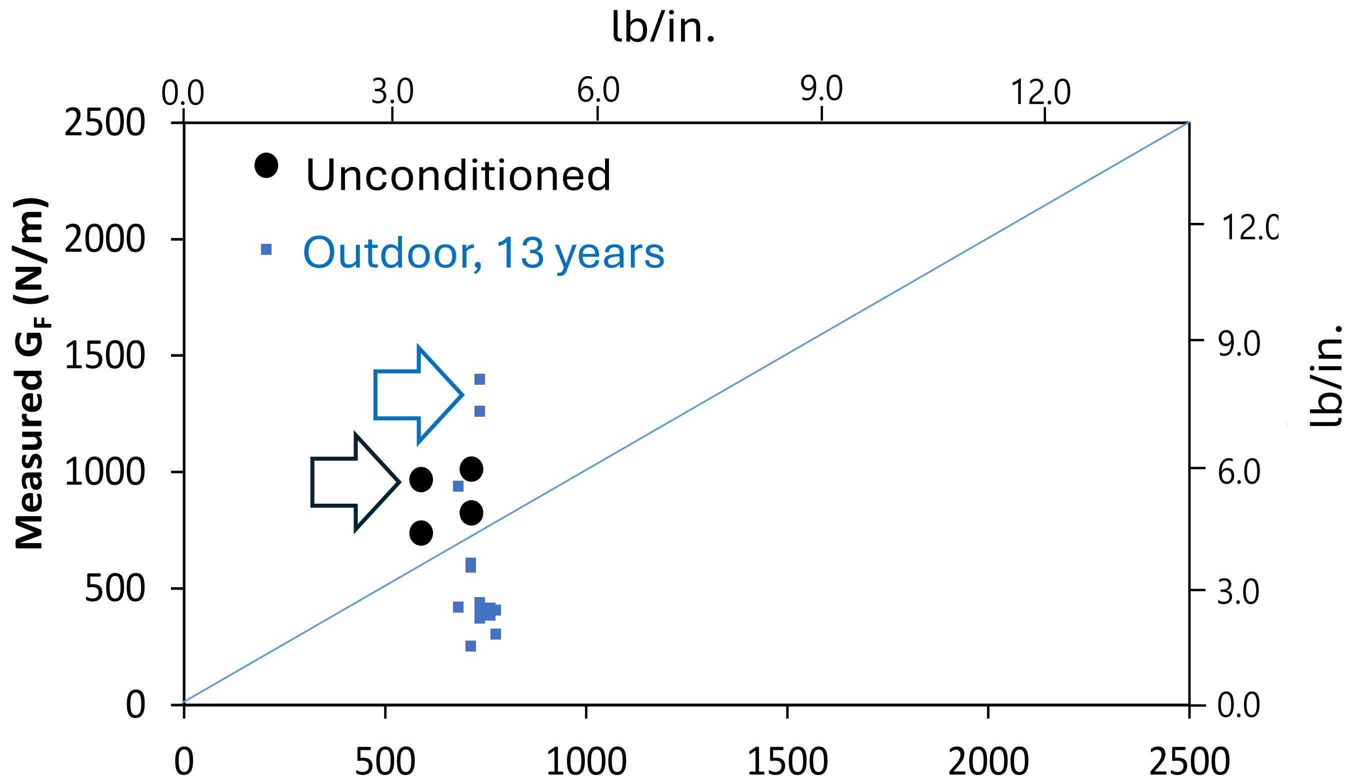
We can account for change in concrete strength using eqn. for G_f by Lu et al. (2005)

$$G_F = 0.308\left(\frac{2.25 - b_f/b_c}{1.25 - b_f/b_c}\right)\sqrt{f_t}$$

- f_t is concrete tensile strength at the time of beam testing [MPa]
- b_c & b_f are widths of concrete & FRP [mm]

Lu, X. Z., Teng, J. G., Ye, L. P. and Jiang, J. J. (2005). Bond–slip models for FRP sheets/plates bonded to concrete, Engineering Structures, 27(6), 920-937.

