Strategically Tuned Absolutely Resilient Structures (STARS)

by

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Outline

- advanced composites
- Strategically Tuned Absolutely Resilient Structures – “STARS”
- design approach – stiffness ratio (n)
- 1st and 2nd generation STARS
- structural and modal analyses
- matrix design from a new perspective
- advanced STARS
- closing remarks and conclusion

Advanced Composites

- continuous fibers suspended in polymeric matrix, typically an epoxy of some type
- underlying technology developed over past sixty years
- advances have been steady but relatively few revolutionary changes of late

Reaching for the "STARS"

Strategically Tuned Absolutely Resilient Structures (STARS)

MAXIMIZE STRESS/DEFORMATION
- compliance
- strength
- location

FORCING FUNCTION
- mechanical
- thermal
- pneumatic
- acoustic

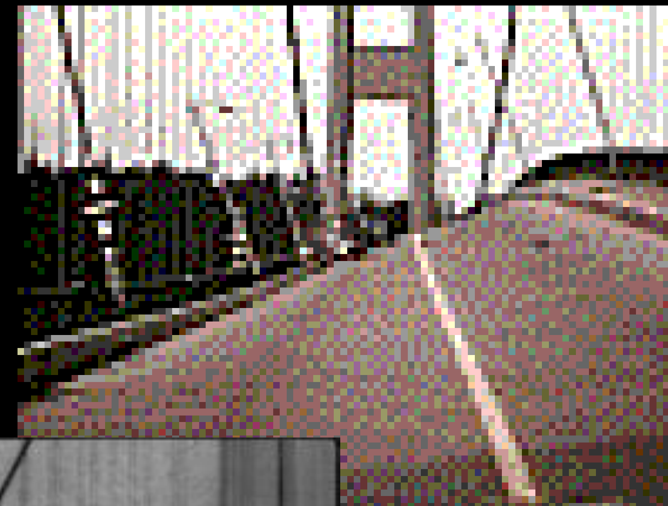
WORK/ENERGY

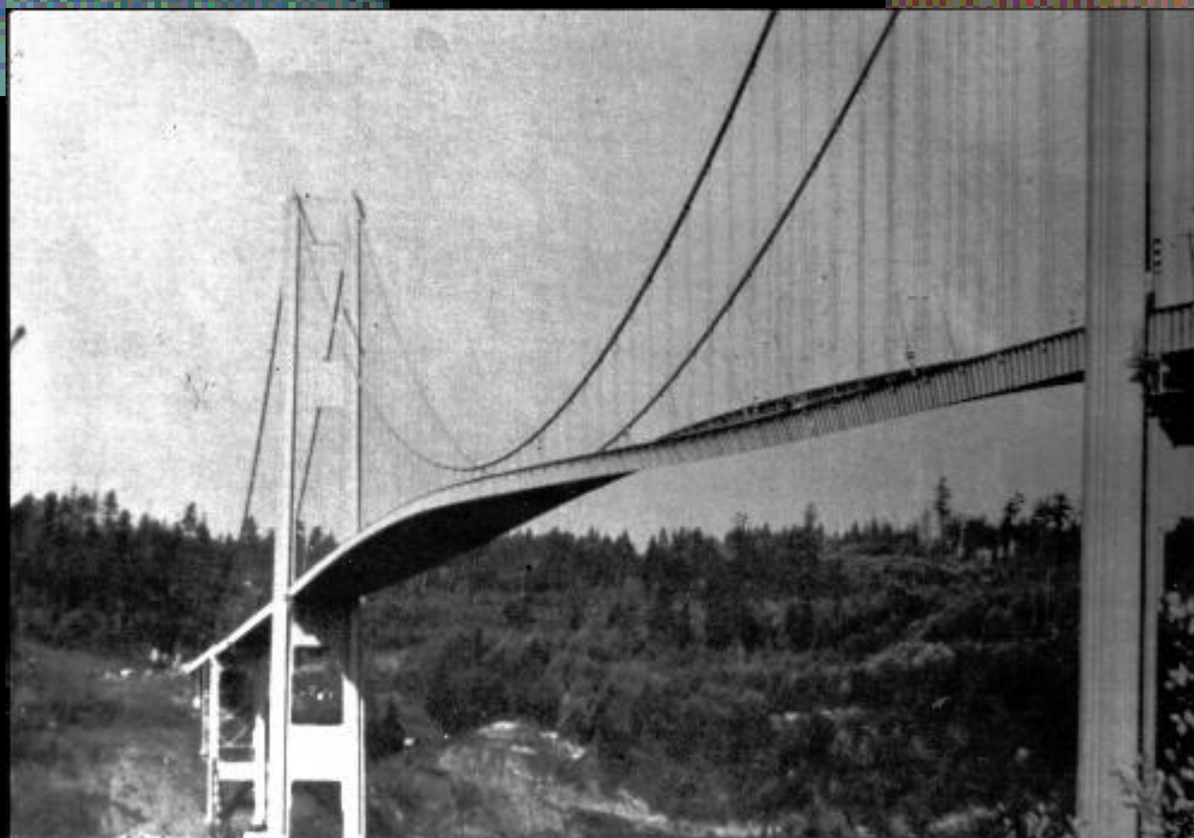
COUPLING
- strategically tune to resonance

RECOVERY
- elastic deformation

PREVENT DAMAGE
- adaptive reinforcement
- integrated sensors
- control elements

Gilbert, J.A., Vaughan, R.E., Ooi, T.K., Toutanji, H.A., "Creating 'STARS' for advanced propulsion with cementitious composites," Proc. of the HATS/TABES Exposition, Huntsville, Alabama, May 15-16 (2001).





Design Approach

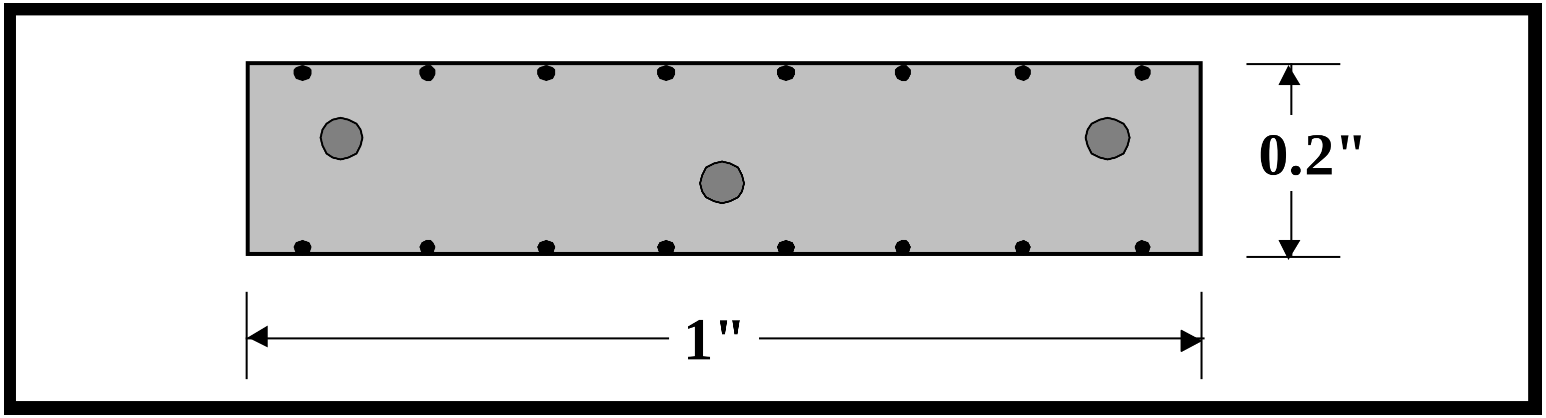
- design composite based on geometry, stiffness, and strength of components
- transfer stresses from a flexible matrix to multiple layers of relatively stiff reinforcement
- adaptive section to resist dynamic loadings and facilitate structural morphing
- monitor performance to avoid failure of the components and the composite

Stiffness Ratio (n)

- Civil Engineering Structures (steel and concrete); n ~ 10
- Aerospace Structures (graphite/Kevlar and epoxy); n ~ 100
- 1st and 2nd generation STARS; (steel/graphite and polymer enhanced concrete); n ~ 300
- Advanced STARS (graphine and polyurea); n ~ 10,000
- STARS provide increased design flexibility

1st Generation (1996)

- 0.2 in. thick; reinforced using two layers of 1/8 in. square steel mesh made from 0.017 in. diameter wires
- spaced using a plastic grid; subjected to 14.7 in.-lb per inch of width

