# Infrastructure Rehabilitation with Innovative Fiber Reinforced Polymer Composites

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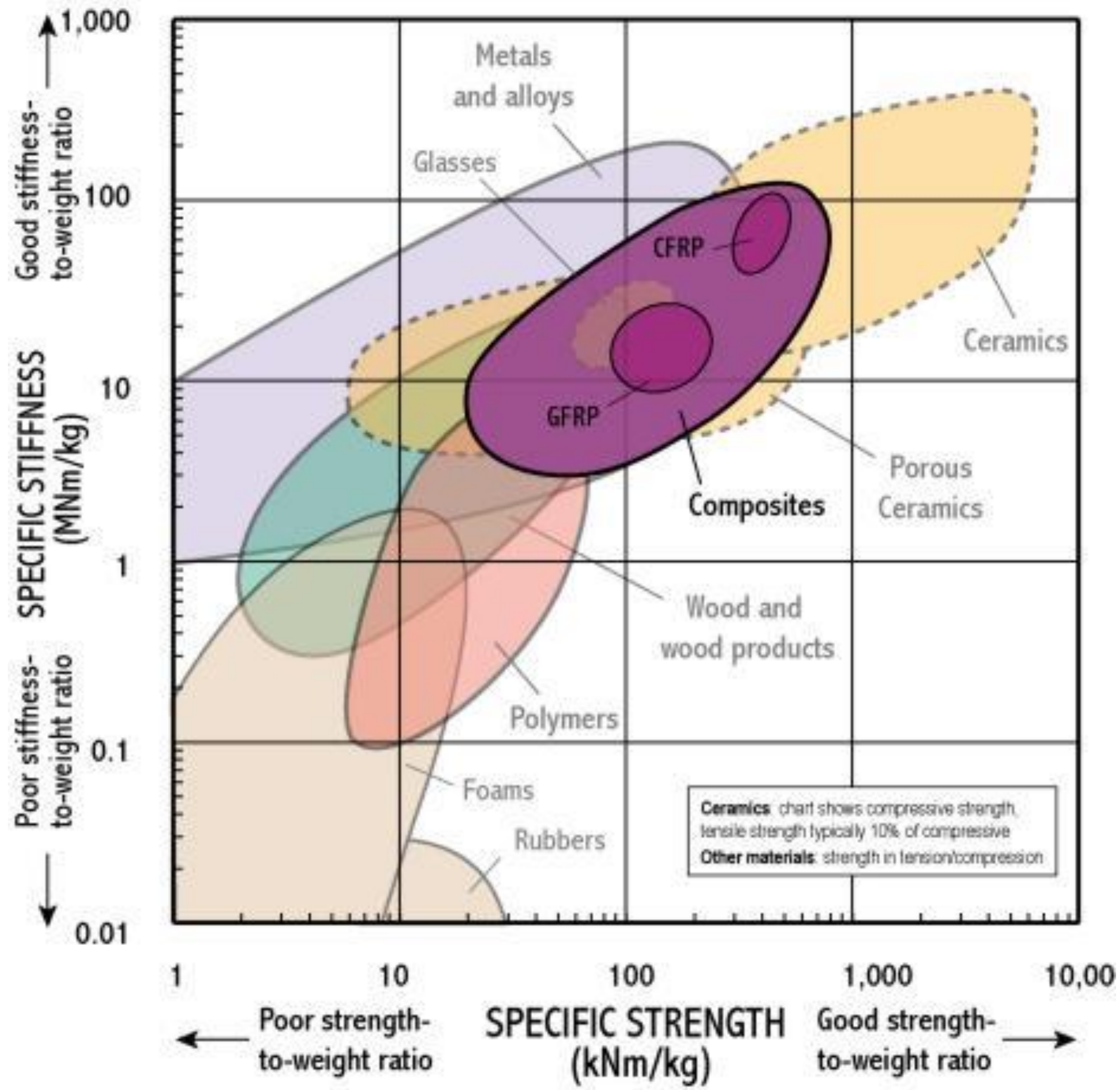
**March 15, 2022**

# Motivation


Resilience

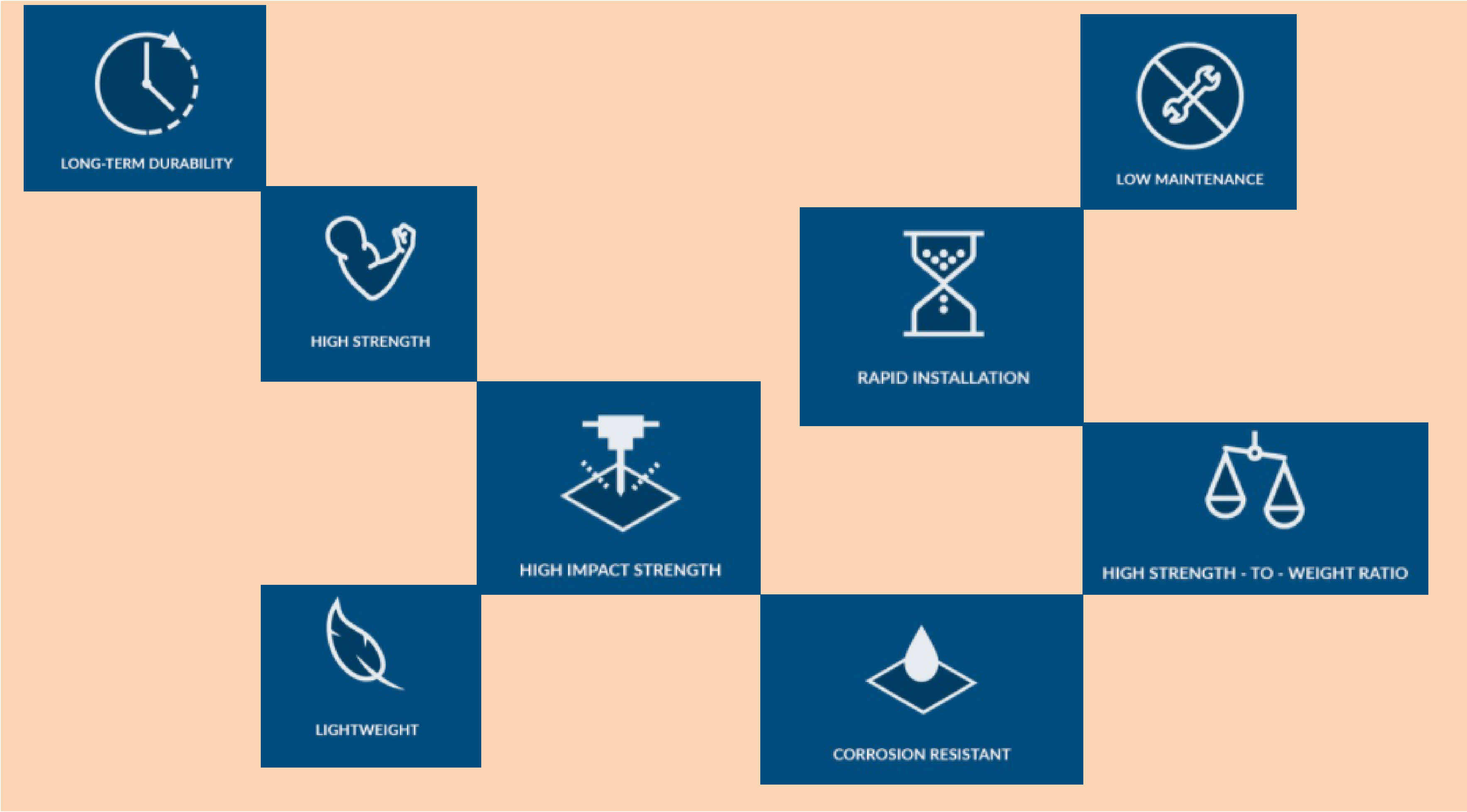
We must utilize new approaches, materials, and technologies to ensure our infrastructure can withstand or quickly recover from natural or man-made hazards.

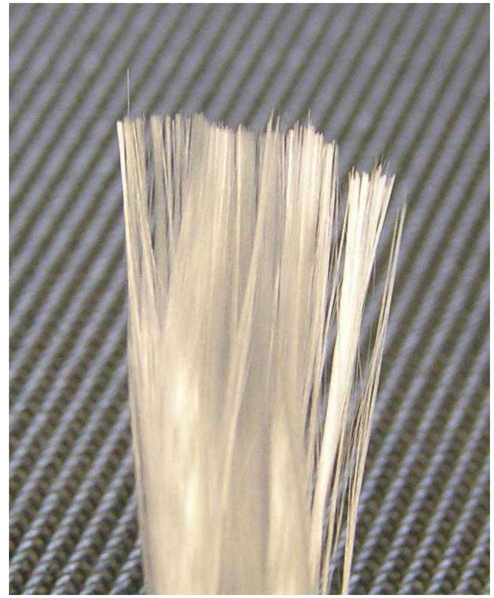
**Surfside, Miami, Florida. June 28, 2021**




Source: Internet

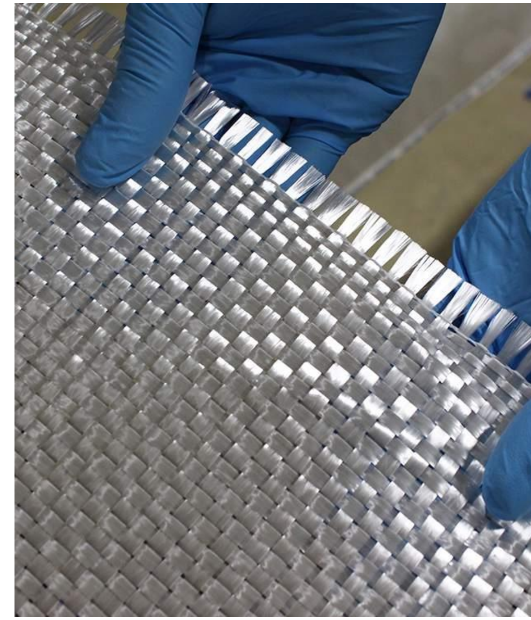
# Fiber Reinforced Polymer (FRP) Composites