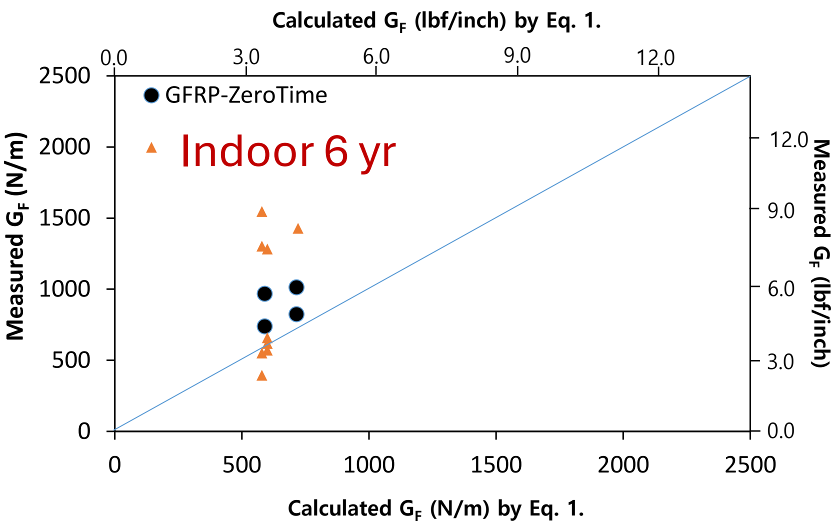
Measured G_F vs. calculated fracture energy according to Lu et al. 2005

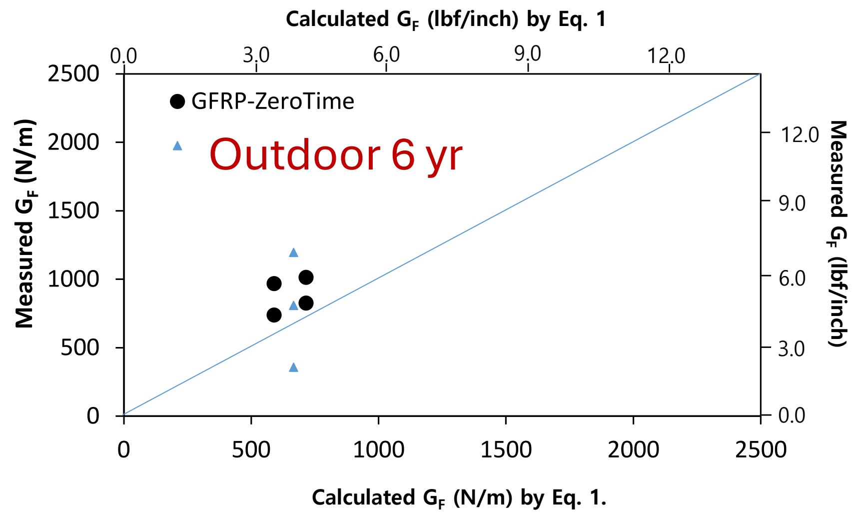


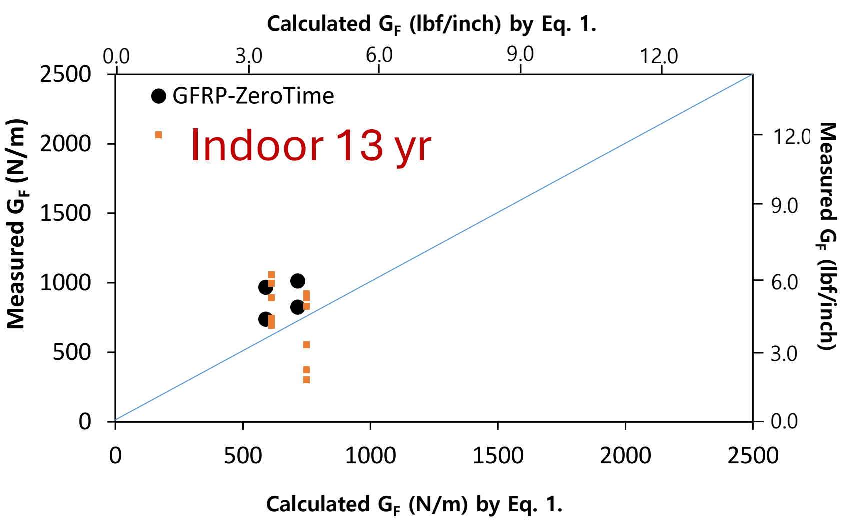
Calculated G_f (N/m) using $G_F = 0.308\left(\frac{2.25 - b_f/b_c}{1.25 - b_f/b_c}\right)\sqrt{f_t}$