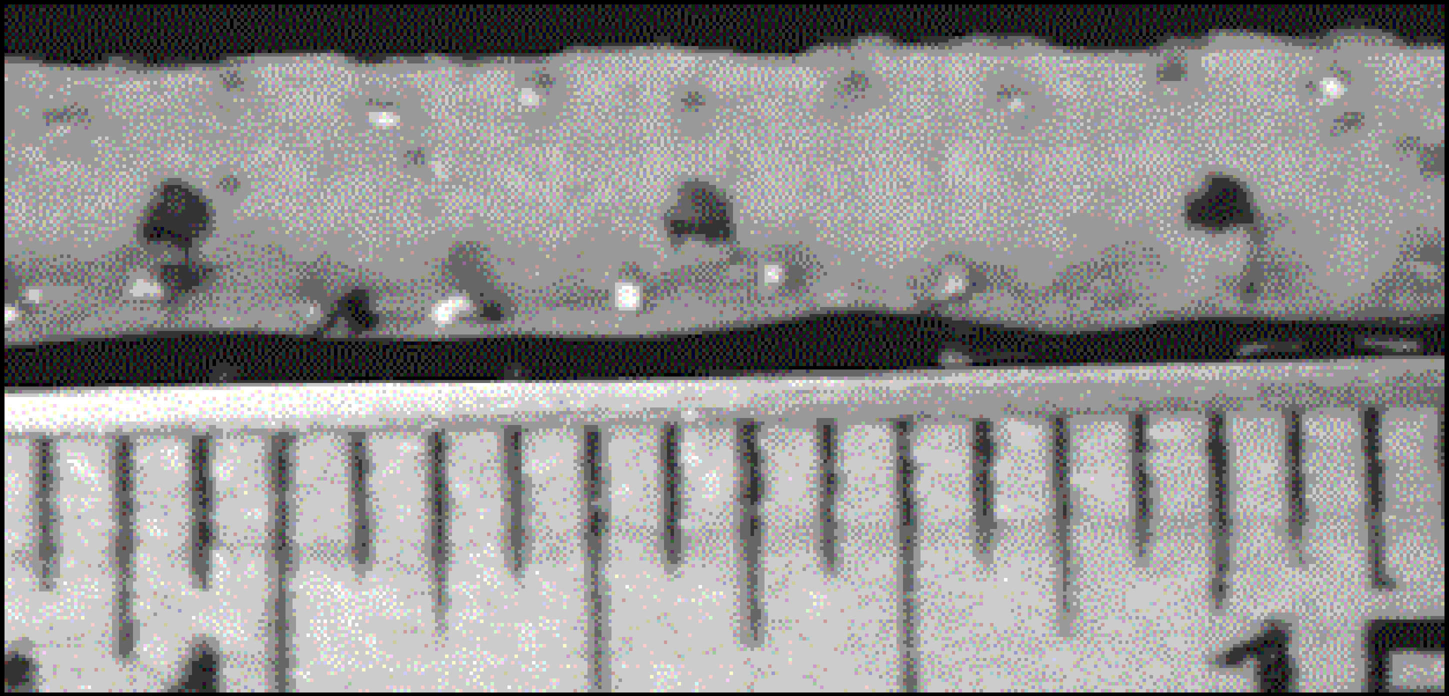


Gilbert, J.A., "A race to innovate," Civil Engineering, January, 1996, pp. 46-48.

Mix Proportions (kg/m^3)

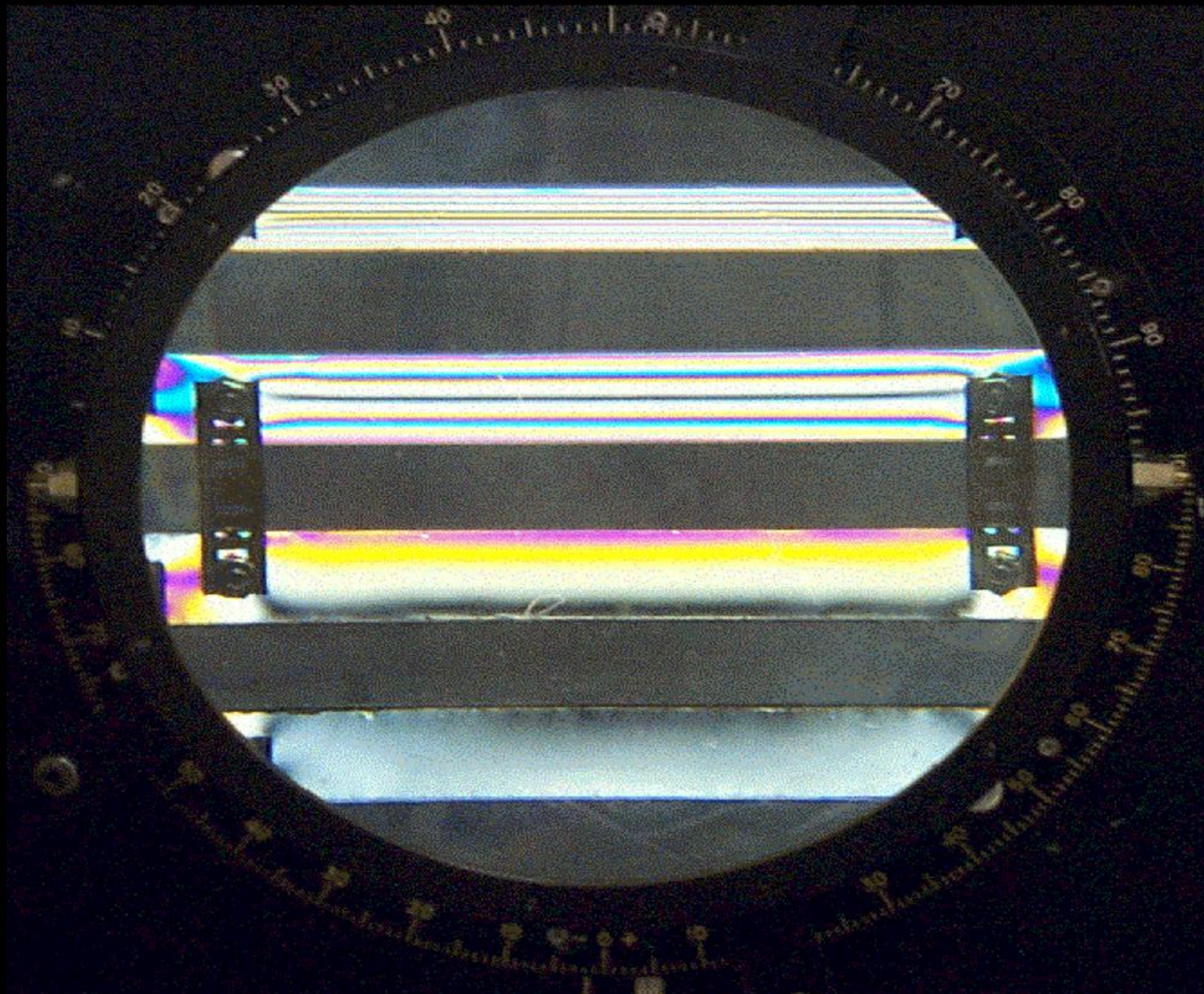
- Portland cement (266); latex (52); acrylic fortifier (16); micro-spheres (104); water (318)
- W/C = 1.2; density (757)
- modulus = 0.8 GPa; Poisson's ratio = 0.28
- compressive strength = 4.8 MPa
- tensile strength = 1.77 MPa
- "n" value (stiffness ratio) = 287

Steel Reinforced



Biszick, K.R., Gilbert, J.A., “Designing thin-walled, reinforced concrete panels for reverse bending," Proc. of the 1999 SEM Spring Conference on Theoretical, Experimental and Computational Mechanics, Cincinnati, Ohio, June 7-9, 1999, pp. 431-434.