Fiberglass drawing

Woven fiber glass textile

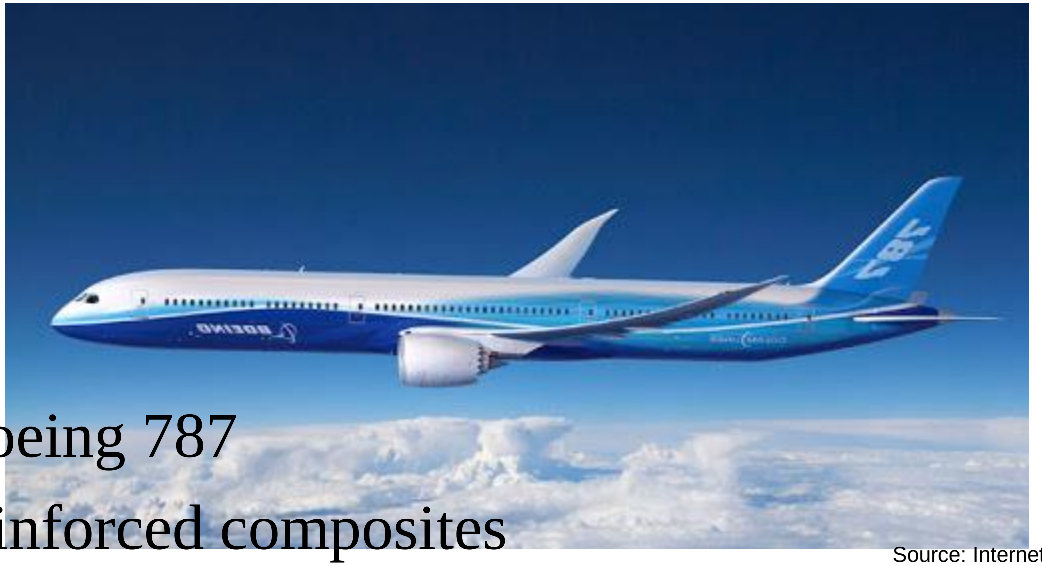



Rovings

Source: Internet


Airbus A350

53% fiber reinforced composites

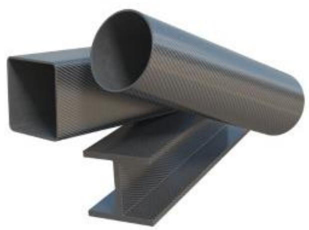


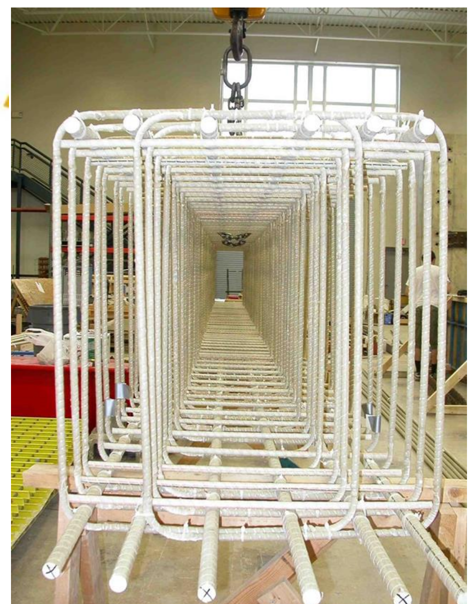

Boeing 787

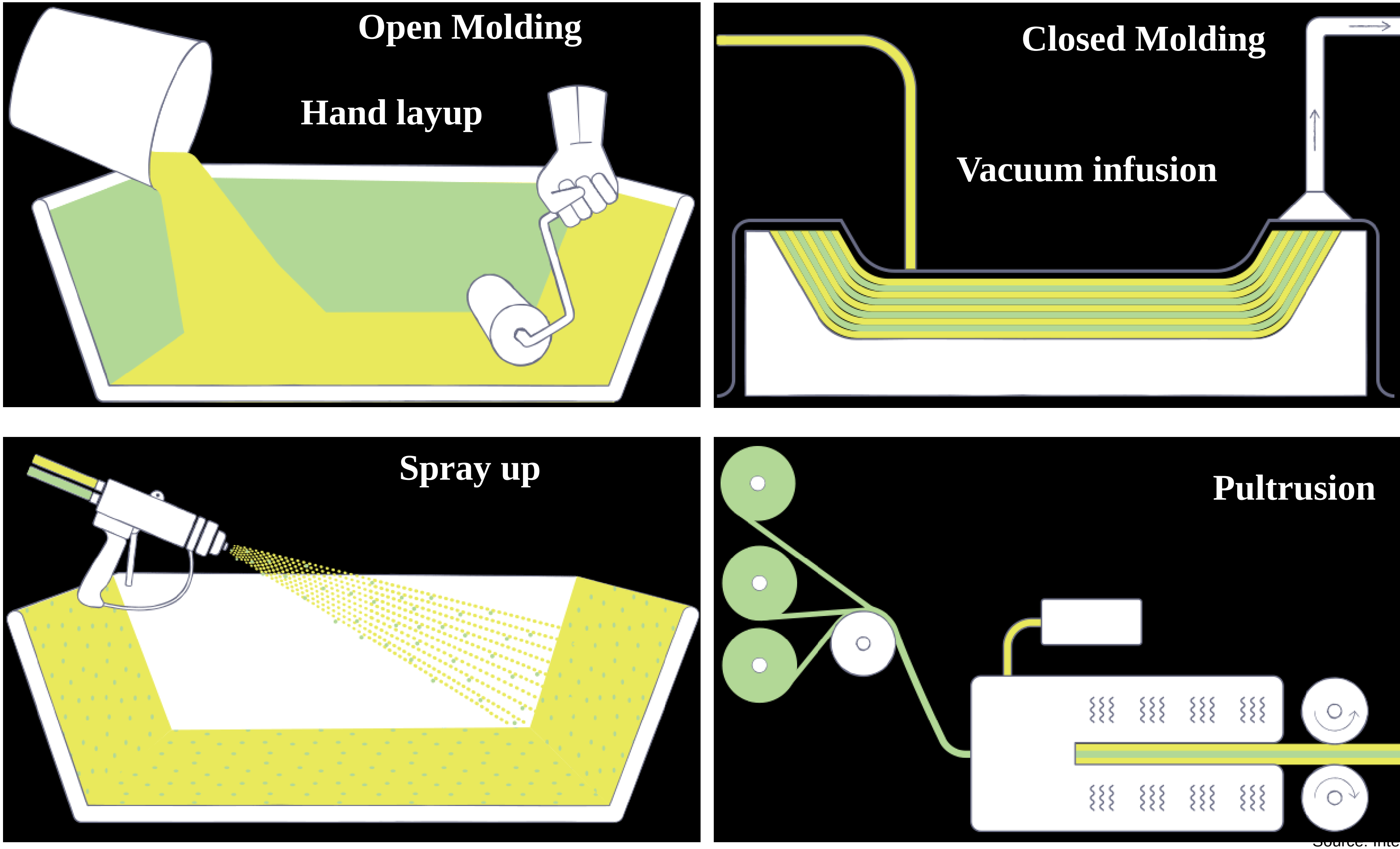
50% fiber reinforced composites

Source: Internet

# Fiber Reinforced Polymer (FRP) Composites








Source: Internet

# Aberfeldy Footbridge - World's first major advanced composite footbridge

Source: Internet

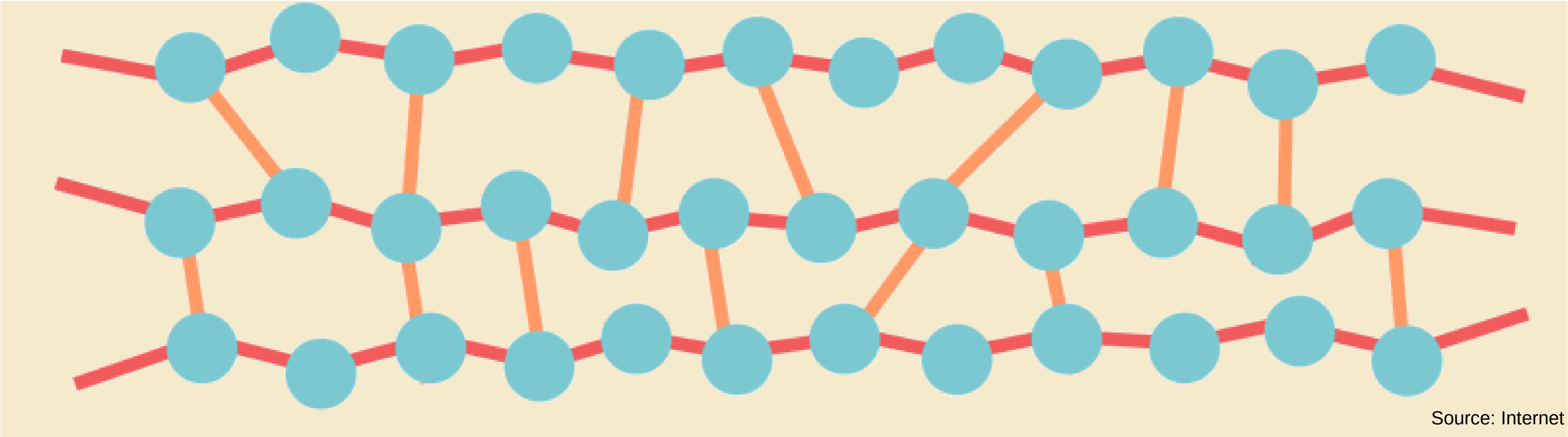
## Kentucky Footbridge

Source: Internet

FRP Pedestrian Bridge in Virginia

Source: Internet

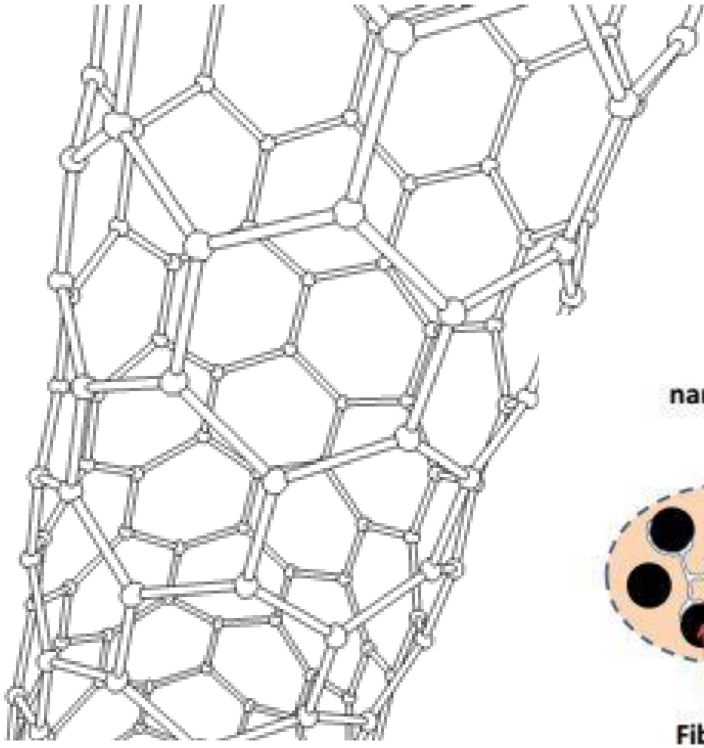
# Nanomodified Resins for FRP Enhancement

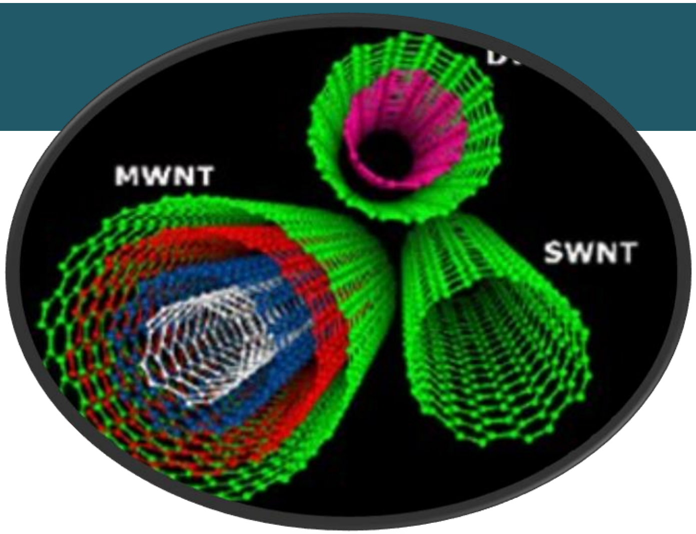


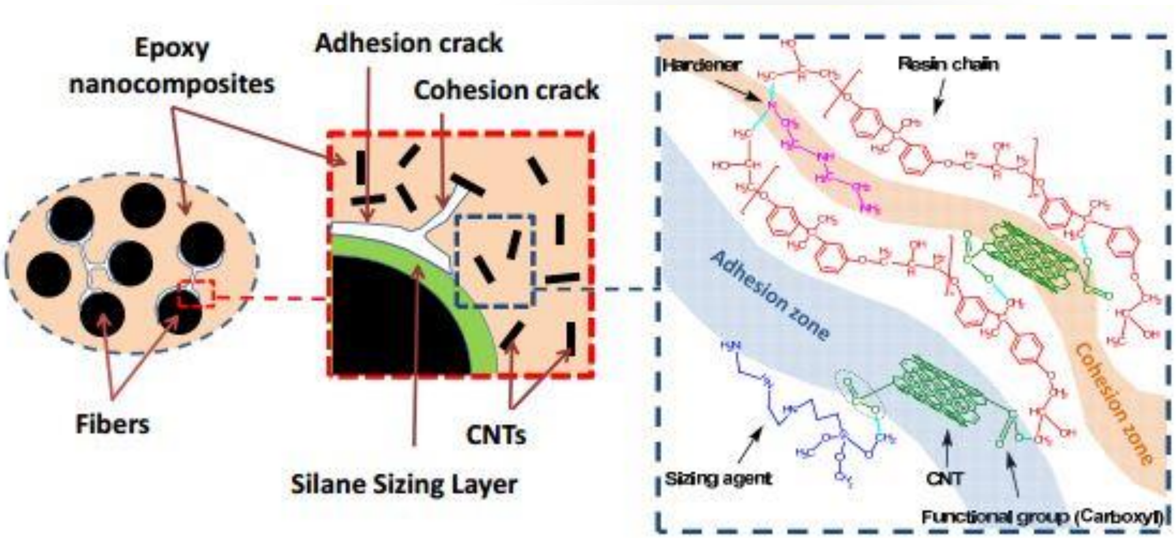

| Resin types |
| --- |
| Polyester |
| Epoxy |
| Vinyl Ester |
| Phenolic |
| Polyurethane |

| Fiber types |
| --- |
| Glass Fibers |
| Carbon Fibers |
| Aramid Fibers (Kevlar) |
| Basalt Fibers |

# Carbon Nanotubes

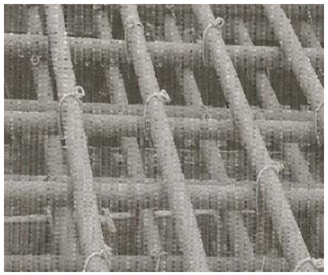


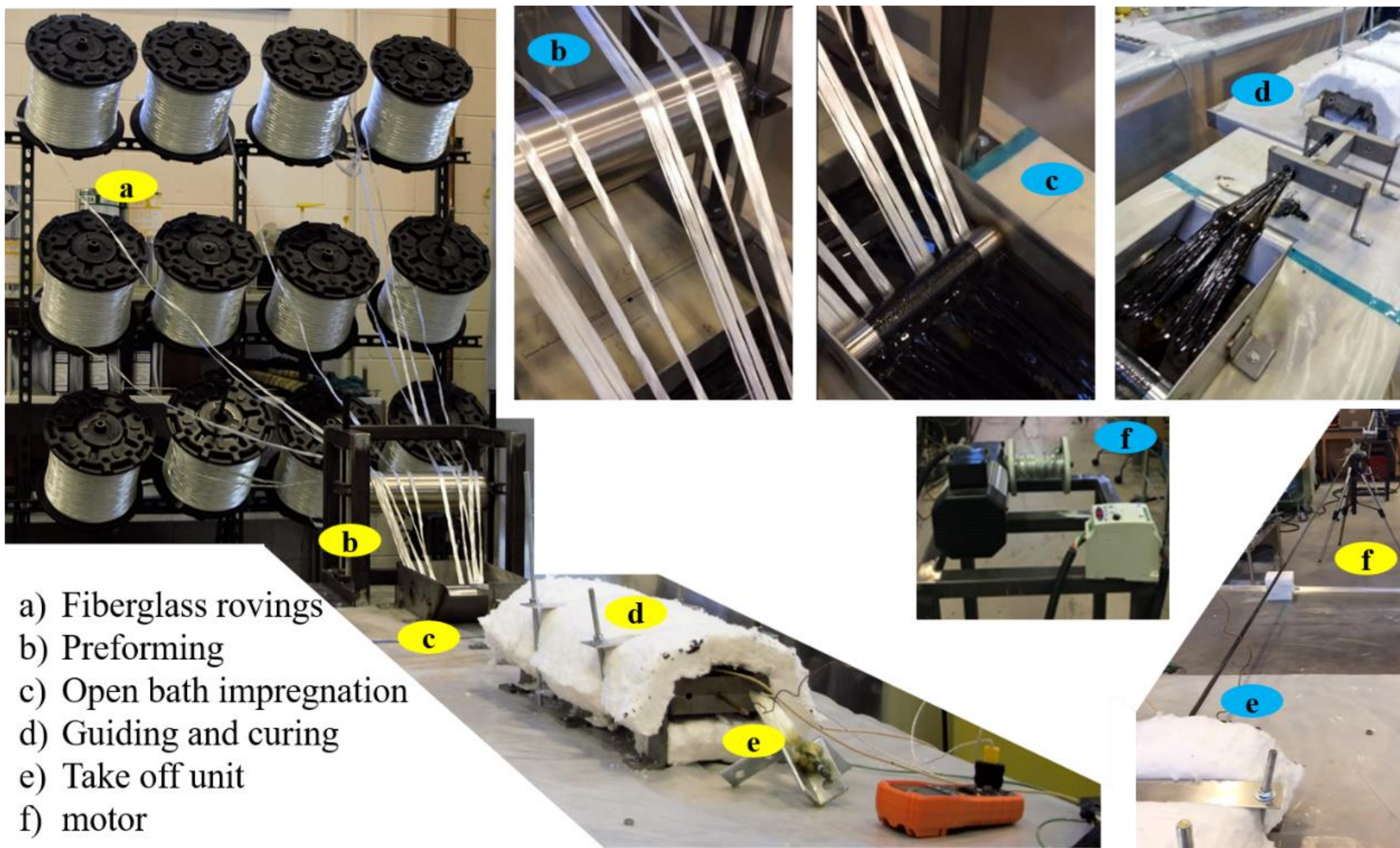



Genedy, M., Daghash, S., Soliman, E., & Taha, M. M. R. (2015). Improving fatigue performance of GFRP composite using carbon nanotubes. *Fibers*, *3*(1), 13-29.