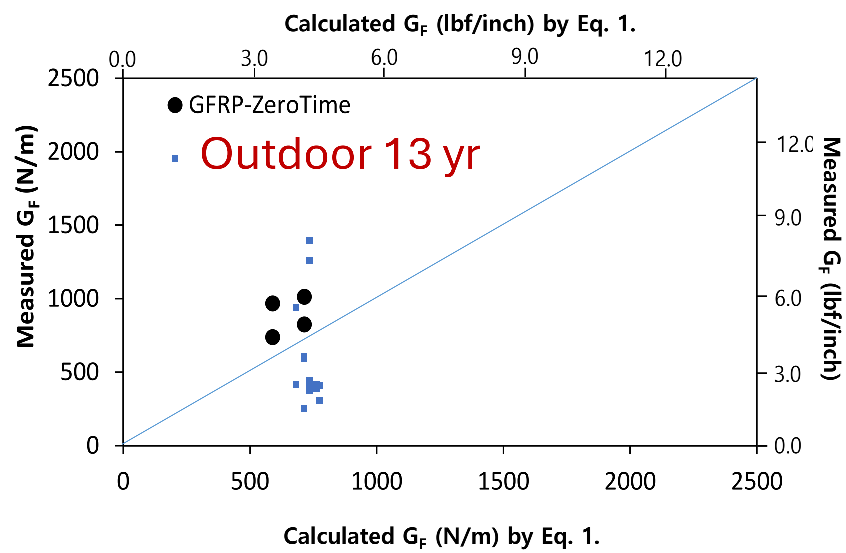
- **Unconditioned:** measured G_F > calculated G_F because Lu eqn. was calibrated with single lap shear data
- **Outdoor, 13 Years:** additional variation in measured G_F attributed to sustained load/environment and variable locations where G_F measured

Measured G_F vs. G_F-Lu $\left(G_F = 0.308\left(\frac{2.25 - b_f/b_c}{1.25 - b_f/b_c}\right)\sqrt{f_t}\right)$



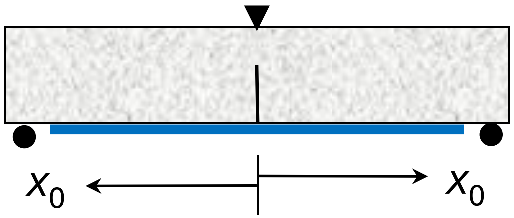






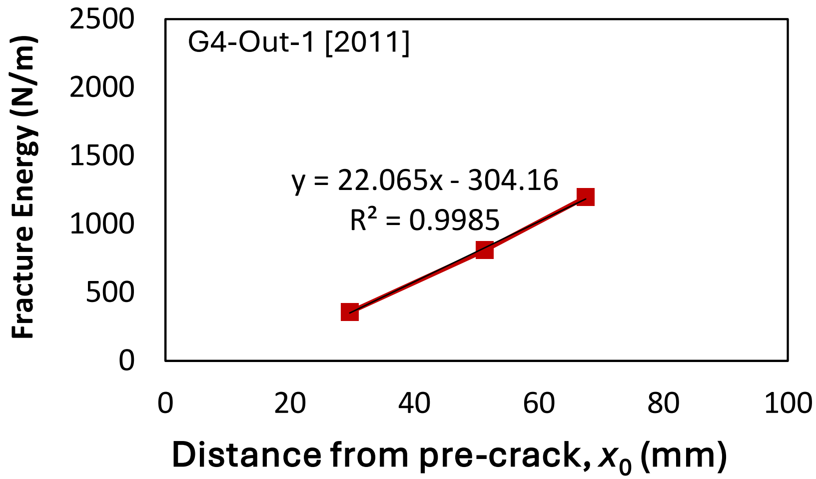
Same observation: several factors affect measured G_F -- concrete strength, environment, sustained loading, and position where G_F measured