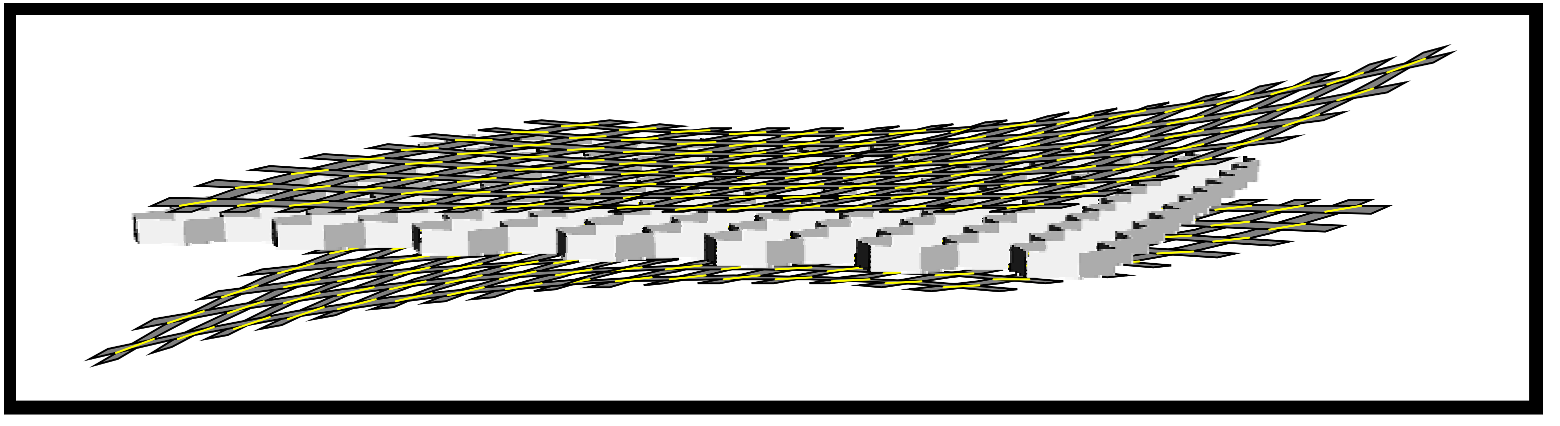
Stress Transfer



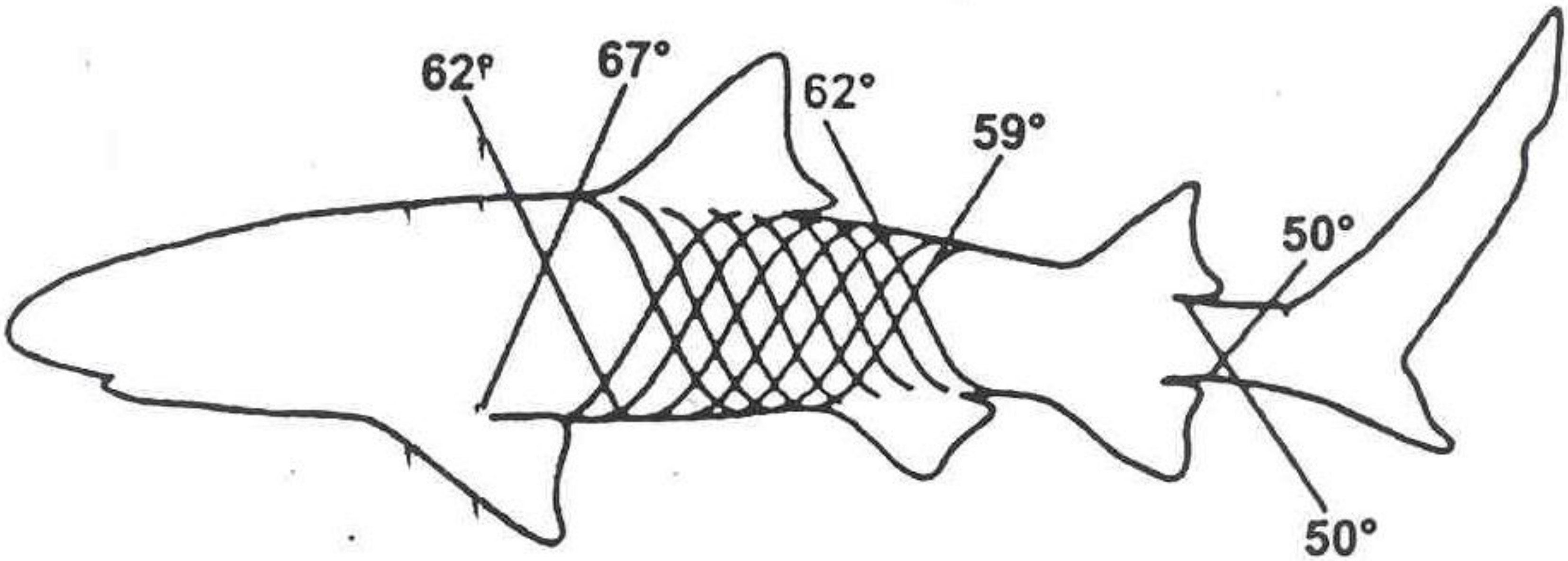
Biszick, K.R., Gilbert, J.A., “Designing thin-walled, reinforced concrete panels for reverse bending," Proc. of the 1999 SEM Spring Conference on Theoretical, Experimental and Computational Mechanics, Cincinnati, Ohio, June 7-9, 1999, pp. 431-434.

2^{nd} Generation (1999)

- non-impregnated graphite 3k tows spaced at 0.125 in.; 0.004 in. thick x 0.042 in. wide
- Mylar hexagonal honeycomb; 0.25 in. across when expanded; 0.22 in. thick

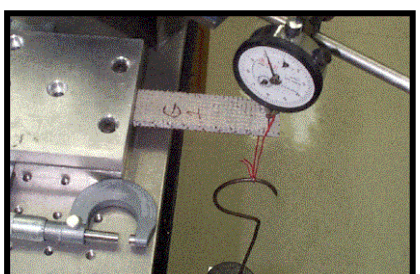


One of Nature's Best Kept Secrets



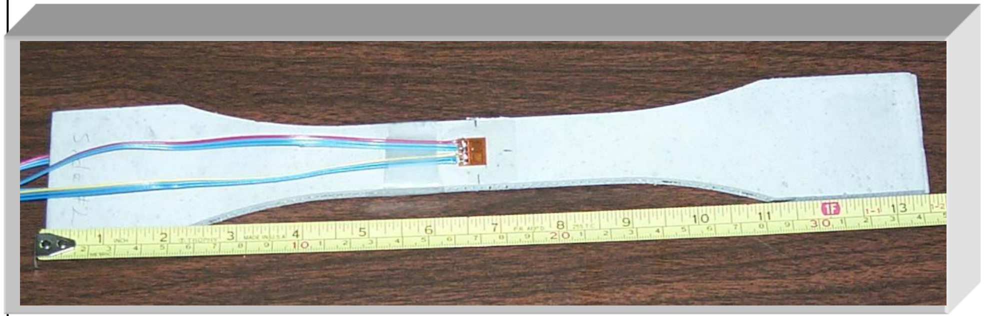
Advancements (2001)

- **rule of mixtures used to establish effective material properties**
- **modified transform section theory developed to determine stress and deflection**
- **laminated composite plate theory applied to study composites having multiple graphite layers with fibers oriented in different directions**

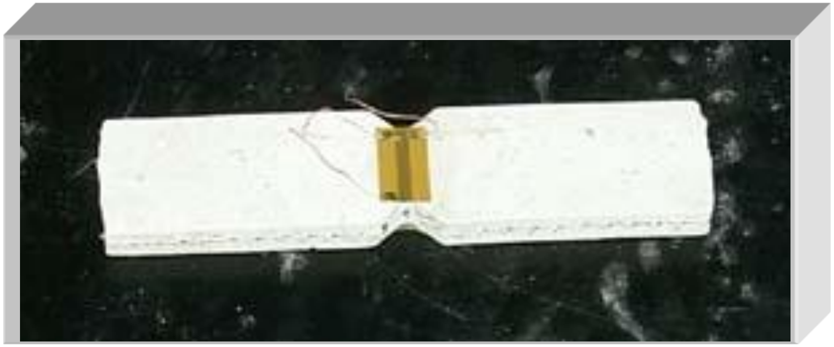


Vaughan, R.E., Gilbert, J.A., "Analysis of graphite reinforced cementitious composites," Proc. of the 2001 SEM Annual Conference and Exposition, Portland, Oregon, June 4-6, 2001, pp. 532-535.