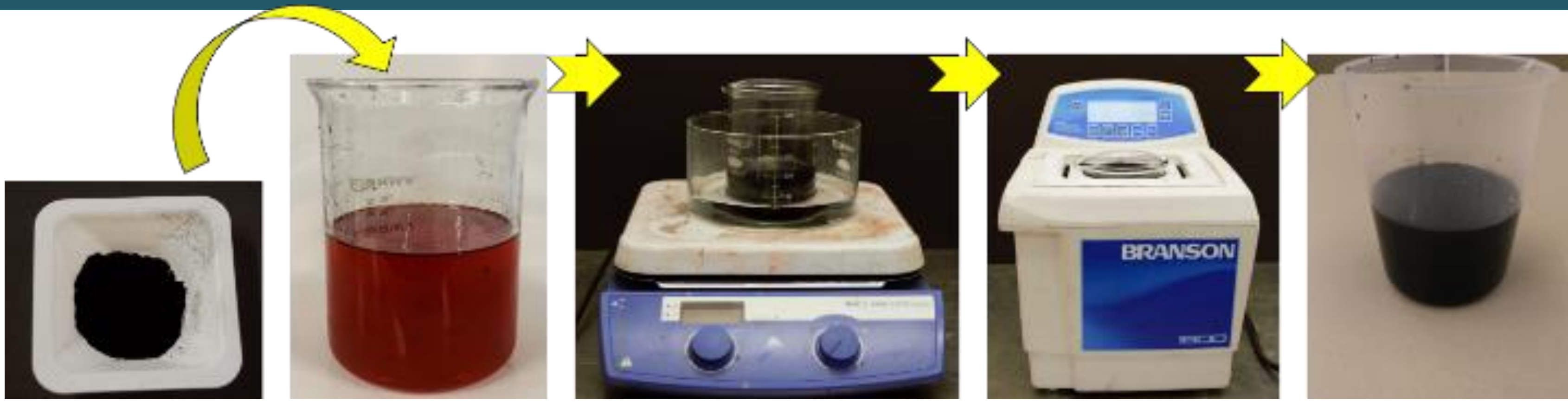
# Carbon Nanotubes in FRP Pultrusion

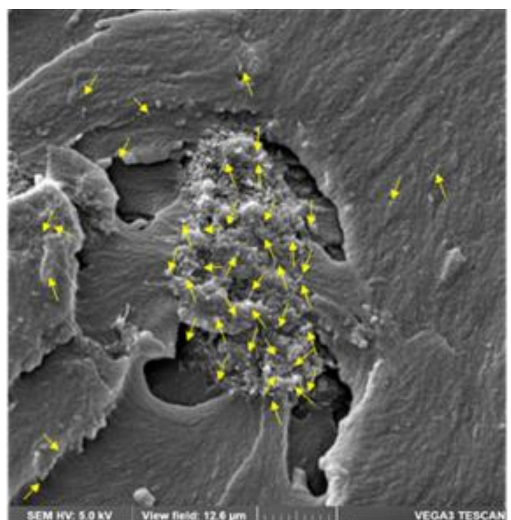





***Vemuganti, S., Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710.***

# Carbon Nanotubes in FRP Pultrusion



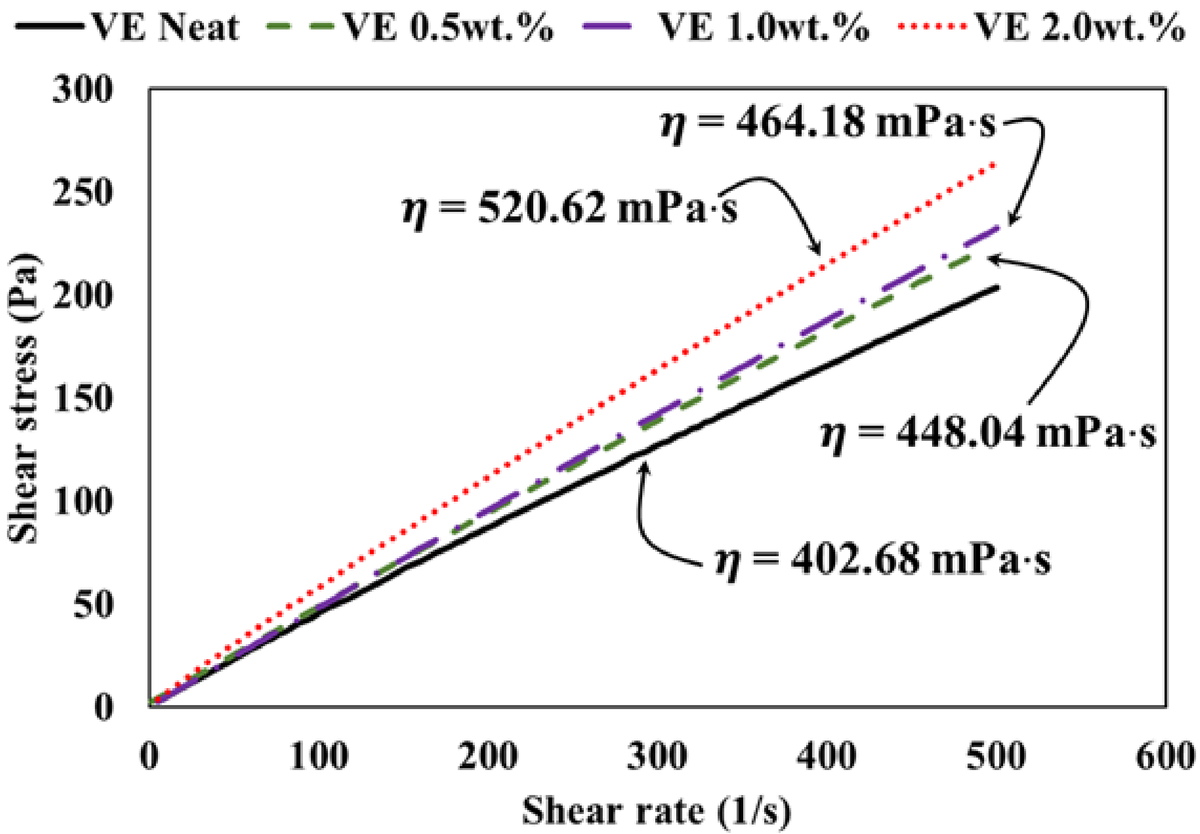




SEM

*Vemuganti, S., Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710.*

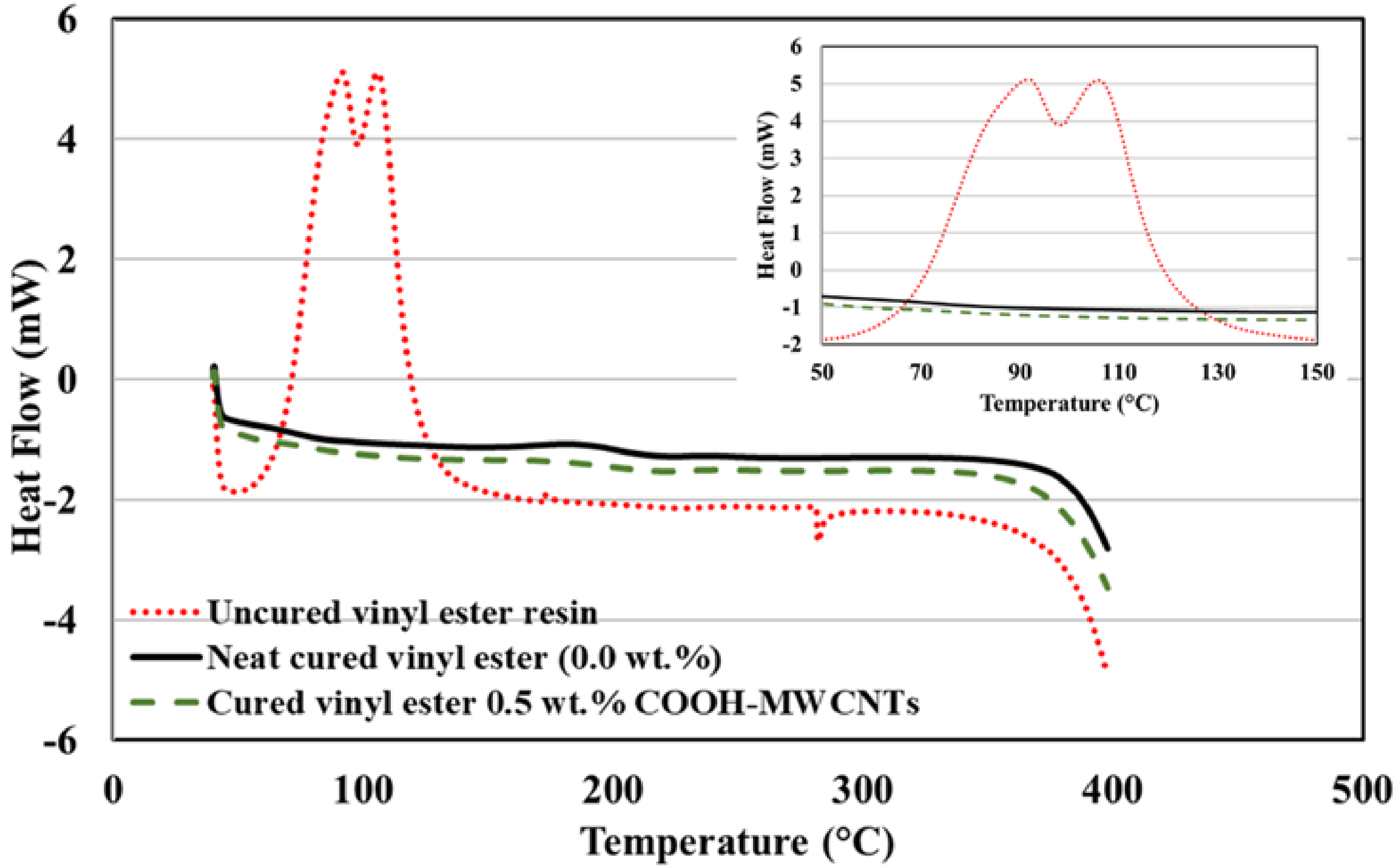
# Carbon Nanotubes in FRP Pultrusion

## Rheological Studies



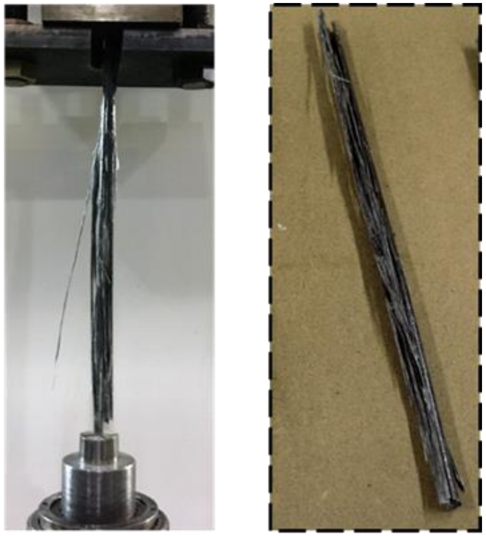

*Vemuganti, S., Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710.*

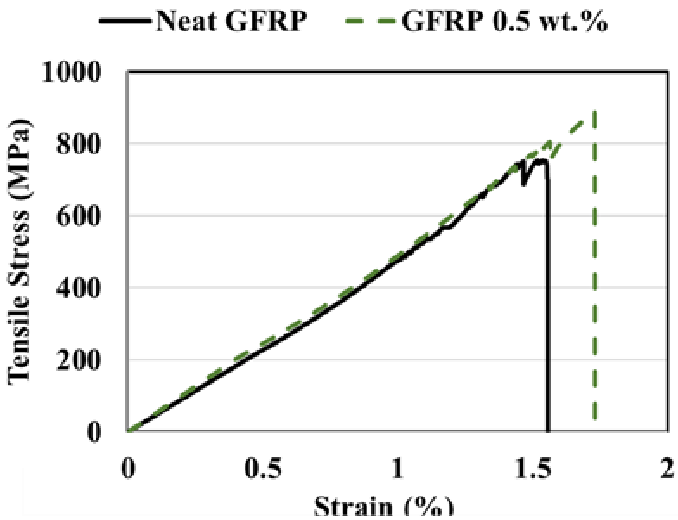
# Carbon Nanotubes in FRP Pultrusion

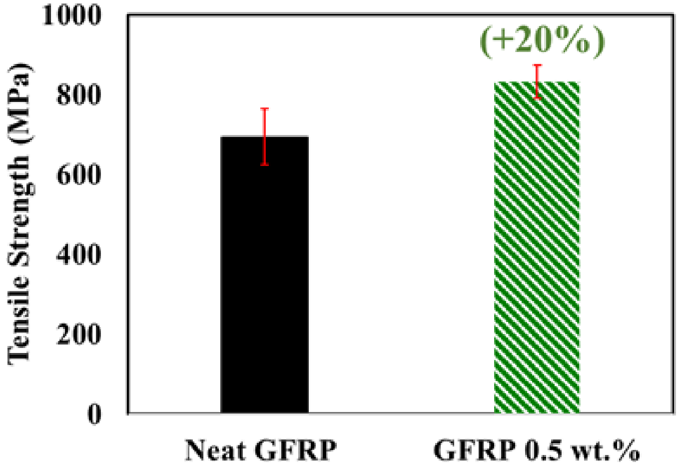



*Vemuganti, S., Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710.*

# Improving mechanical properties of pultruded FRP

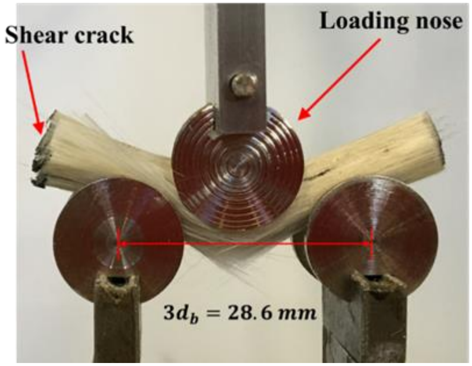


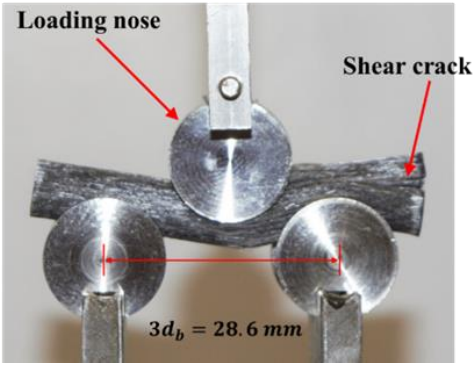


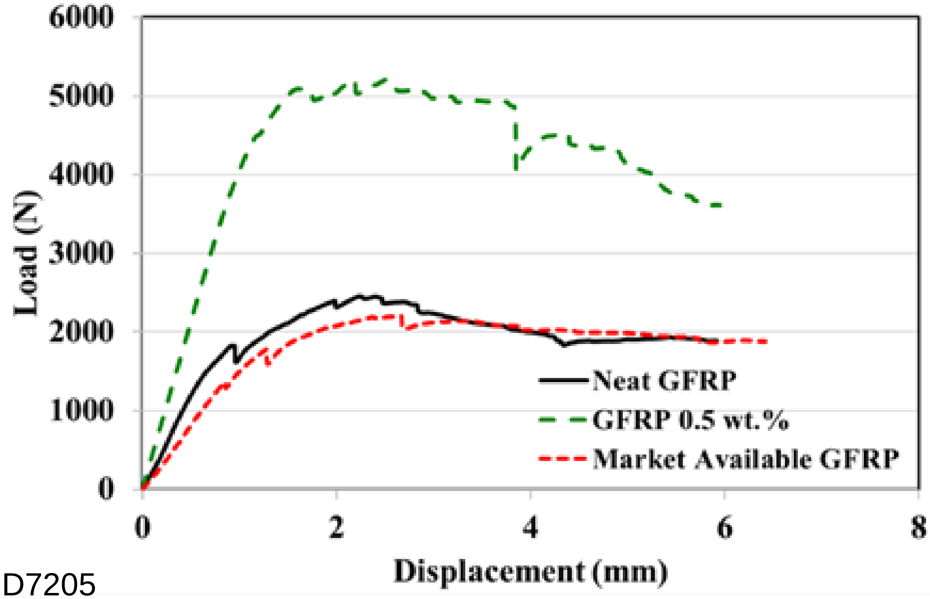



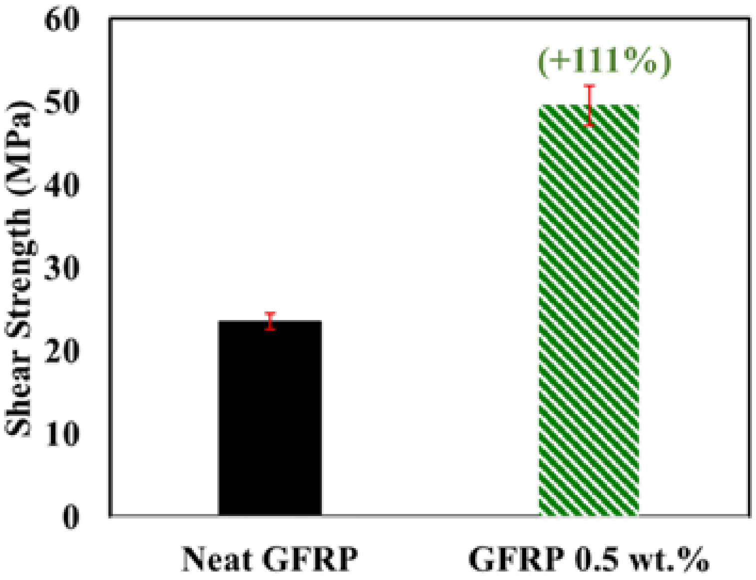

ASTM D4475

# Improving mechanical properties of pultruded FRP



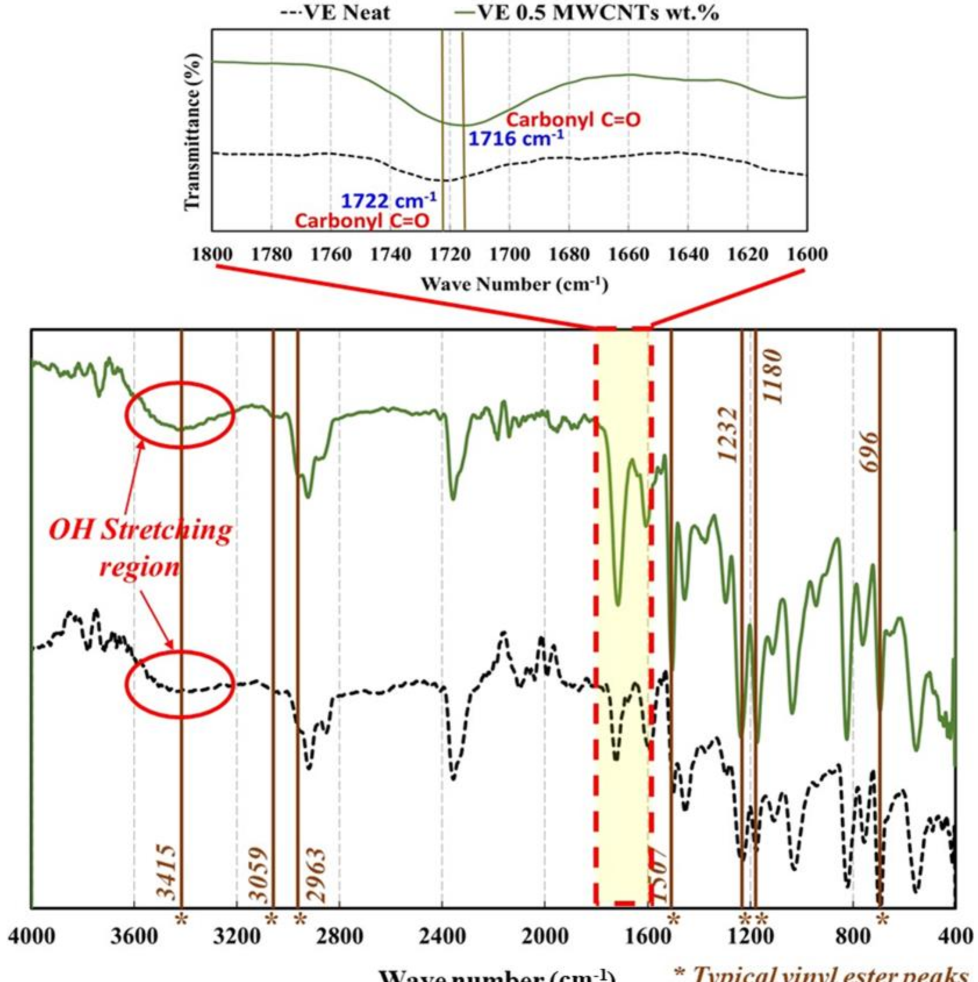



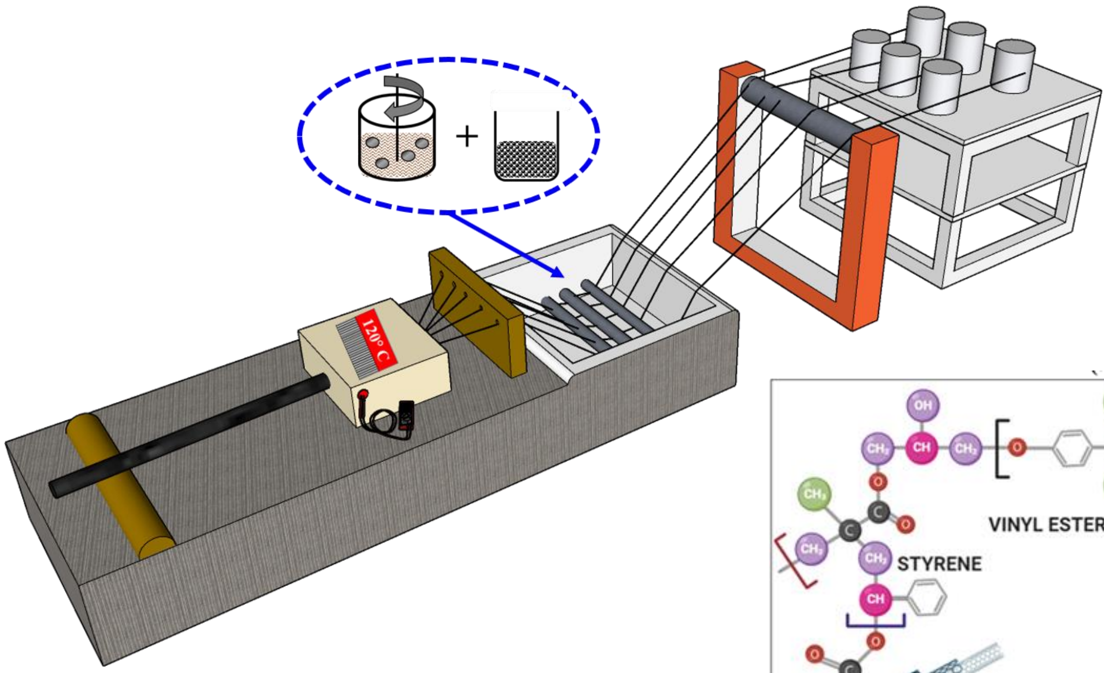

ASTM D7205