Variation of experimental G_F with distance from pre-crack

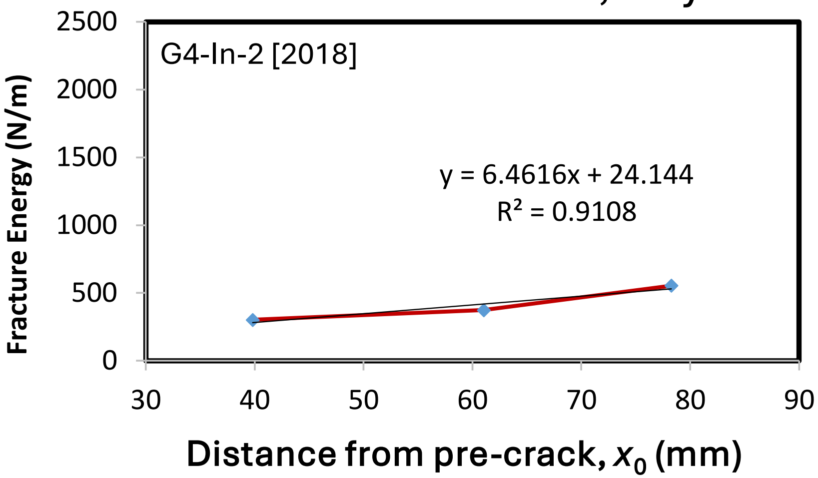


x_0 = location of max. local bond stress

40 GPa concrete, Outdoor, 5 years



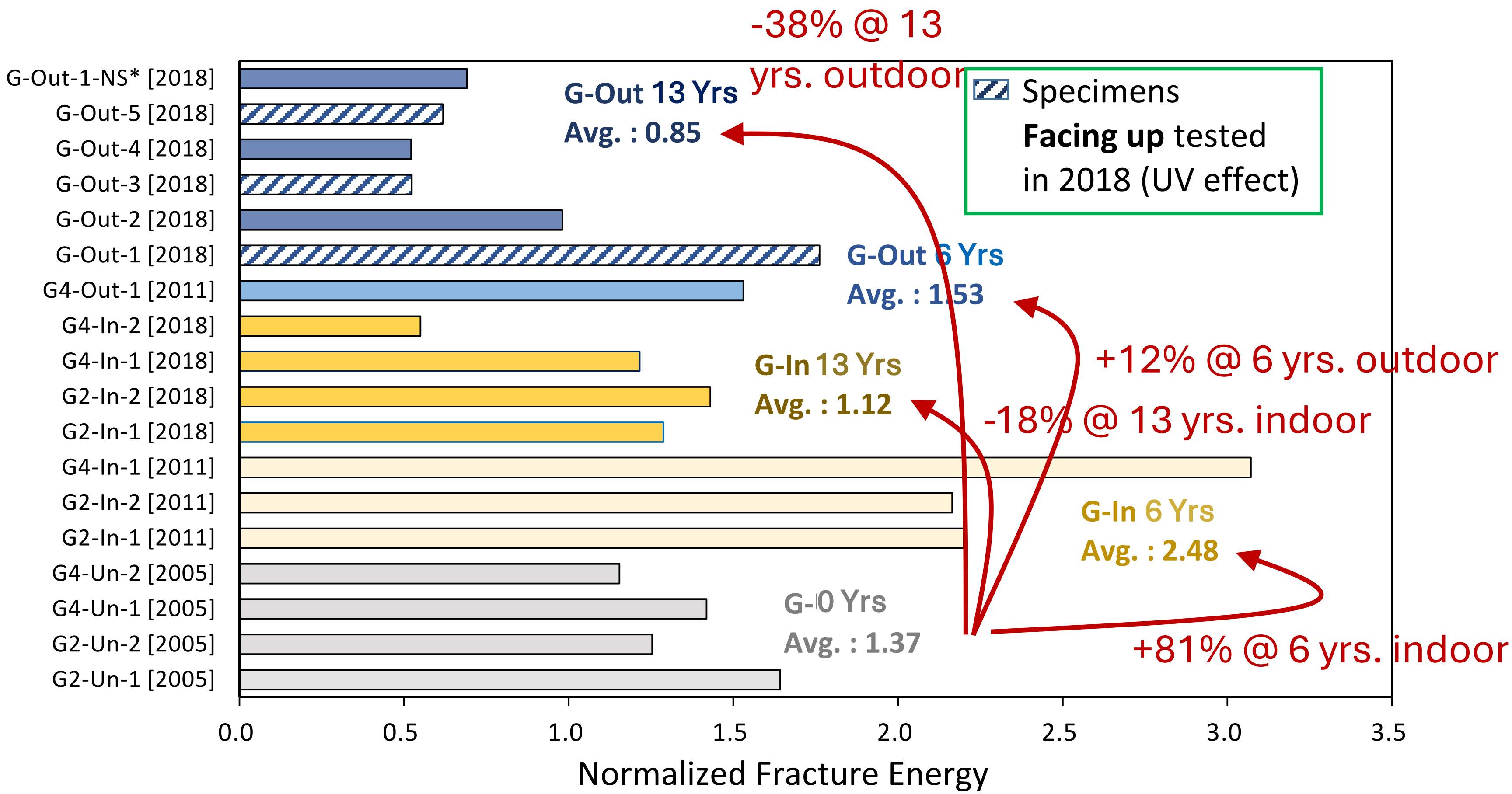
40 GPa concrete, Indoor, 13 years



- G_F increases with distance from pre-crack
  - Sustained bond stress near pre-crack decreases G_F?
  - Additional dissipative mechanisms increase G_F as de-bonded region grows?
- Subsequent analysis of fracture energy:
  - Determine G_F at x_0 = 60 mm from pre-crack, using interpolation
  - Divide by G_F by G_F-Lu (2005) to minimize effect of concrete strength

Normalized G_F 60 mm from pre-crack

$$G_F / \left(0.308 \left(\frac{2.25 - b_f/b_c}{1.25 - b_f/b_c} \right) \sqrt{f_t} \right)$$