Prepared and Tested Specimens



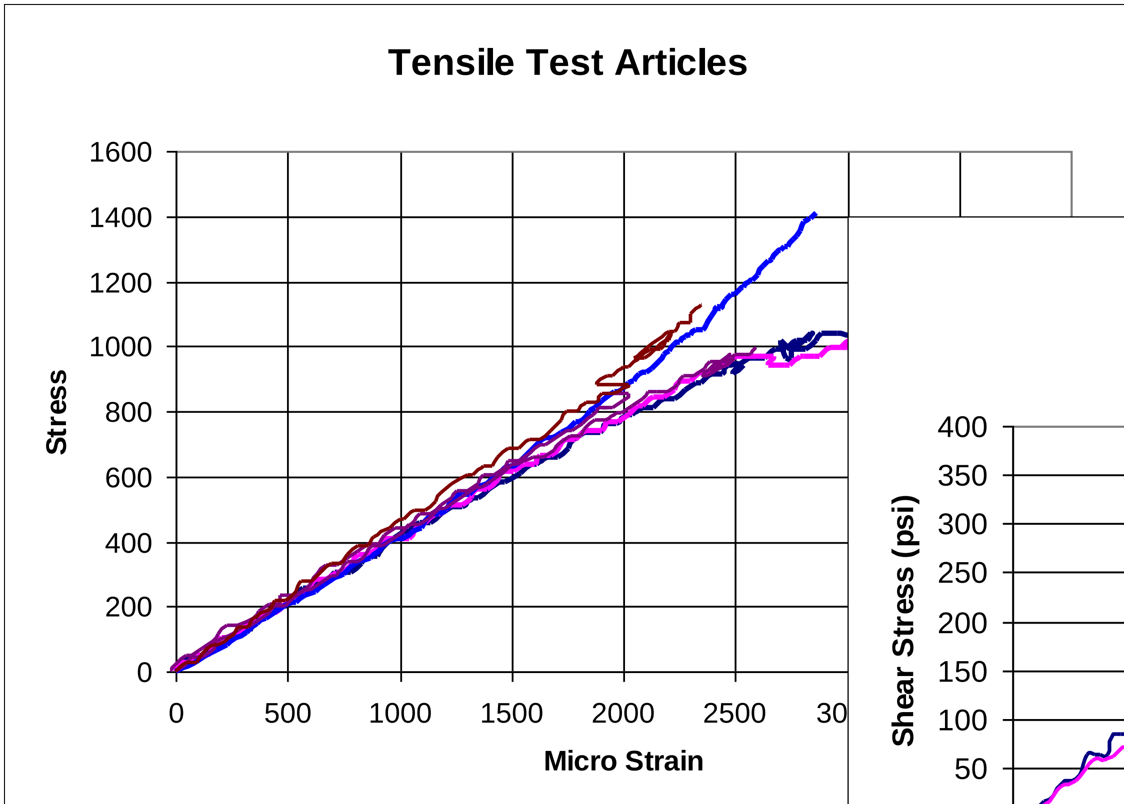
Typical dog bone specimen with Strain Gages Attached



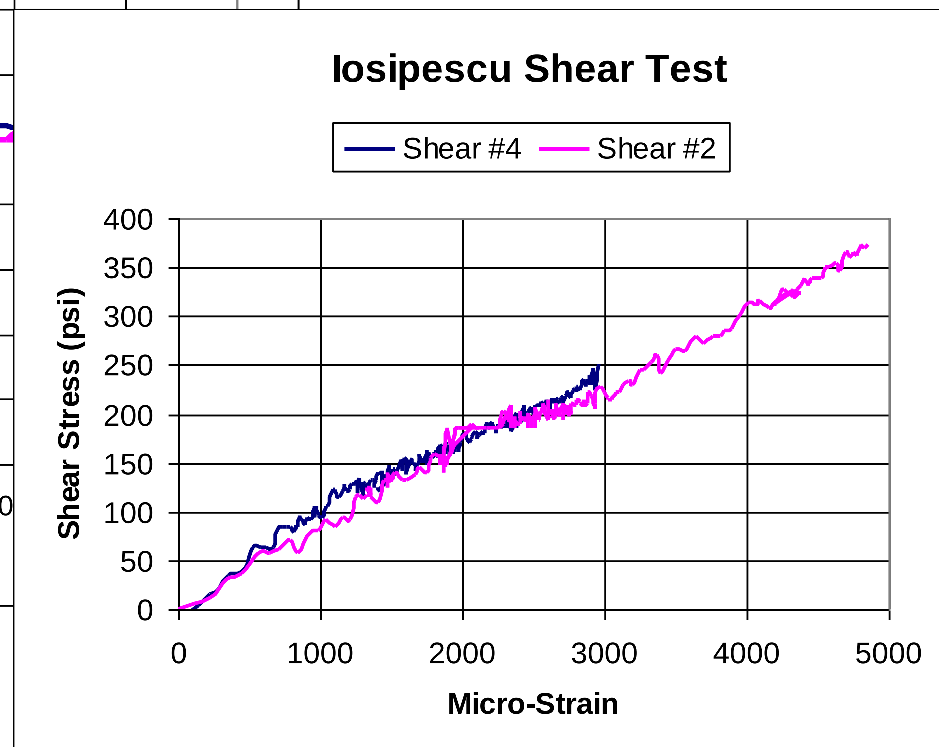
Shear Test Specimen with Strain Gages Attached

Cementitious Composite Test Specimen

Material Property Tests

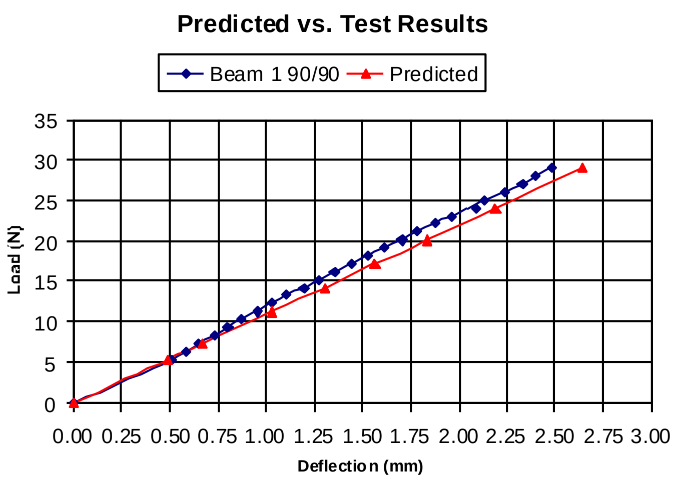


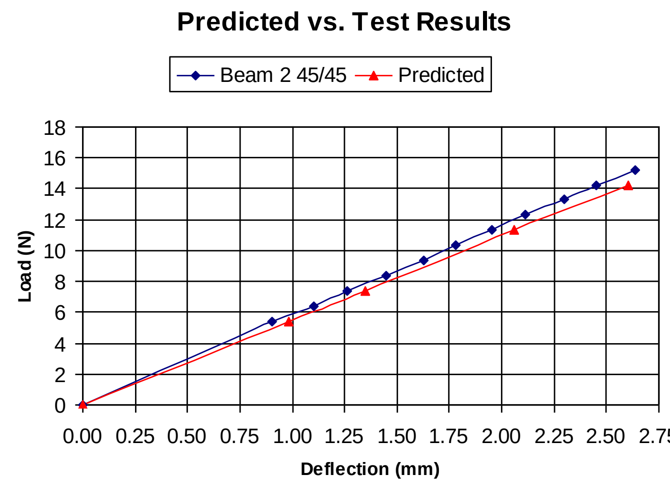
Shear Modulus

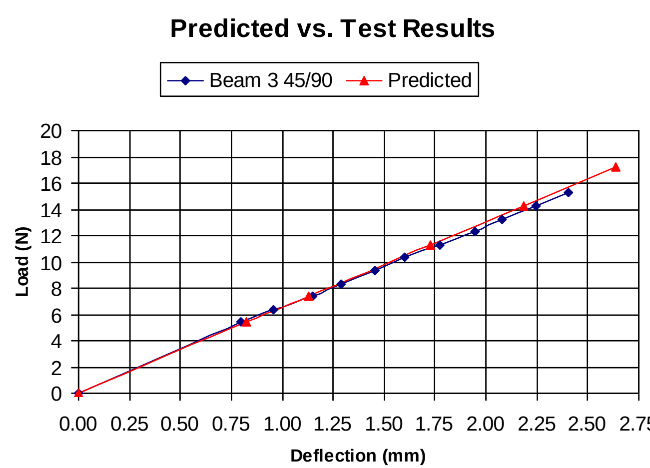


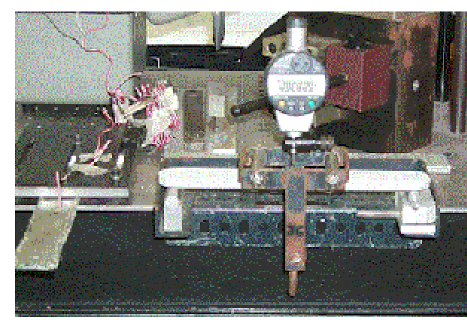
Elastic Modulus

Multi-Layered Composites









Laminated Plate Theory

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & B_{11} & B_{12} & B_{13} \\ A_{21} & A_{22} & A_{23} & B_{21} & B_{22} & B_{23} \\ A_{31} & A_{32} & A_{33} & B_{31} & B_{32} & B_{33} \\ B_{11} & B_{12} & B_{13} & D_{11} & D_{12} & D_{13} \\ B_{21} & B_{22} & B_{23} & D_{21} & D_{22} & D_{23} \\ B_{31} & B_{32} & B_{33} & D_{31} & D_{32} & D_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_{0x} \\ \varepsilon_{0y} \\ \gamma_{0xy} \\ K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

where $(A_{ij}, B_{ij}, D_{ij}) = \sum_{r=1}^{N} \int_{z_r}^{z_{r+1}} Q_{ij}^{(r)} (1, z, z^2)\, dz$ and

N_x, N_y, N_{xy} = resultant force and shear force in x-axis, y-axis, and x-y plane, respectively.