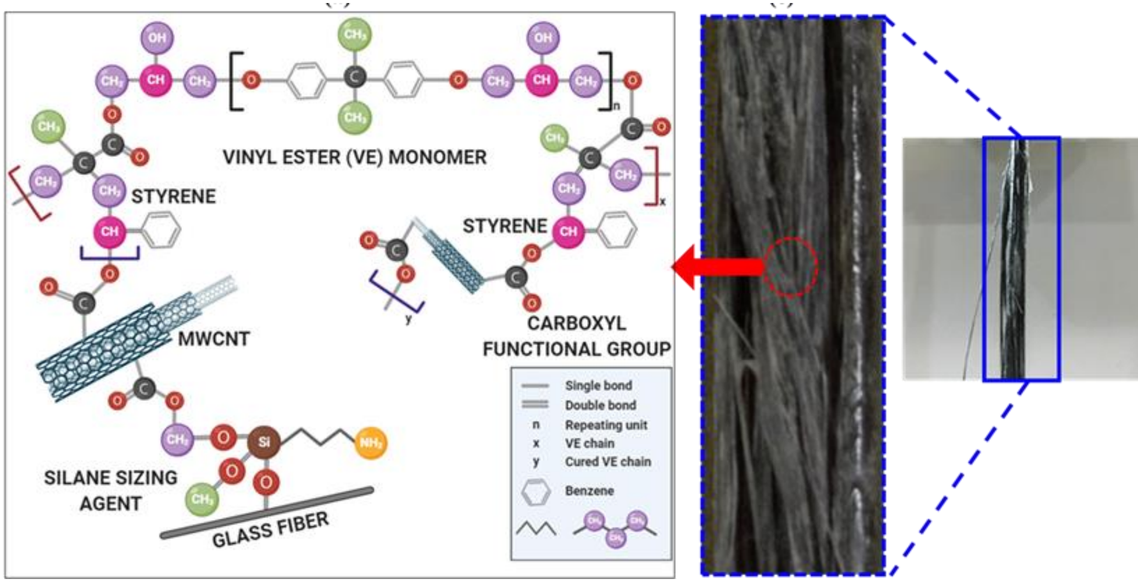
# Improving mechanical properties of pultruded FRP



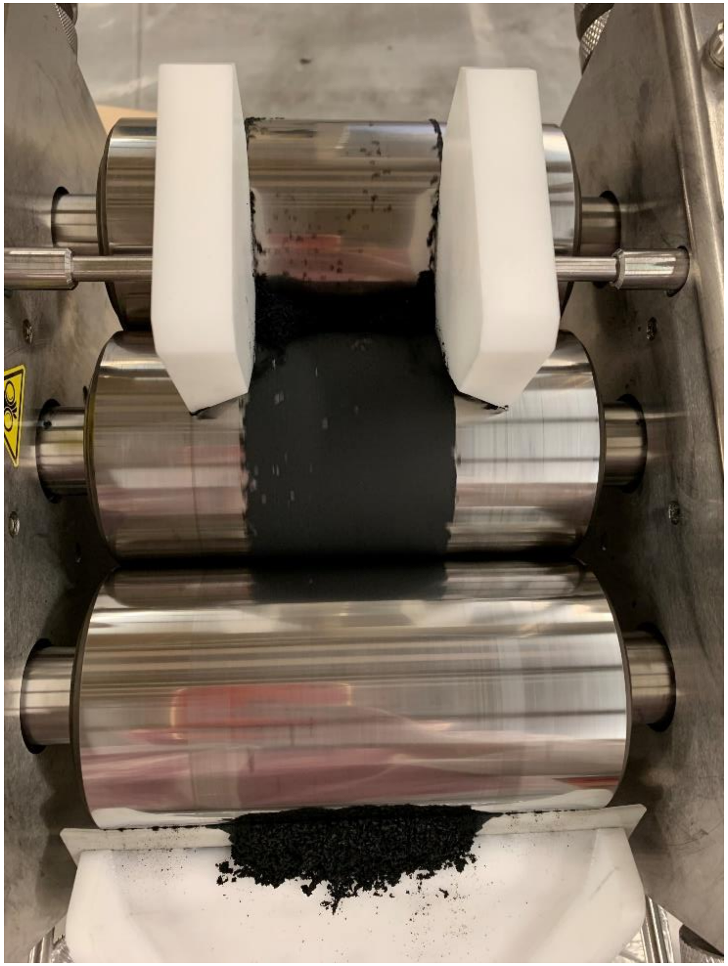

*Vemuganti, S., Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710.*

# Nanomodified Pultruded Sections

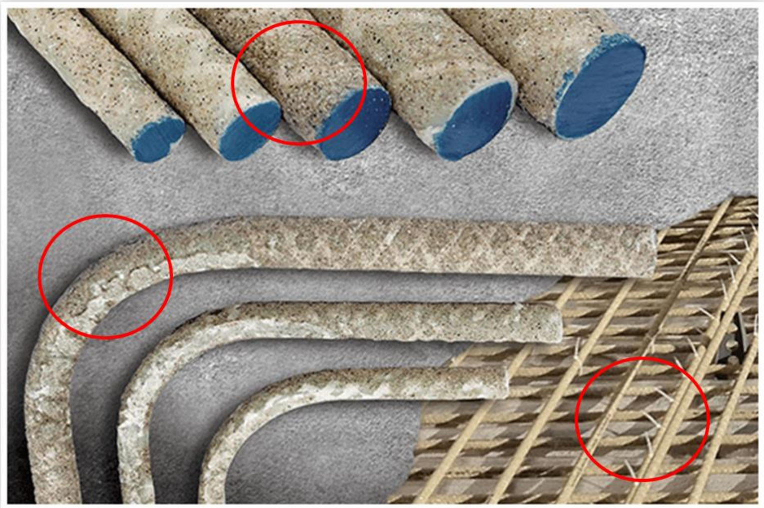


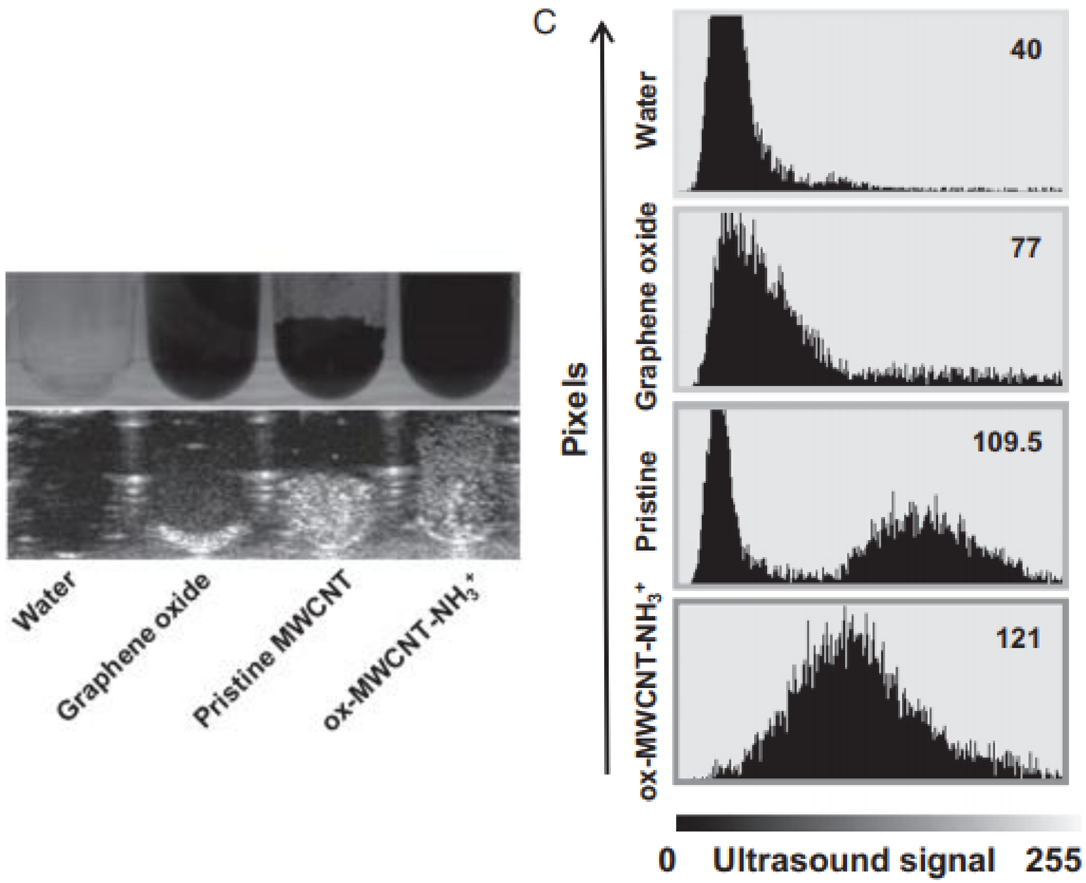



# Enhanced nanomodification through calendaring



# Enhanced imaging and mapping





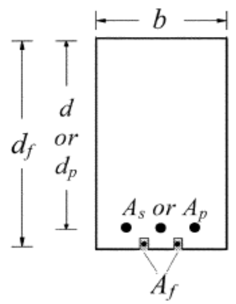
# FRP for externally bonded rehabilitation

# Strengthening Reinforced Concrete structures

“ACI-440 2R-08”

## CHAPTER 10—FLEXURAL STRENGTHENING

For NSM FRP applications, the value of $\varepsilon_{fd}$ may vary from $0.6\varepsilon_{fu}$ to $0.9\varepsilon_{fu}$ depending on many factors such as member dimensions, steel and FRP reinforcement ratios, and surface roughness of the FRP bar. Based on existing studies (Hassan and Rizkalla 2003; De Lorenzis et al. 2004; Kotynia 2005), the committee recommends the use of $\varepsilon_{fd} = 0.7\varepsilon_{fu}$. To achieve the debonding design strain of NSM FRP bars $\varepsilon_{fd}$, the bonded length should be greater than the development length given in Chapter 13.