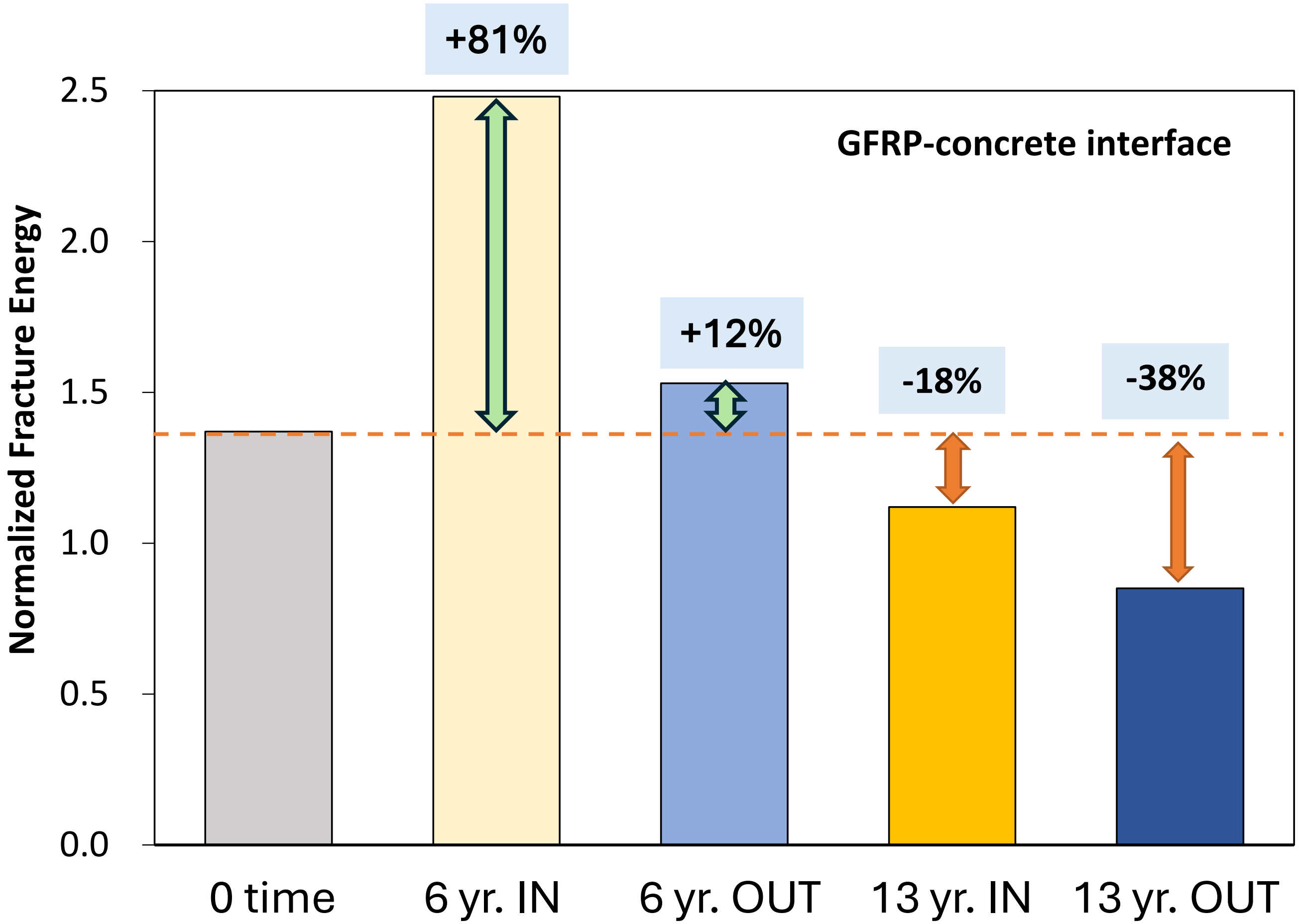


**G-Out-1-NS [2018] is a GFRP specimenthat was outdoors for 13 years without sustained load*

- No obvious effect of direct/indirect UV exposure (limited data)
- Normalized G_F increased @ 6 years and decreased @ 13 years

Normalized G_F 60 mm from pre-crack: Summary

$$G_F / \left(0.308 \left(\frac{2.25 - b_f/b_c}{1.25 - b_f/b_c} \right) \sqrt{f_t} \right)$$



Conclusions

- Compared to 0-time beams, the 6-year beams exhibited an increase in normalized fracture energy
  - More for indoor (+81%) than outdoor (+12%)
  - This is believed to be due to beneficial stress redistribution within the bond transfer zone

- Compared to 0-time beams, the 13-year beams exhibited a decrease in normalized fracture energy
  - More for outdoor (-38%) than indoor (18%)
  - This is believed to be due to interfacial weakening at the GFRP/concrete interface

- No evidence of ultraviolet degradation even though no UV protection used

Caveats: these conclusions are limited to the materials, specimen preparation methods, sustained exposure conditions, and bond test method used in this investigation

For more detailed information about this work:

- Lee, J., Kim, J., Bakis, C. E., & Boothby, T. E. (2021). Durability assessment of FRP-concrete bond after sustained load for up to thirteen years. *Composites Part B: Engineering*, **224**, 109180.
- Lee, J., Artun, K., Bakis, C. E., Lopez, M. M., & Boothby, T. E. (2023). Changes in fracture energy at FRP-concrete interfaces following indoor and outdoor exposure with sustained loading. *Construction and Building Materials*, **392**, 131905.

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