M_x, M_y, M_{xy} = resultant moment and twisting about x-axis, y-axis, and x-y plane, respectively

Z_r, Z_{r+1} = thickness coordinates of the lower and the upper surface of the r-th ply

$Q_{ij}^{(r)}$ = material stiffnesses of the r-th ply

Z = laminate transverse direction, normal to x-y plane

N = number of plies in the laminate

ε_{0x} = midplane strain in x-axis

ε_{0y} = midplane strain in y-axis

γ_{0xy} = midplane shear strain in x-y plane

K_x = plate bending curvature in the x-z plane

K_y = plate bending curvature in the y-z plane

K_{xy} = plate twisting curvature in the x-y plane

A_{ij} = extensional stiffnesses

B_{ij} = bending-extension coupling stiffnesses

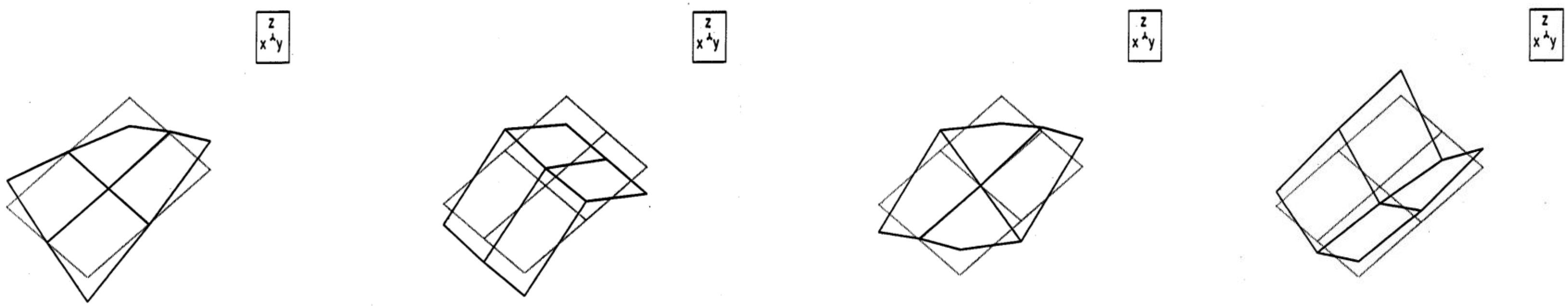
D_{ij} = bending stiffnesses

Dynamic Performance (2003)

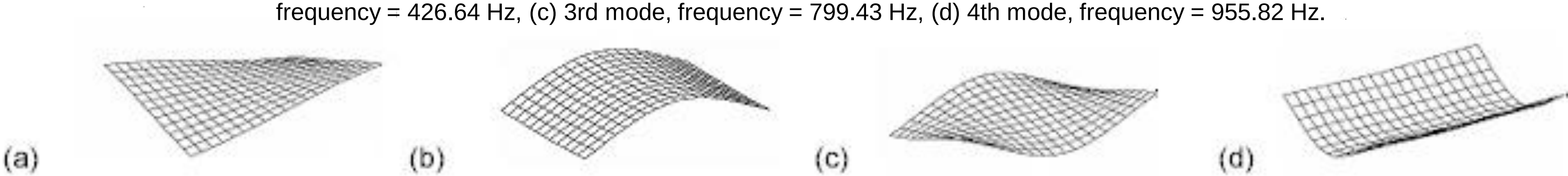
- quantified dynamic characteristics of GRCC laminated plates having different aspect ratios
- developed a dynamic finite element model to evaluate natural frequencies and mode shapes of "STAR" structures
- laminated composite plate theory applied to study builds having multiple graphite layers

Ooi, T.K., Vaughan, R.E. Gilbert, J.A., Engberg, R.C. Bower, M.V., "Dynamic characteristics of highly compliant graphite reinforced cementitious composite plates," Proc. of the 2003 SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Charlotte, North Caroline, June 2-4, 2003, Paper No. 133, 7 pages.

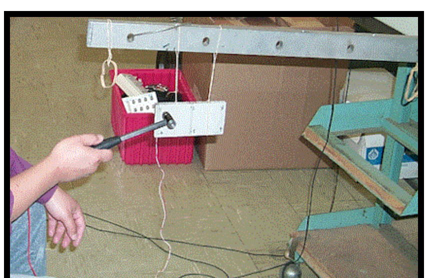
Structural Analysis (2005)



AR = 1.5. Experimental results for a 152.40 mm x 228.60 mm (6 in. x 9 in.) GRSPMC plate, (a) 1st mode, frequency = 342.11 Hz, (b) 2nd mode, frequency = 426.64 Hz, (c) 3rd mode, frequency = 799.43 Hz, (d) 4th mode, frequency = 955.82 Hz.



AR = 1.5. Finite element results for a 152.40 mm x 228.60 mm (6 in. x 9 in.) GRSPMC plate, (a) 1st mode, frequency = 269.50 Hz, (b) 2nd mode, frequency = 410.86 Hz, (c) 3rd mode, frequency = 674.20 Hz, (d) 4th mode, frequency = 913.14 Hz.



Ooi, T.K., Gilbert, J.A., Bower, M.V., Vaughan, R.E., Engberg, R.C., "Modal analysis of lightweight graphite reinforced silica/polymer matrix composite plates," Experimental Mechanics, 45(3), pp. 1-5 (2005).

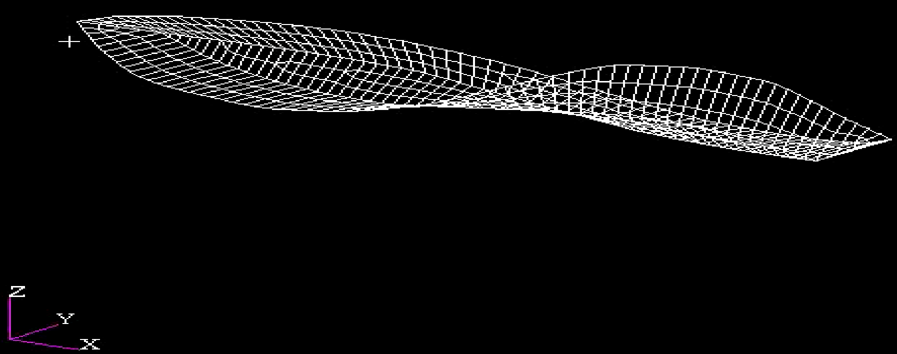
Gilbert, J.A., Ooi, T.K., Biszick, K.R., Marotta, S.A., Vaughan, R.E., Engberg, R.C., "Strategically tuned absolutely resilient structures," Proc. of SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Portland, Oregon, June 7-9, 2005, Paper No. 222, 14 pages.

Dynamic Tuning (2006)

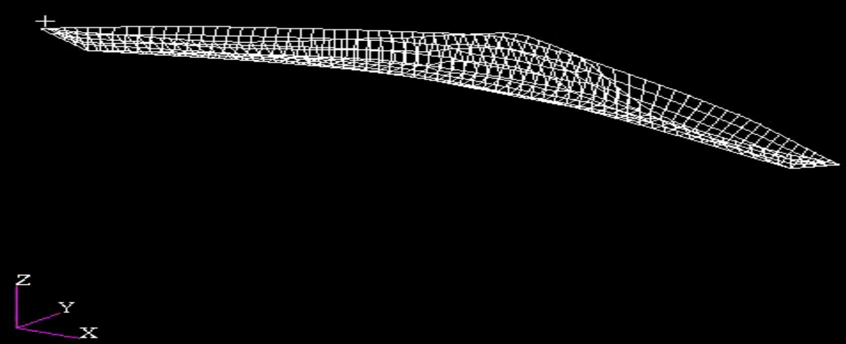
- design composite section to store **maximum strain energy**
- **drive structure to controlled resonance** to store elastic strain energy
- **release energy in a controlled fashion** to do useful work
- **attain significant advantages** through energy storage and conversion