*(b) NSM bars*

## CHAPTER 11—SHEAR STRENGTHENING

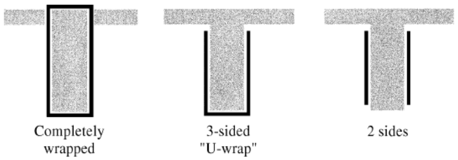
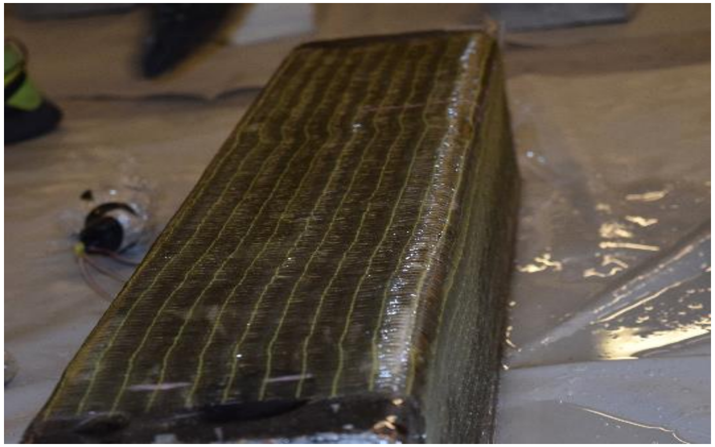



*Fig. 11.1—Typical wrapping schemes for shear strengthening using FRP laminates.*

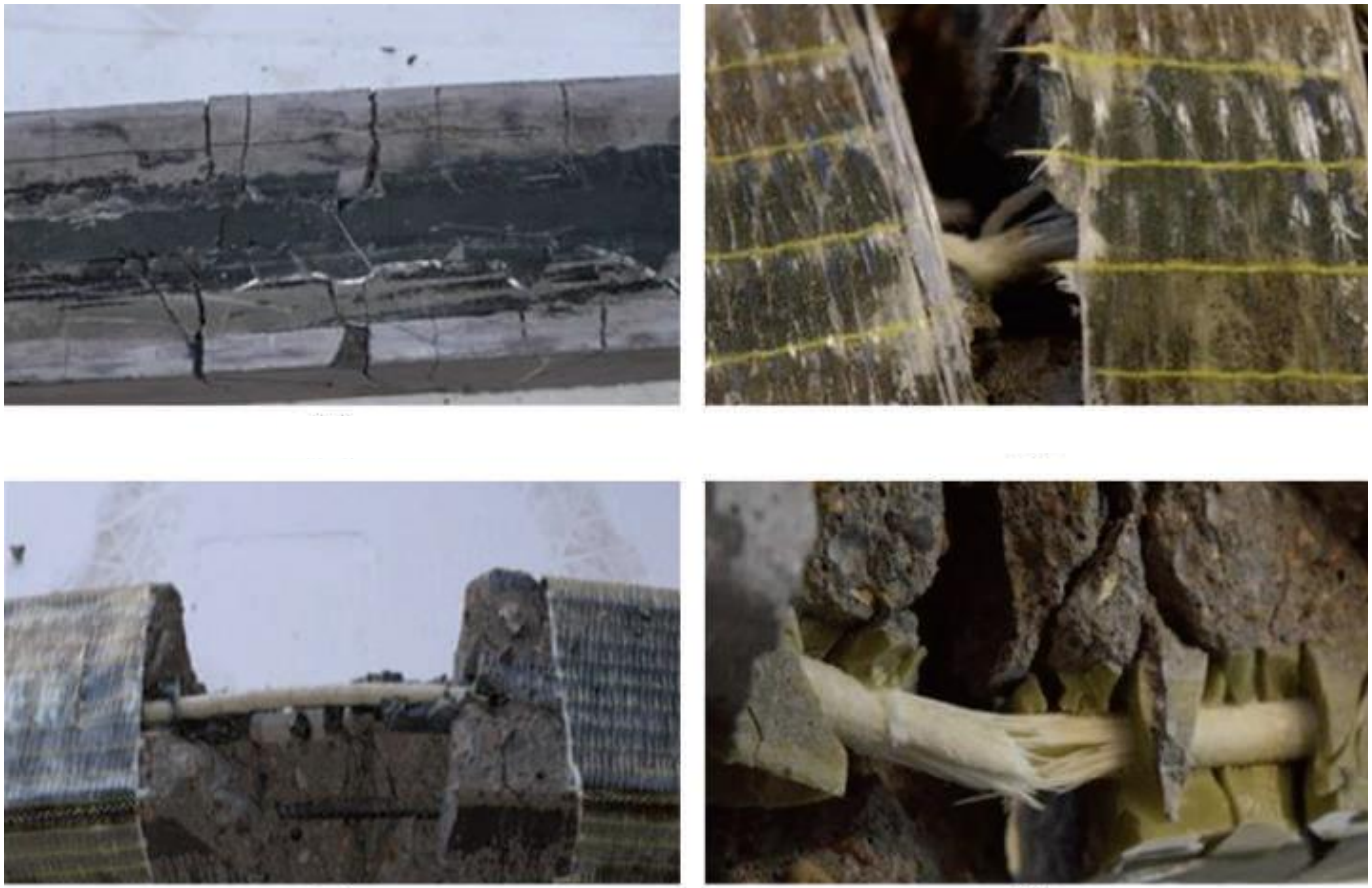
**Table 11.1—Recommended additional reduction factors for FRP shear reinforcement**

| | |
|---|---|
| $\psi_f = 0.95$ | Completely wrapped members |
| $\psi_f = 0.85$ | Three-side and two-opposite-sides schemes |



*Chennareddy, R., & Taha, M. M. R. (2017). Effect of combining near-surface-mounted and U-wrap fiber-reinforced polymer strengthening techniques on behavior of reinforced concrete beams. ACI Structural Journal, 114(3), 719.*

# Strengthening Reinforced Concrete structures



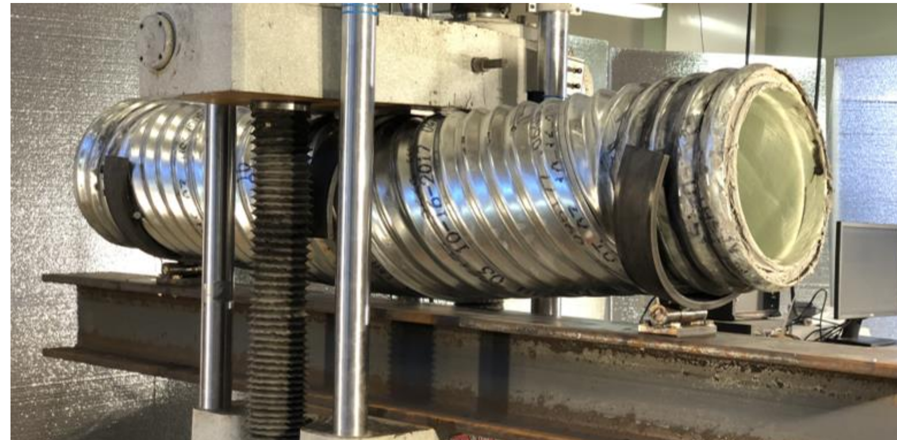
***Chennareddy, R., & Taha, M. M. R. (2017). Effect of combining near-surface-mounted and U-wrap fiber-reinforced polymer strengthening techniques on behavior of reinforced concrete beams. ACI Structural Journal, 114(3), 719.***

# FRP for culvert rehabilitation

# Retrofit and rehabilitation of existing corroded culverts

*Chennareddy, R. (2019). Retrofit of Corroded Metal Culverts Using GFRP Slip-Liner (Doctoral dissertation, The University of New Mexico).*

# Retrofit and rehabilitation of existing corroded culverts



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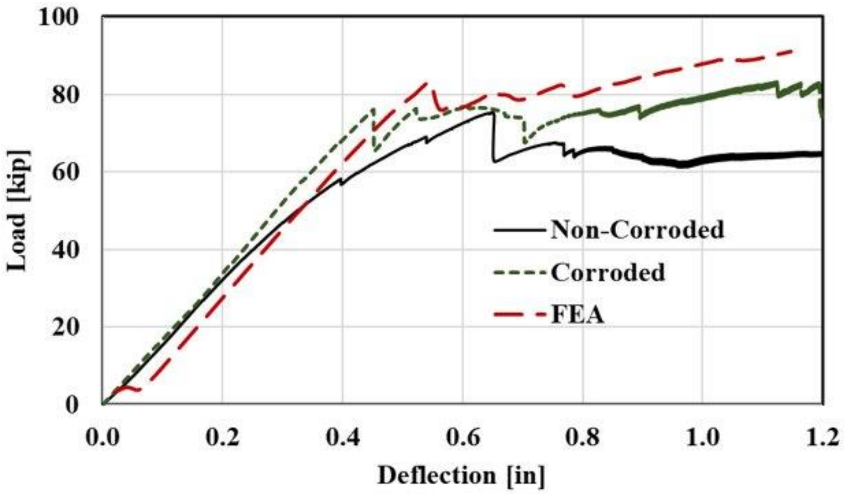
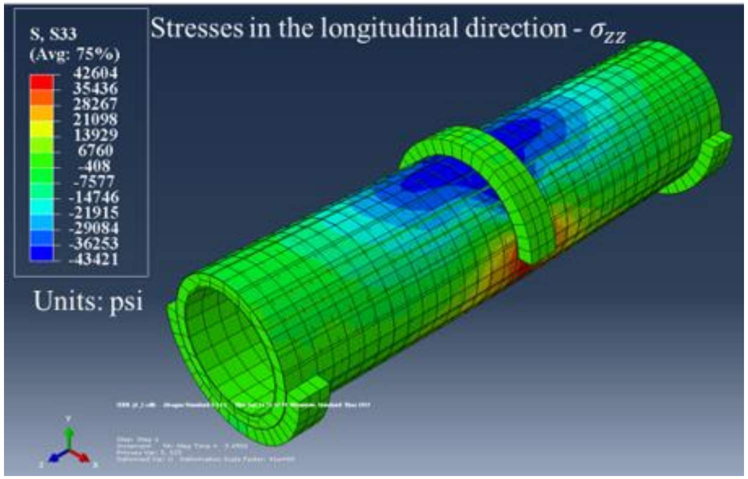
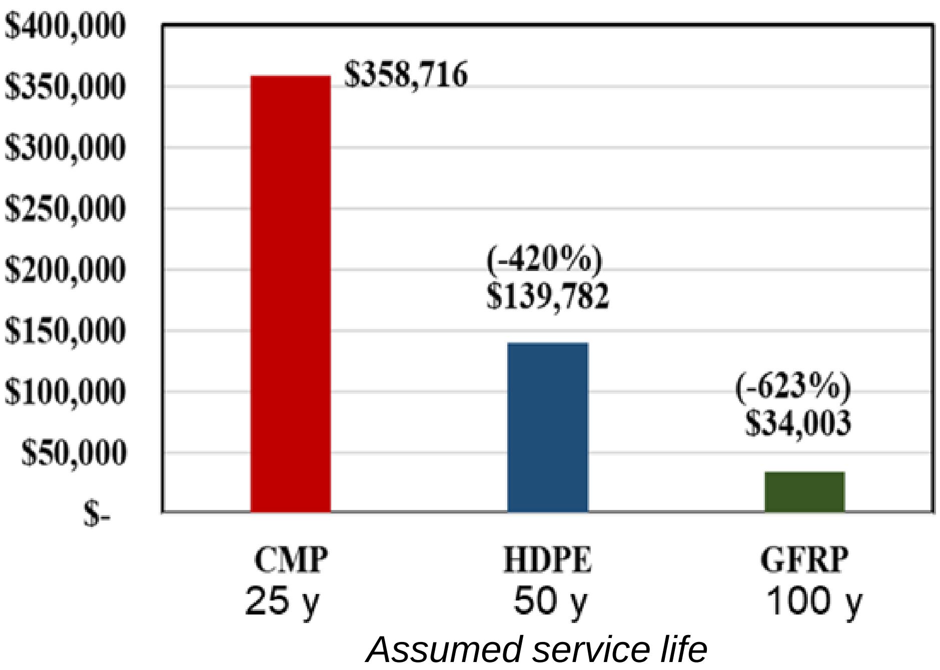


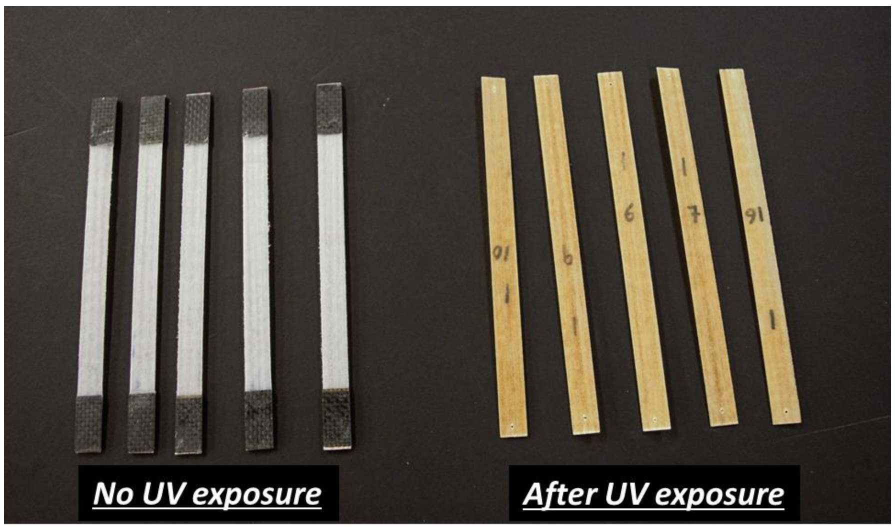

New Mexico DEPARTMENT OF TRANSPORTATION
MOBILITY FOR EVERYONE

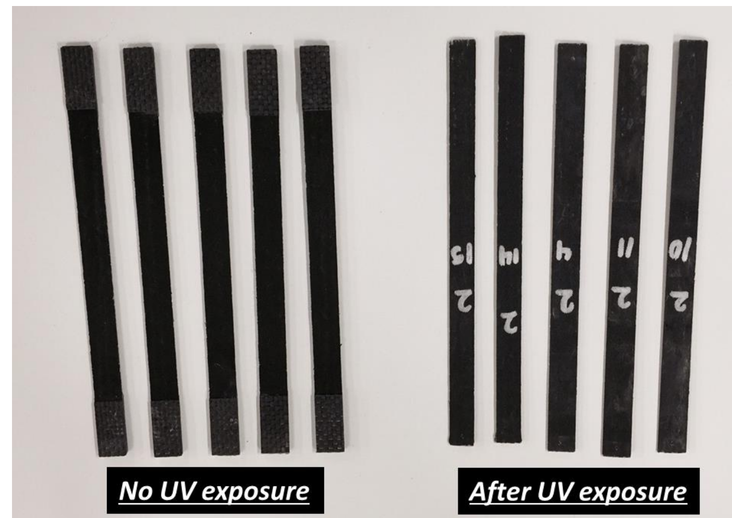
*Chennareddy, R. (2019). Retrofit of Corroded Metal Culverts Using GFRP Slip-Liner (Doctoral dissertation, The University of New Mexico).*

# FRP for extreme weather conditions

# UV degradation

**UV causes a relatively high degradation to FRP**




**GFRP – No Nanomodification**

**1.0wt.% of MWCNTs!**

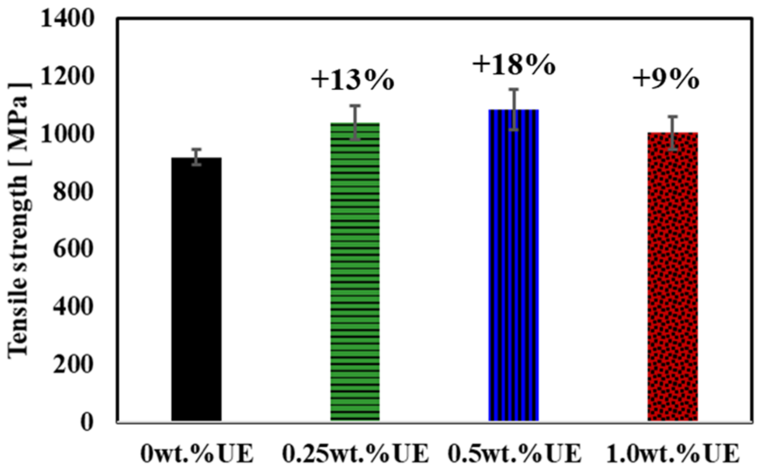
**Significant change in color showing UV degradation!**

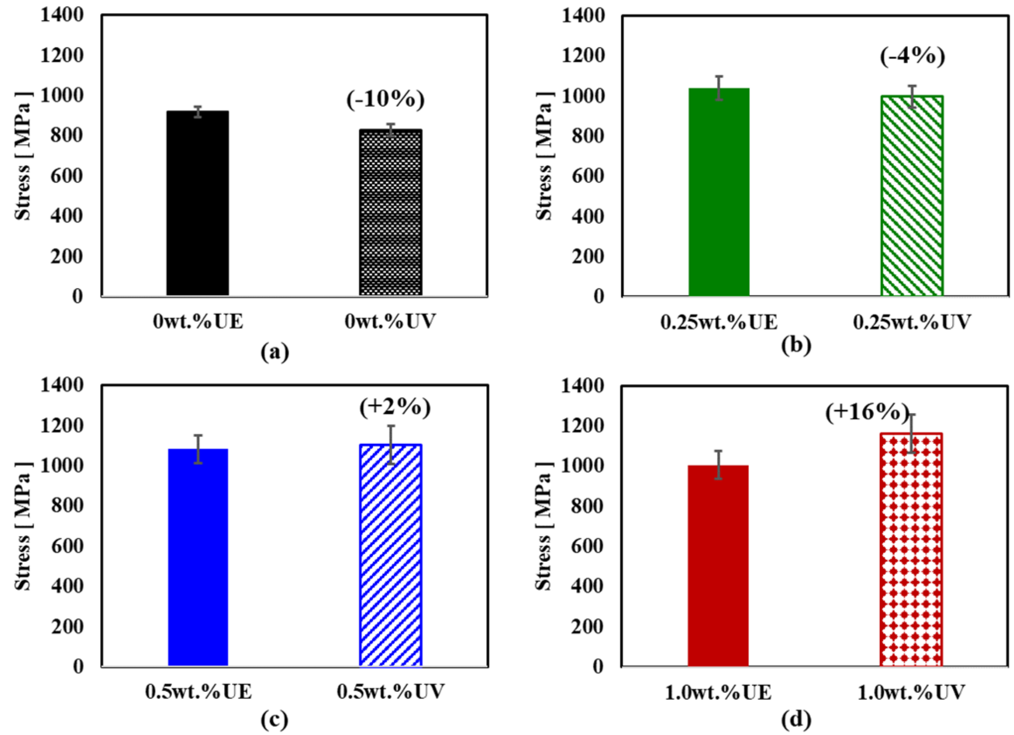
**No change in color of the samples showing no UV degradation**

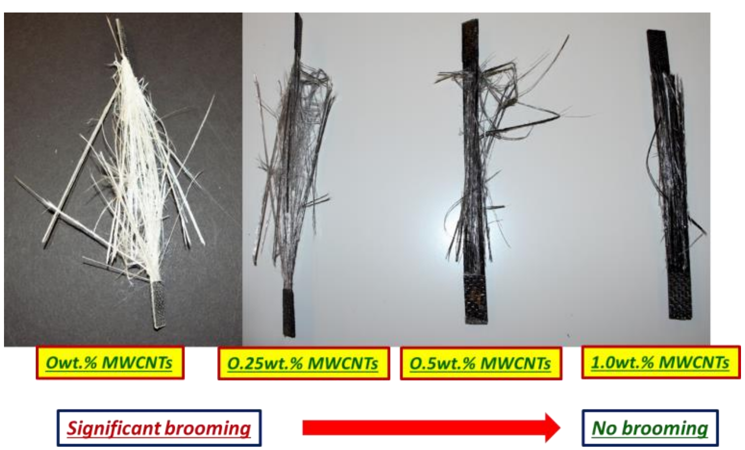
*Chennareddy, R., Tuwair, H., Kandil, U. F., ElGawady, M., & Taha, M. R. (2019). UV-resistant GFRP composite using carbon nanotubes. Construction and Building Materials, 220, 679-689.*

# Carbon Nanotubes on strength improvements

*Chennareddy, R., Tuwair, H., Kandil, U. F., ElGawady, M., & Taha, M. R. (2019). UV-resistant GFRP composite using carbon nanotubes. Construction and Building Materials, 220, 679-689.*

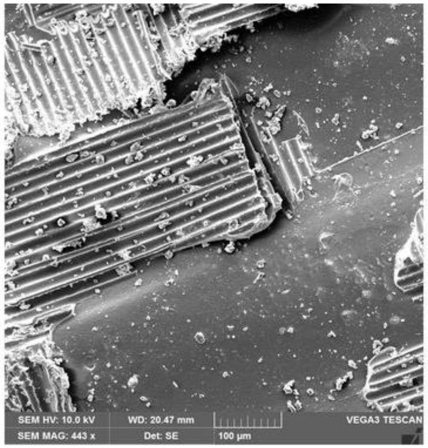


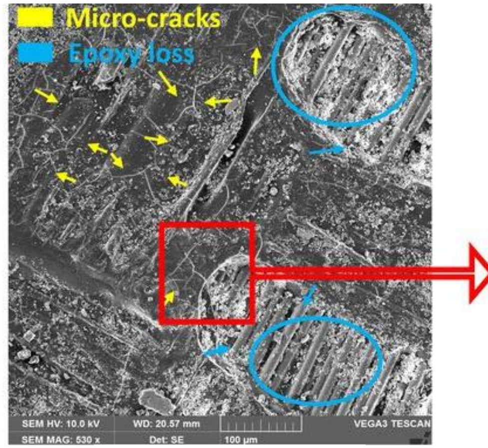



# Carbon Nanotubes on bond disassociation

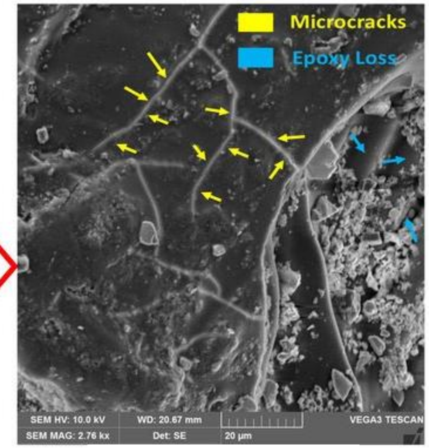
**SEM**



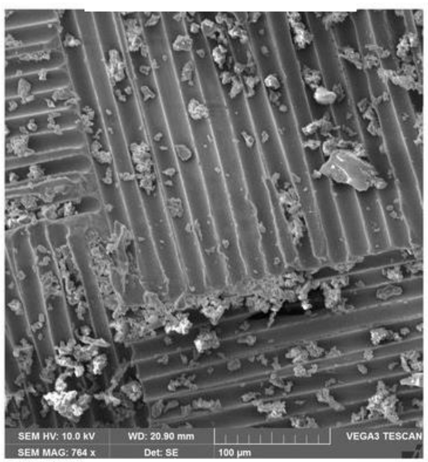

0wt.% UE



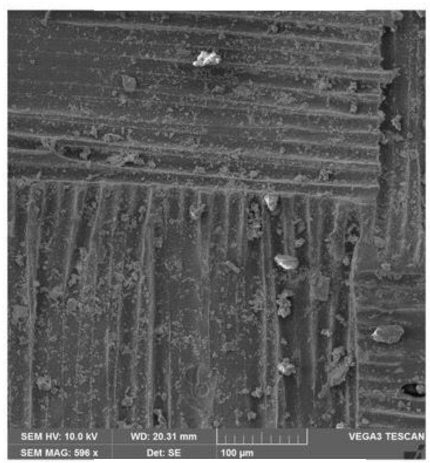

0wt.% UV




0wt.% UV
(magnified)




1.0wt.% UE




1.0wt.% UV

*Chennareddy, R., Tuwair, H., Kandil, U. F., ElGawady, M., & Taha, M. R. (2019). UV-resistant GFRP composite using carbon nanotubes. Construction and Building Materials, 220, 679-689.*

# Freeze-thaw conditions

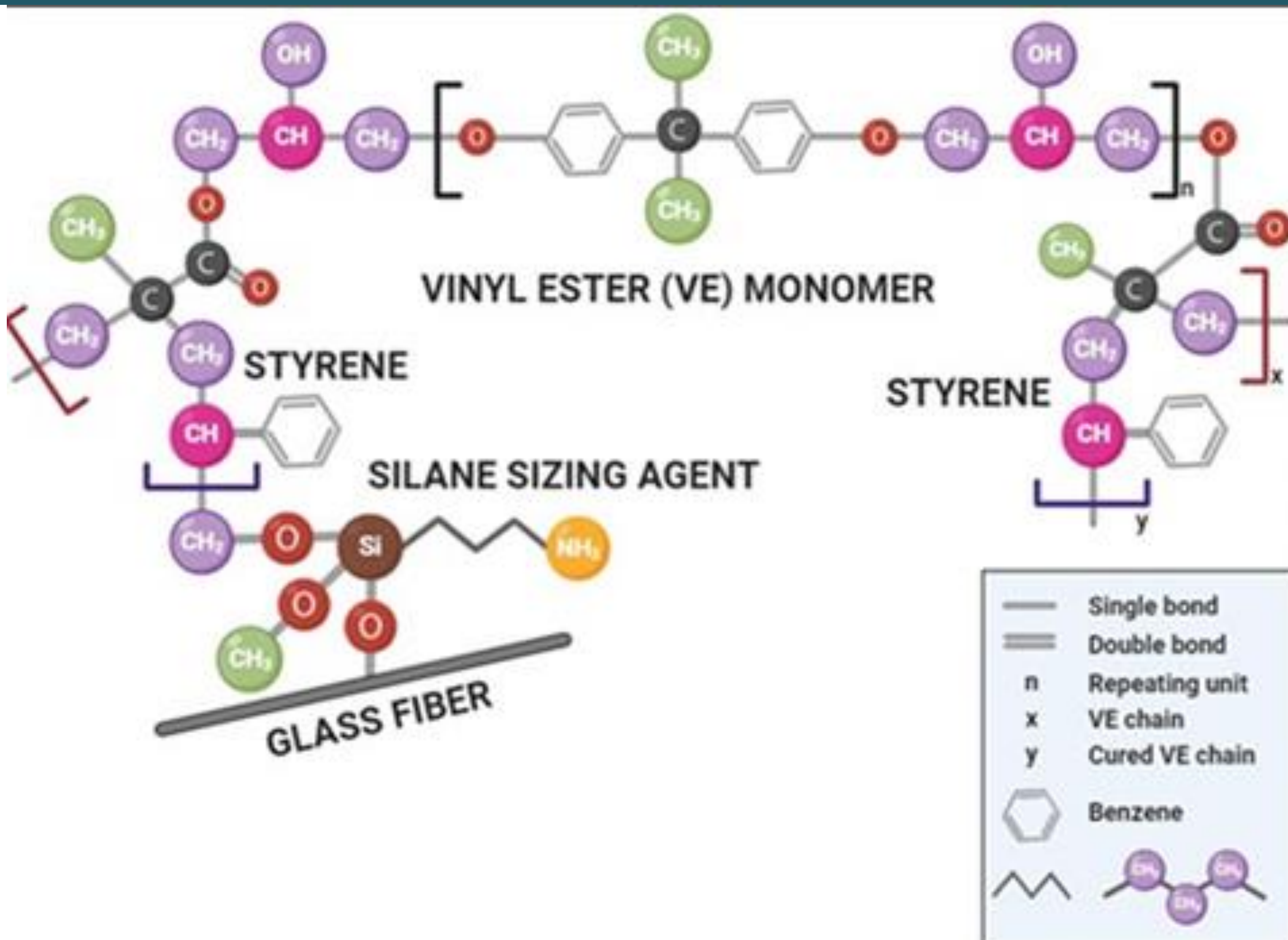

Cold Room

Inside Cold Room

# Freeze-thaw conditions


Shi, Jia-Wei, Hong Zhu, Gang Wu, and Zhi-Shen Wu. "Tensile behavior of FRP and hybrid FRP sheets in freeze–thaw cycling environments." *Composites Part B: Engineering* 60 (2014): 239-247.