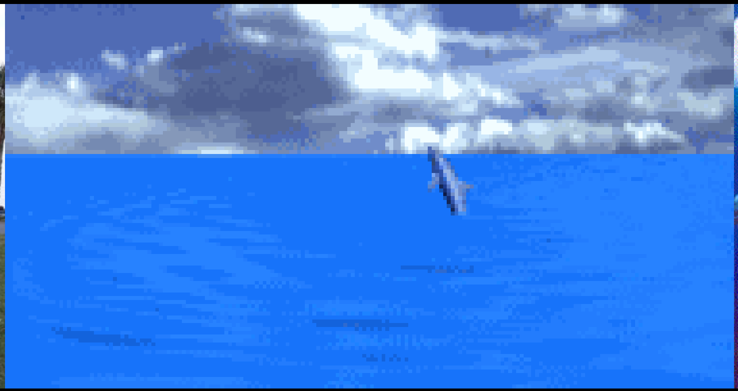
Structural Morphing

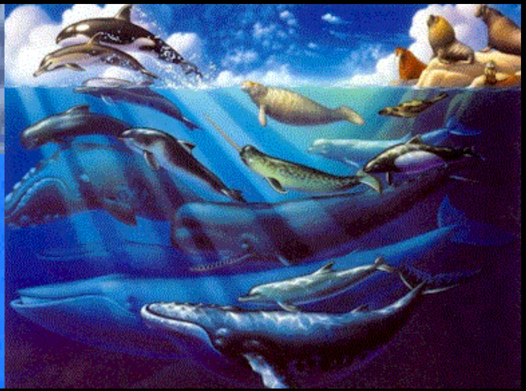
1st Mode
Anti-Symmetrical Torsion



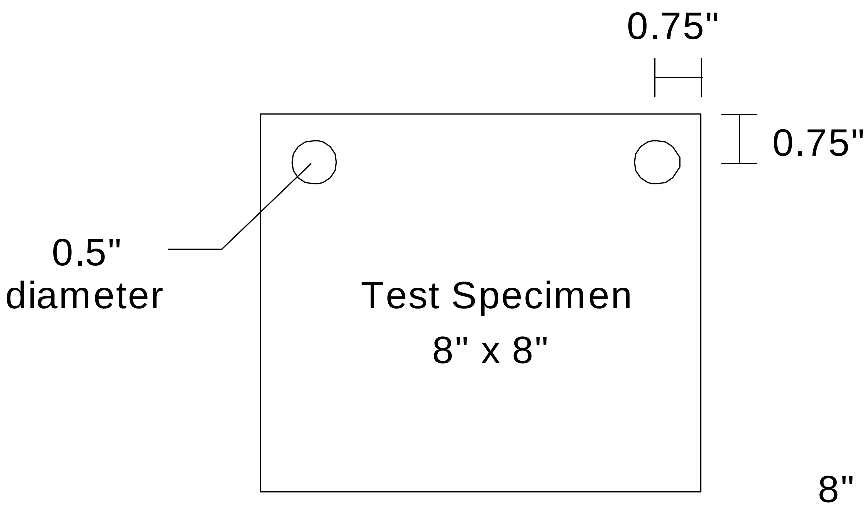
2nd Mode
Flutter Bending

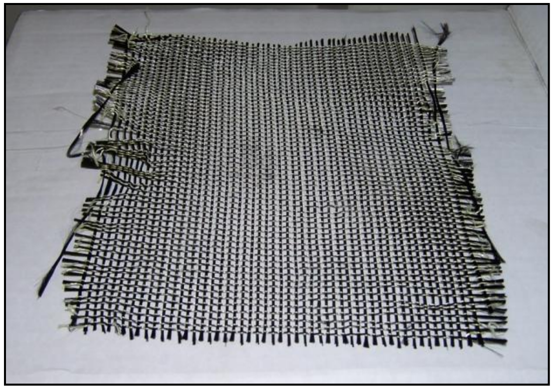


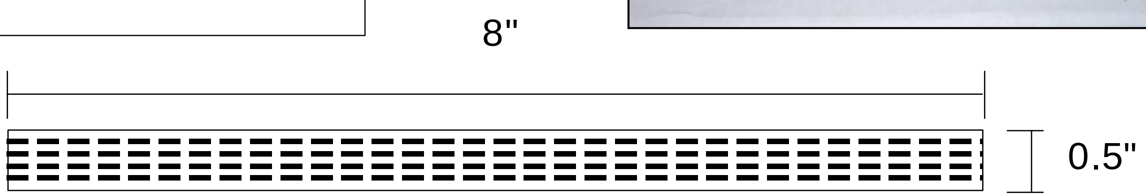




Ballistic Studies (2007)







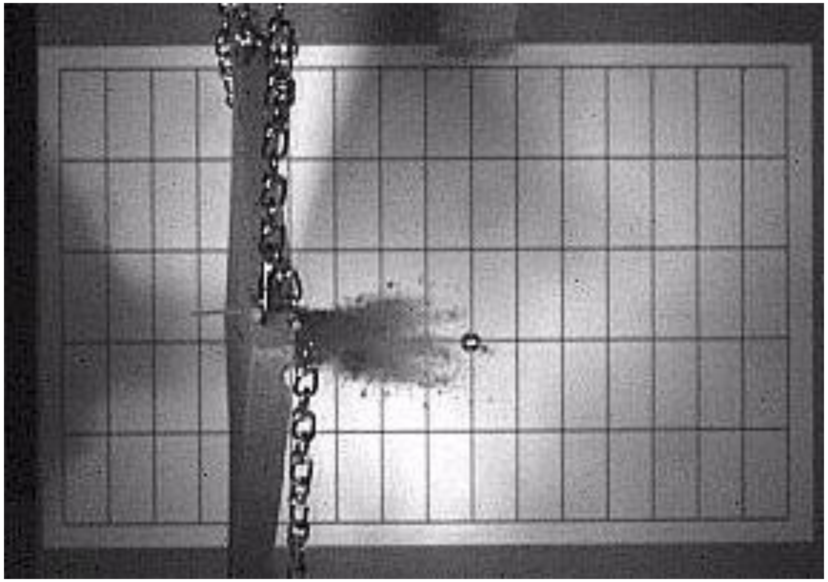
All concrete layers are 0.1" thick.

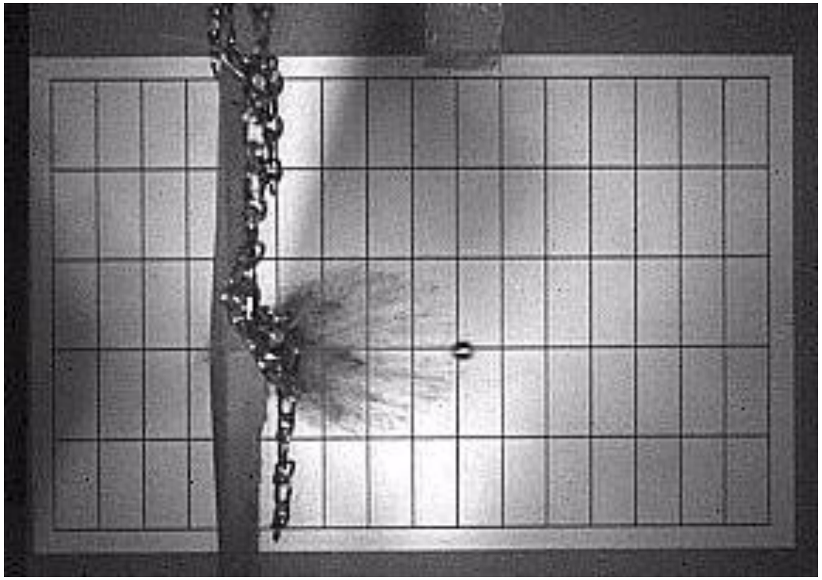
Graphite layers (- - -) spaced 0.1" apart.

Binek, L.A., Gilbert, J.A., Ooi, T.K., Bower, M.V., Biszick, K.R., "Ballistic testing of STARS," Proc. of SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Springfield, Massachusetts, June 3-6, 2007, Paper No. 196, 10 pages.