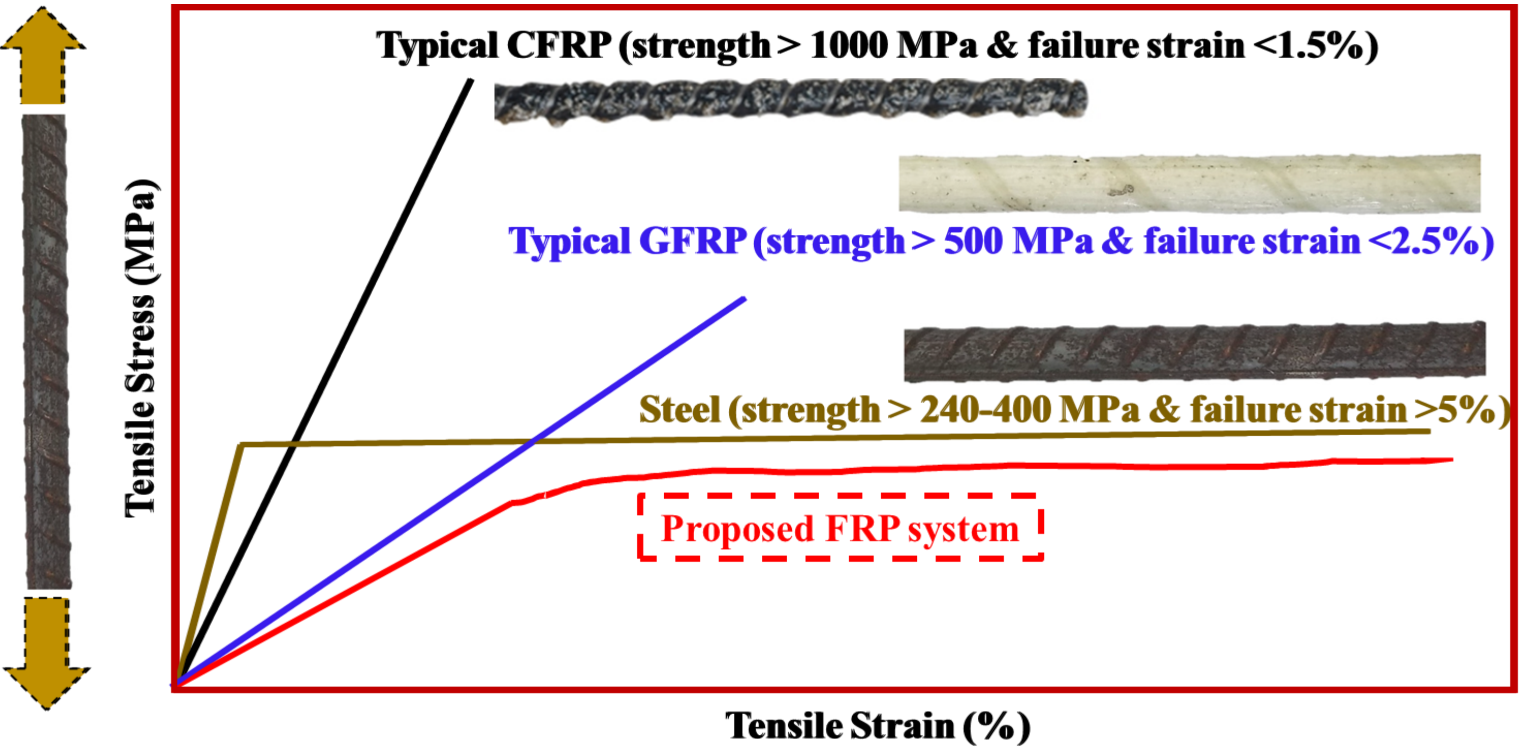
# Freeze-thaw conditions

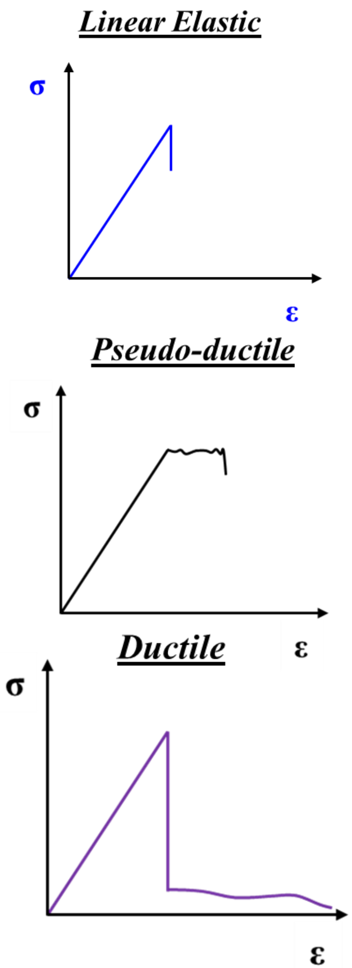



*Vemuganti, S., Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710.*

# Ductile FRP through 3D printing

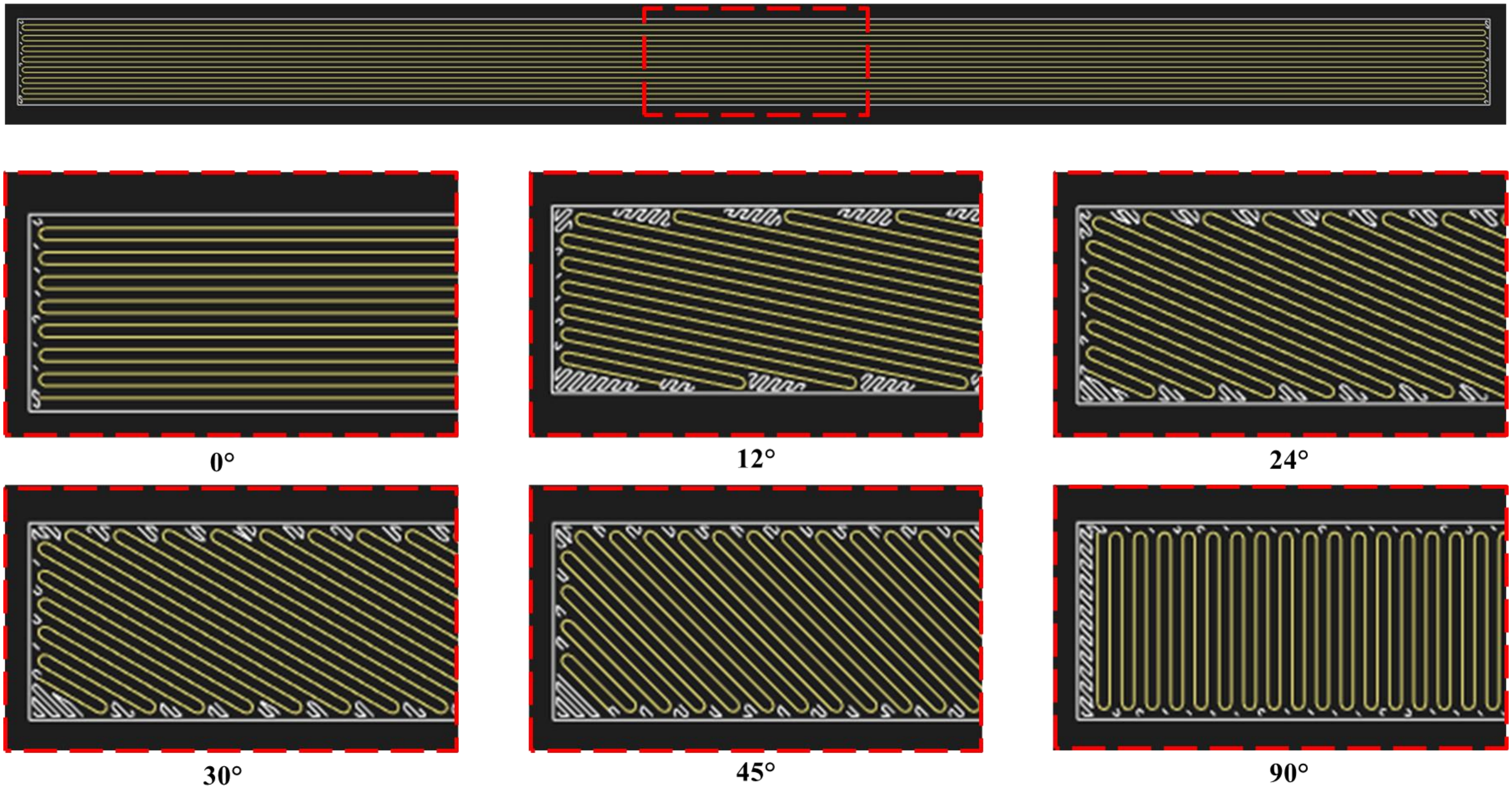
# 3D printed FRP Composites



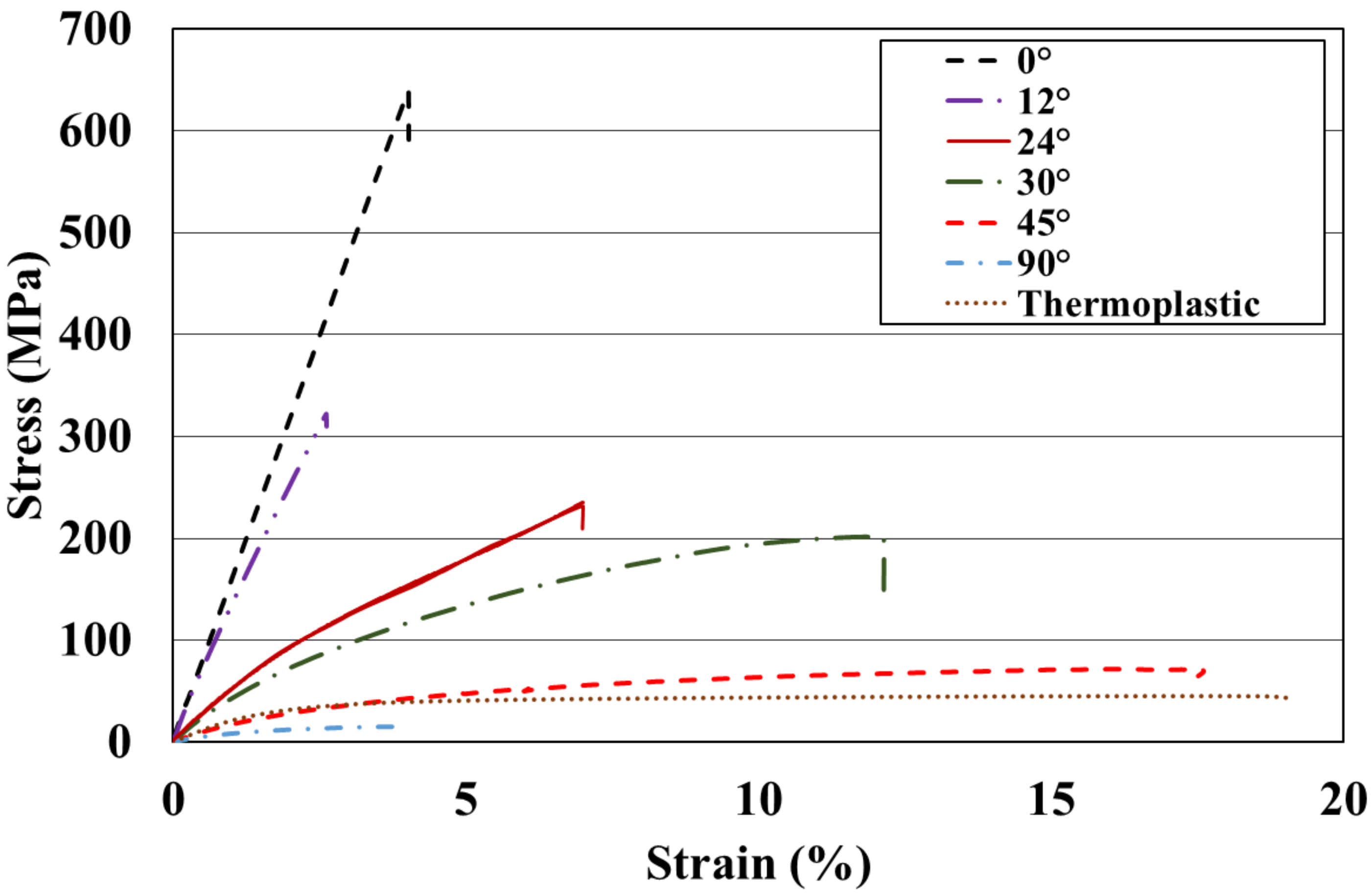




*Vemuganti, S., Soliman, E., & Reda Taha, M. (2020). 3D-printed pseudo ductile fiber-reinforced polymer (FRP) composite using discrete fiber orientations. Fibers, 8(9), 53.*

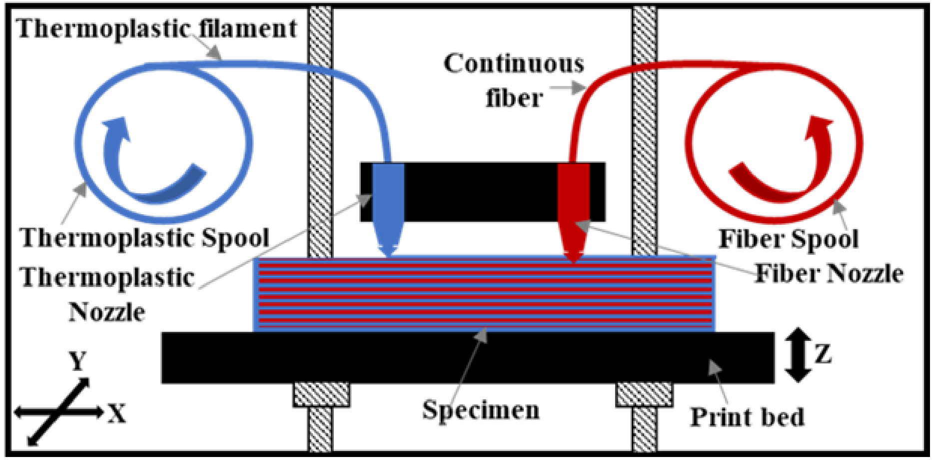
# Anisotropic FRP

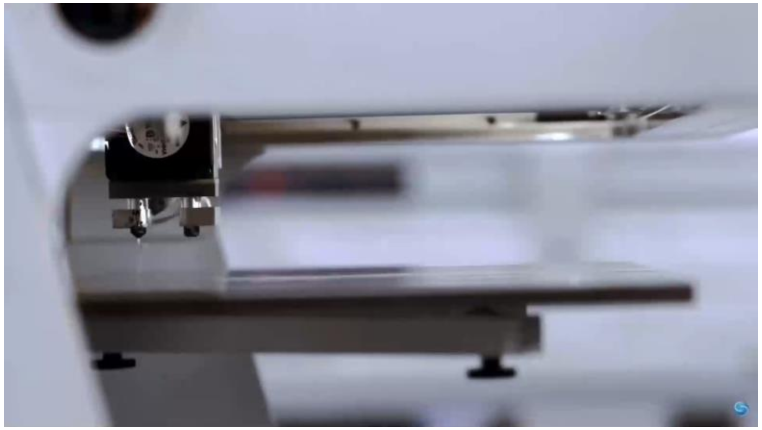


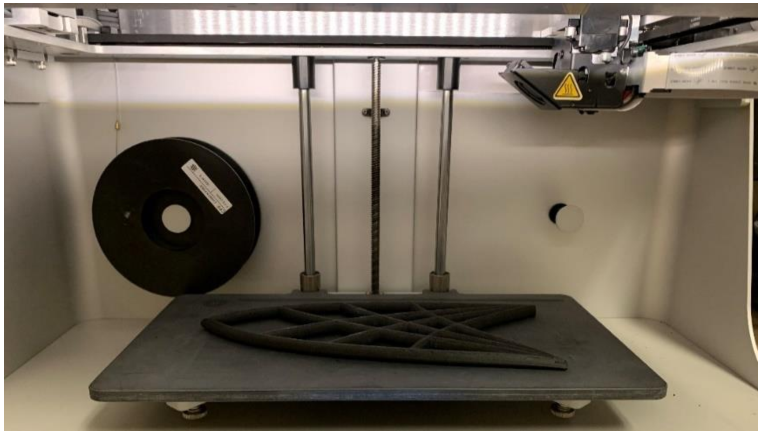
# Anisotropic FRP

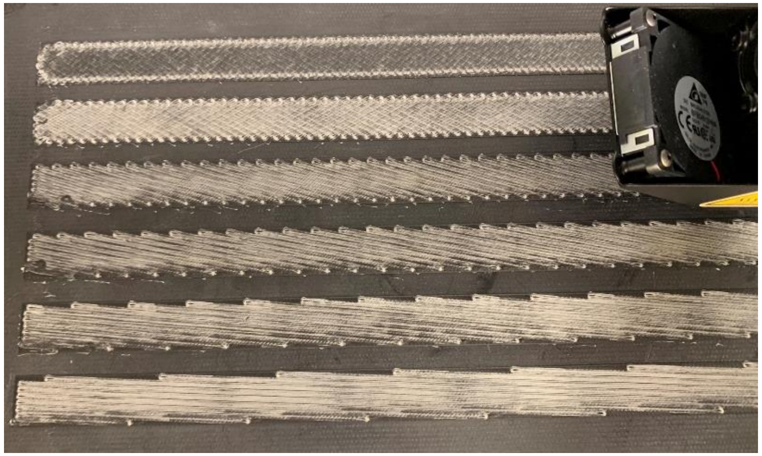


# 3D printed FRP Composites



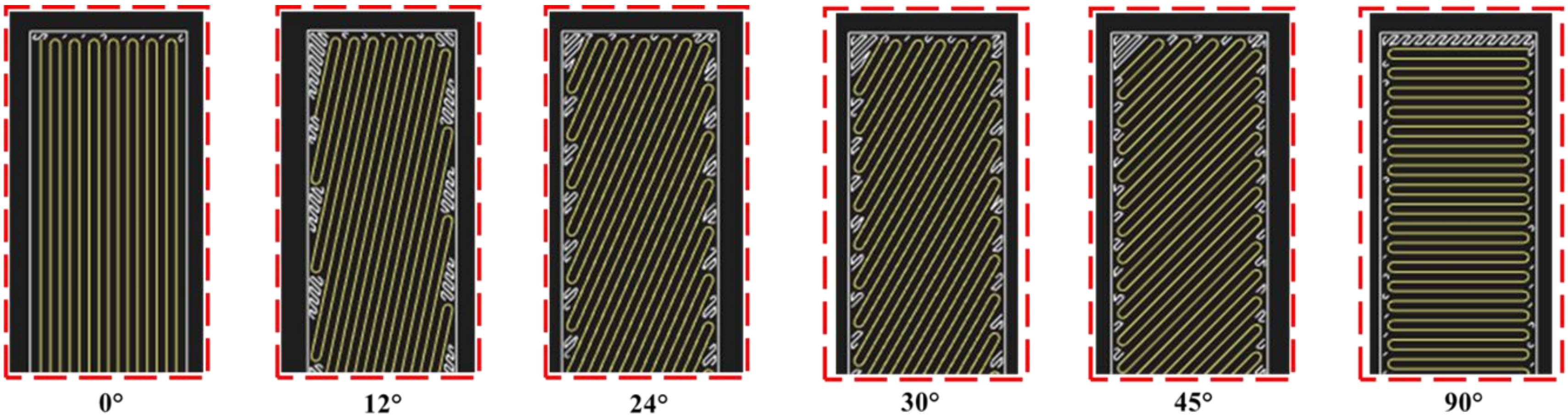







**<u>Continuous Filament Fabrication (CFF)</u>**

# 3D printed FRP Composites



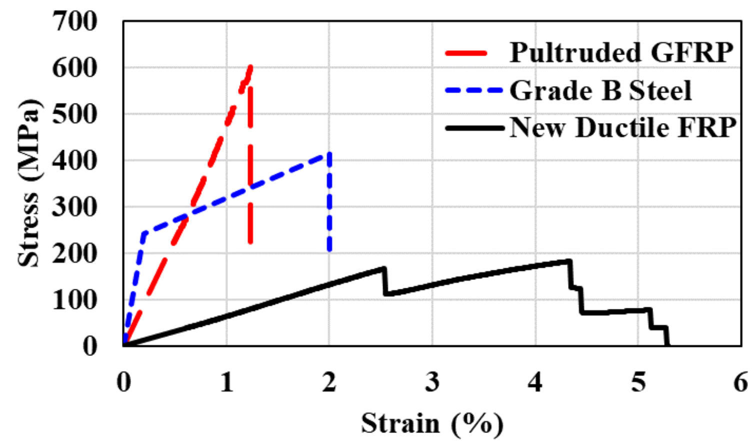

| Parameters | Units | Fiber Orientation | | | | |
|---|---|---|---|---|---|---|
| | | ±12° | ±12°& ±24° | ±24° | ±24° & ±30° | |
| Area of 1 layer | mm$^2$ | 1.5 | 1.5 | 1.5 | 1.5 | |
| No. of layers | | 8 | 8 | 16 | 16 | |
| Load sharing (initial) | % | 27% | 21% | 29% | 24% | COV = 14% |
| Load sharing (peak) | % | 31% | 21% | 27% | 21% | COV = 18% |

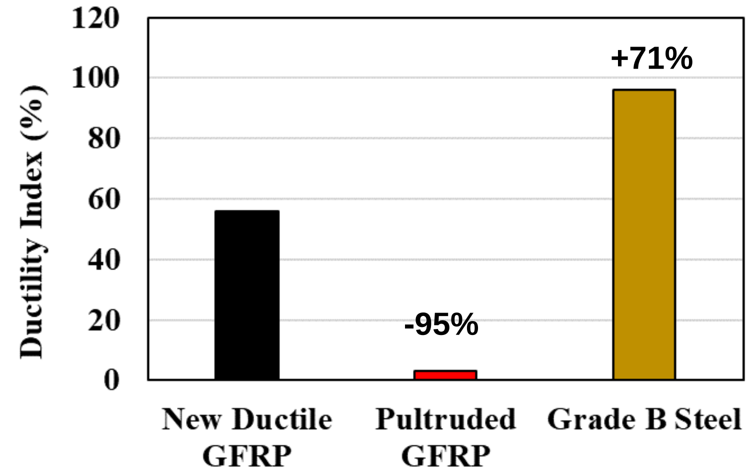
# 3D printed FRP Composites

*Pultruded GFRP with Brittle failure*

*New FRP with Progressive sequential Drops*

*Steel Ductile*

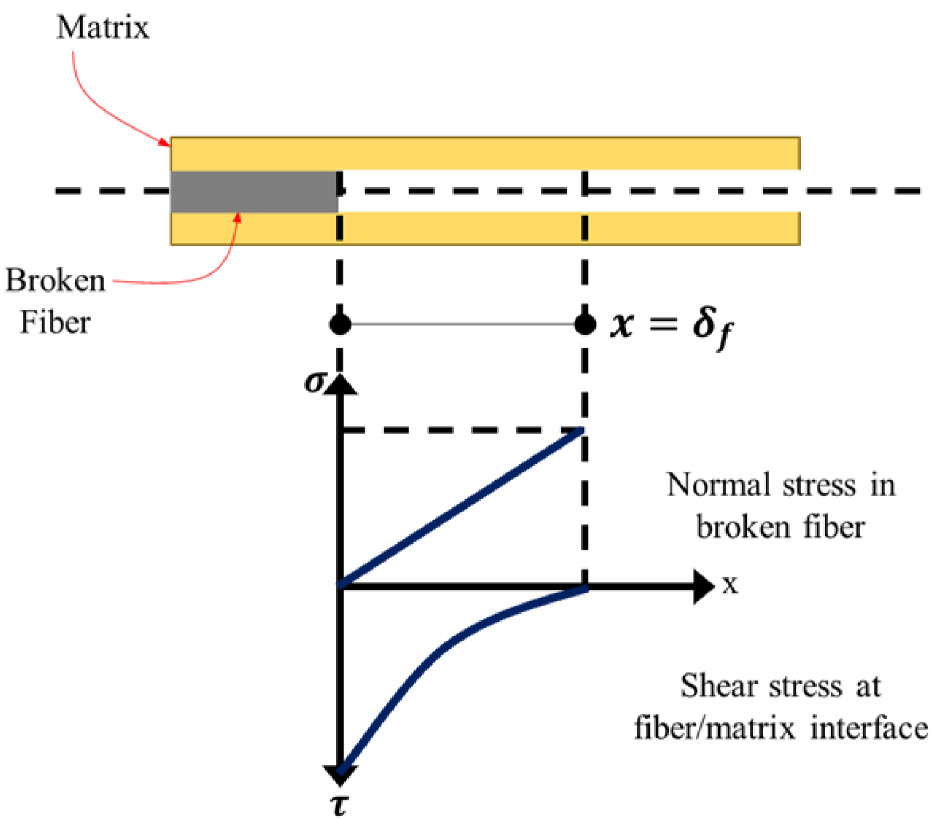



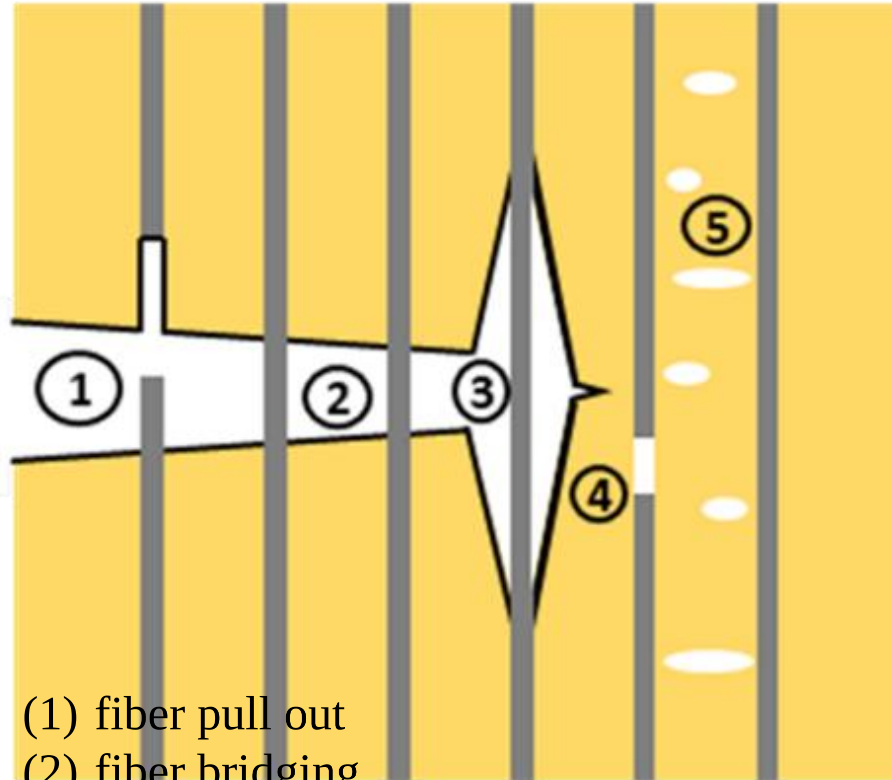



# Ductile 3D printed FRP reinforcement

Transpo Industries, Inc.

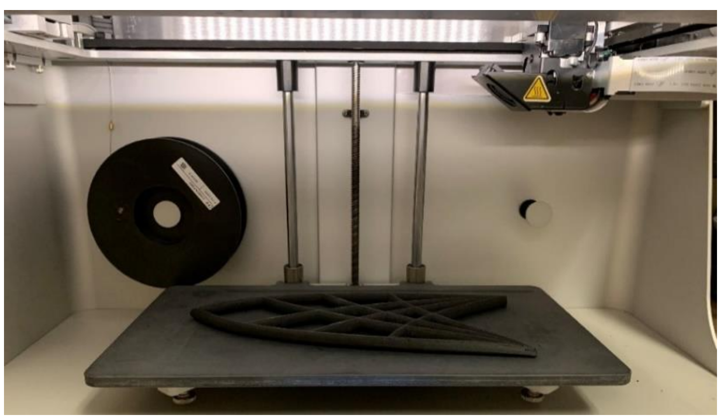
# Alternative bond in 3D printed FRP



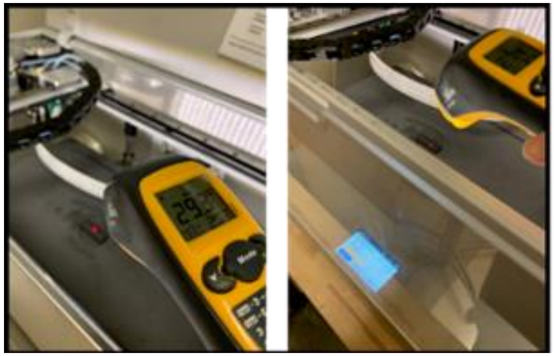



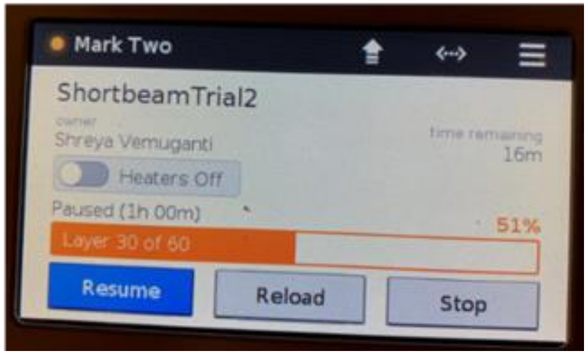

(1) fiber pull out
(2) fiber bridging
(3) fiber matrix debonding
(4) fiber failure
(5) matrix cracking

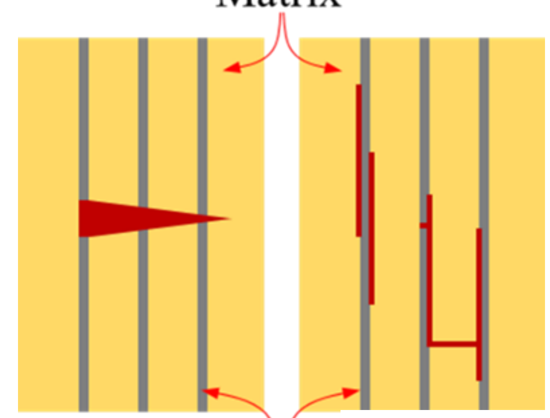
# Alternative bond in 3D printed FRP

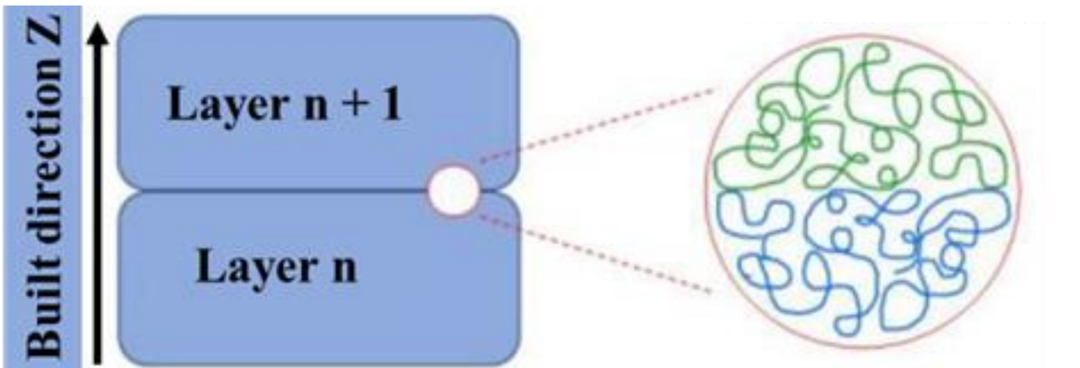



# Thermal blocks in 3D printed FRP

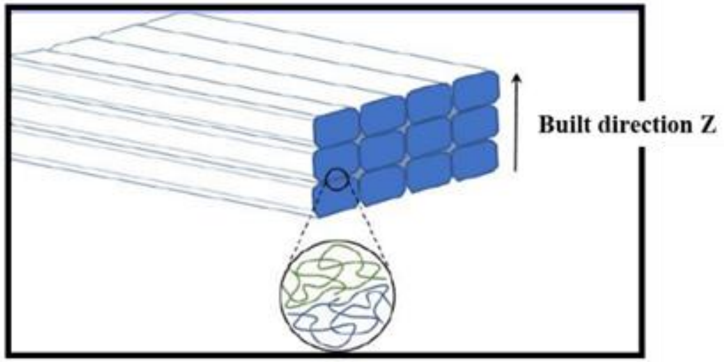





Partial bonding of crystals
on layer n with layer n+1



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# Publications

**Journal papers:**

1. **Vemuganti, S.**, Stormont, J. C., Pyrak-Nolte, L. J., Dewers, T., & Taha, M. R. (2021). Cement sensors with acoustic bandgaps using carbon nanotubes. Smart Materials and Structures, 30(3), 035011.
2. **Vemuganti, S.**, Soliman, E., & Reda Taha, M. (2020). 3D-Printed Pseudo Ductile Fiber-Reinforced Polymer (FRP) Composite Using Discrete Fiber Orientations. Fibers, 8(9), 53. ***Cover of Issue 9, Volume 8, 2020***
3. **Vemuganti, S.**, Chennareddy, R., Riad, A., & Taha, M. M. R. (2020). Pultruded GFRP Reinforcing Bars Using Nanomodified Vinyl Ester. Materials, 13(24), 5710. ***Editor's Choice Paper***
4. **Vemuganti. S.**, Rahman, M.K., Reda Taha, M. M. (2019). Evolution of Elastic Modulus and Creep of Nanoclay Modified Oil Well Cement. Special Publication, 335, 128-144.

**Patents:**

1. Reda Taha M., **Vemuganti S.**, Stormont J., Han S. M., Dewers T., Pyrak-Nolte L. J., "Cementitious Sensors Exhibiting Stopbands in Acoustic Transmission Spectra and Methods of Making", STC Technology Ref. No. 2019-01

# Publications

**Conference papers:**

1. **Vemuganti, S.**, Chennareddy, R., Riad, A., & Taha, M. M. R. (2021) “Incorporating Nanomaterials to Enhance Mechanical Behavior of GFRP Reinforcing Bars”, Al-Azhar Engineering fifteenth international conference, Cairo, Egypt.
2. **Vemuganti, S.**, Stormont, J., Han, S.M., Dewers, T. and Pyrak-Nolte, L.J., Reda Taha, M. M. (2019) “Cementitious Sensors with Acoustic Stopbands Using Carbon Nanotubes”, Proceedings of Sixth International Symposium on Nanotechnology in Construction, NICOM6, Hong Kong, China.
3. Rahman, M. K., **Vemuganti, S.**, Reda Taha, M. M., (2019) “Elastic and viscoelastic properties of nanoclay modified oil well cement”, Proceedings of Sixth International Symposium on Nanotechnology in Construction, NICOM6, Hong Kong, China.
4. Moreu, F., Bleck, B., **Vemuganti, S.**, Rogers, D., & Mascarenas, D. (2017). Augmented reality tools for enhanced structural inspection. Structural Health Monitoring 2017, (SHM)
5. **Vemuganti, S.**, Ozdagli, A., Liu, B., Bajric, A., Moreu, F., Brake, M. R., & Troyer, K. (2017). Sensing and rating of vehicle–railroad bridge collision. In Dynamics of Civil Structures, Volume 2 (pp. 227-234). Springer, Cham
6. **Vemuganti, S.**, & Moreu, F. (2017). Survey about Bottom Surface Abrasion of Concrete Crossties (No. 17-06121)
7. Gomez, L., **Vemuganti, S.**, & Moreu, F. (2017). Invited Student Paper-Cyber-Physical Systems Related to Historic Infrastructure Maintenance (No. 17-06016)
8. **Vemuganti, S.**, & Moreu, F. (2017). Survey about Bottom Surface Abrasion of Concrete Crossties (No. 17-06121)
9. **Vemuganti, S.**, Ozdagli, A., Liu, B., Bajric, A., Moreu, F., Brake, M. R., & Troyer, K. L. (2016). Impact Rating System for Vehicle Railway Bridge Collision (No. SAND2016-11012C). Sandia National Labs. (SNL-NM), Albuquerque, NM
10. Ozdagli, A. I., Moreu, F., Gomez, J. A., Garp, P., & **Vemuganti, S.** (2016, July). Data Fusion of Accelerometers with Inclinometers for Reference-free High-Fidelity Displacement Estimation. In 8th European Workshop on Structural Health Monitoring