Observations Re: Debris

193 m/s (633 ft/s) | **403 m/s (1323 ft/s)**



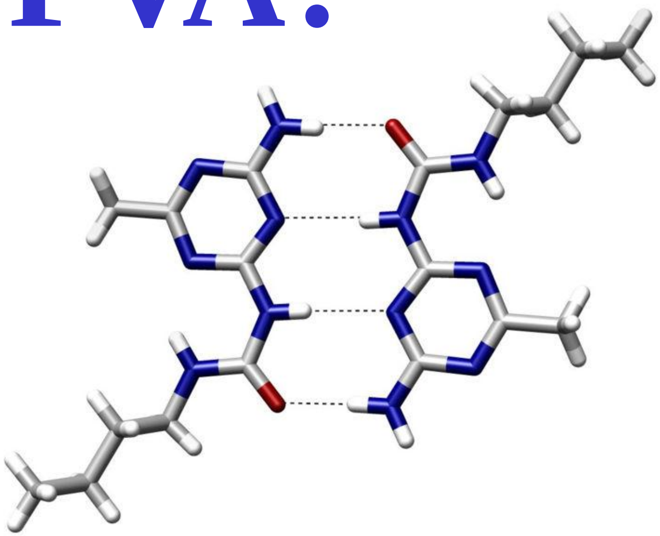


- **small particulates and no shear plugging**
- **slower strikers create more spall leading to greater mass reduction**

PVB/PVA Blends (2008)

- design composite by using Poly(vinyl butyral) (PVB) as the only aggregate
- reinforce the matrix with free fibers made from Poly(vinyl alcohol) (PVA)
- capitalize on nanotechnology and supramolecular chemistry to improve bonding in the interfacial transition zone (ITZ) to improve mechanical properties

Why PVB/PVA?

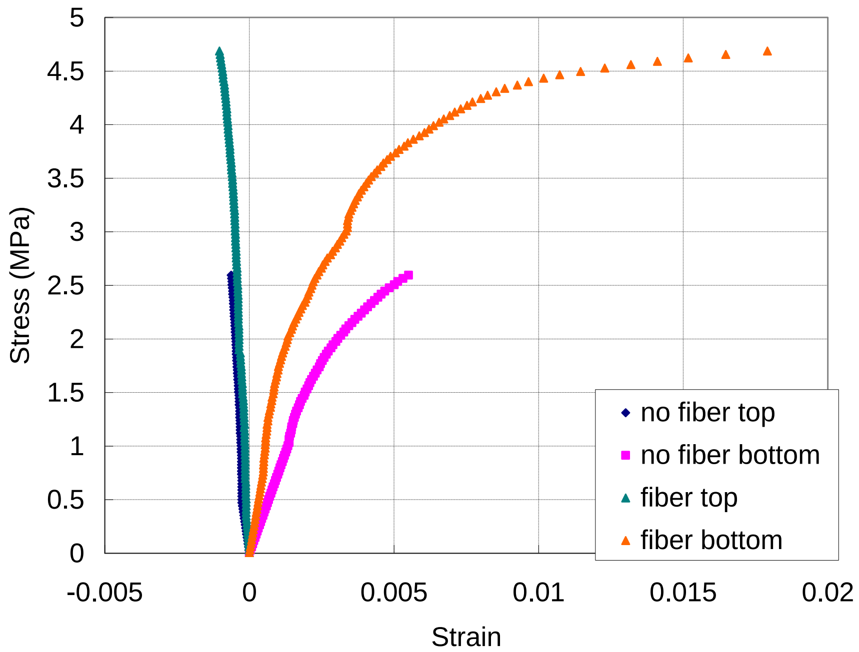


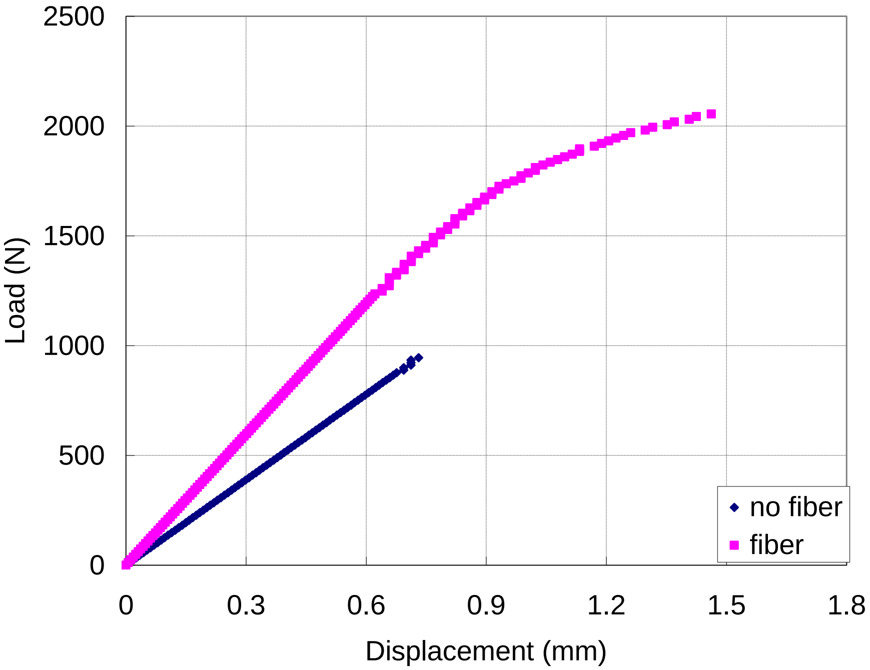
- hydroxyl groups form a strong hydrogen bond between and within molecules
- remarkable changes in the surface bond strength

  aggregate/matrix
  fiber/matrix
  fiber/aggregate

Lavin, T., Toutanji, H., Xu, B., Ooi, T.K., Biszick, K.R., Gilbert, J.A., "Matrix design for strategically tuned absolutely resilient structures (STARS)," Proc. of SEM XI International Congress on Experimental and Applied Mechanics, Orlando, Florida, June 2-5, 2008, Paper No. 71, 12 pages.

High Performance Cementitious Composites – HPC² (2010)



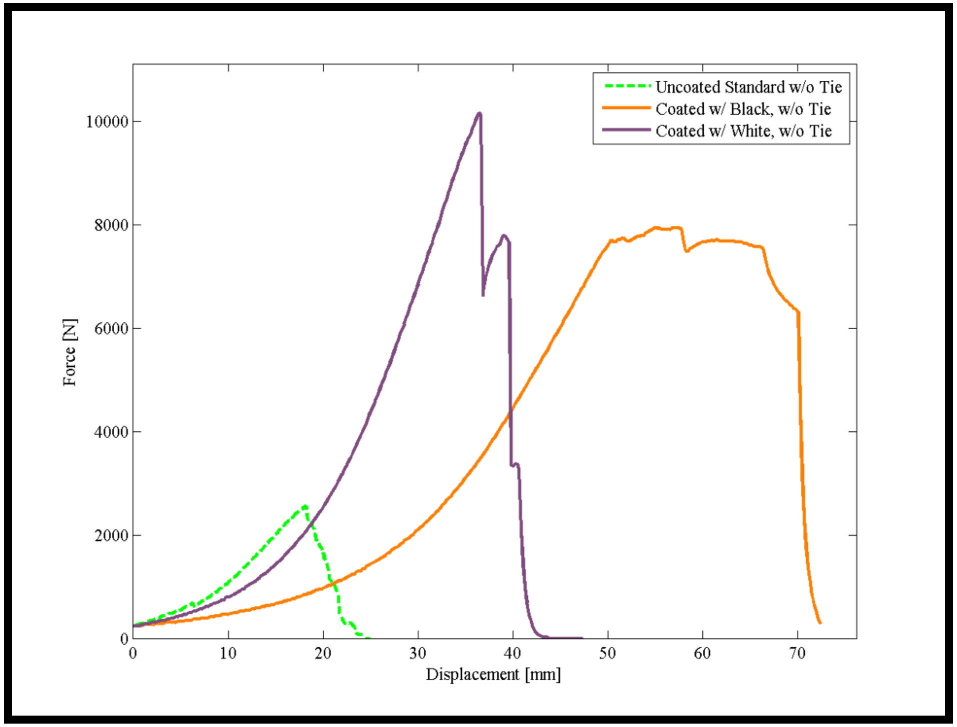


Toutanji, H., Xu, B., Lavin, T., Gilbert, J.A., "Properties of poly(vinyl alcohol) fiber reinforced high-performance organic aggregate cementitious material," Proc. ICPIC 2010 – 13th International Congress on Polymers in Concrete, Madeira Islands, Portugal, February 10-12, 2010, 8 pages. Selected by ICPIC's Special Committee for publication in "Advances in Polymers in Concrete , Switzerland.

High Performance Polyurea Composites – HP²C (2011)

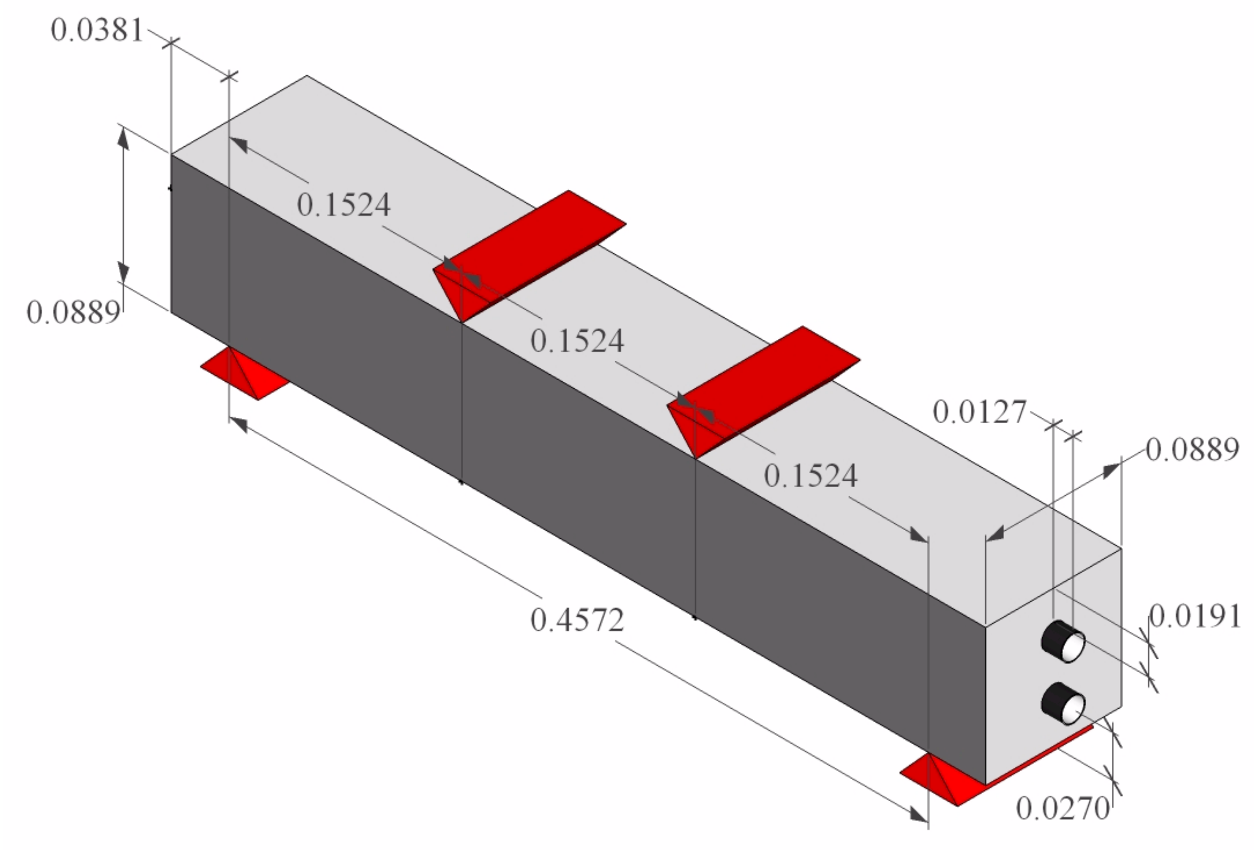
Standard

Unreinforced
No Coating



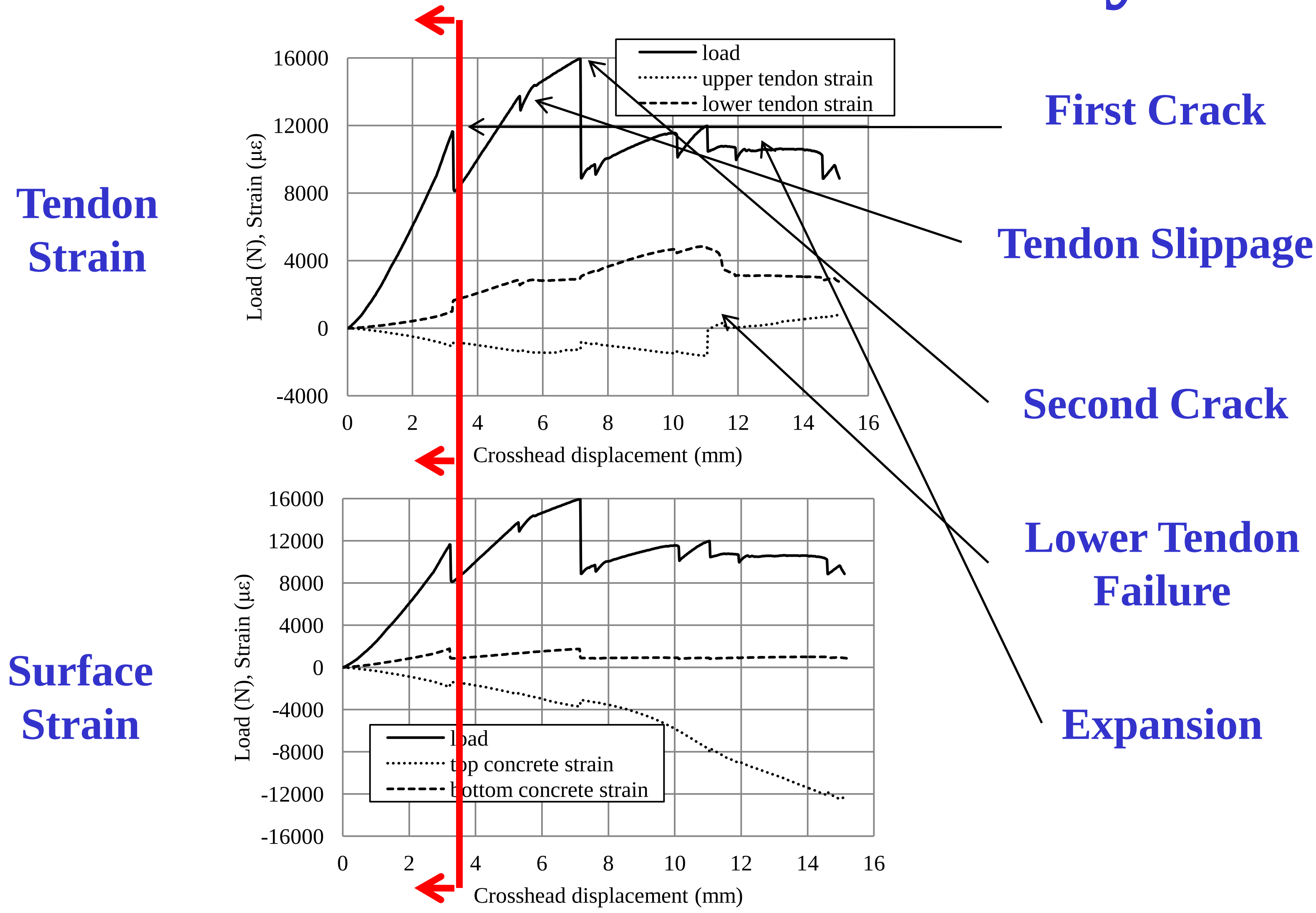
Alldredge, D.J., Gilbert, J.A., Toutanji, H, Lavin, T., Balasubramanyam, M.S., "Structural enhancement of framing members using polyurea," Proc. of SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Uncasville, Connecticut, June 13 - 16, 2011, Paper No. 143, 15 pages.

Doubly Reinforced Beams (2012)



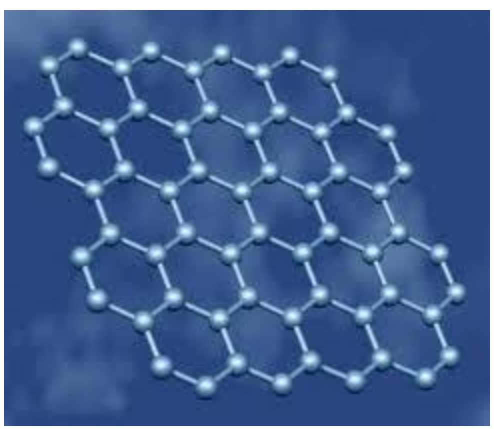
Biszick, K.R., Gilbert, J.A., Toutanji, H., Britz, M.T., "Doubly reinforcing cementitious beams with instrumented hollow carbon fiber tendons," to be published in Experimental Mechanics, ISSN 0014-4851, doi: 10.1007/s11340-012-9665-6, accepted 8/1/12.

Structural Information System



Advanced STARS (2013)

- **Graphene** - a one atom thin sheet of carbon atoms arranged in a Hexagonal format
- **Polyurea** – an elastomer that is derived from the reaction product of an isocyanate component and a synthetic resin blend component



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n = 10,000

Conclusions

- extremely efficient and lightweight structures can be designed and constructed to resist reverse loadings
- design based on both compliance and strength of materials
- construction relies on a flexible matrix placed over multiple layers of relatively stiff reinforcement

Conclusions - Con't

- structural performance can be monitored by integrated sensing
- store significant strain energy without sustaining damage
- stored energy can be strategically released and converted to work
- significant potential for many new civil, mechanical, and aerospace engineering applications