Advanced Composite Material Applications in Structural Engineering

Advances and Challenges

By

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OUTLINE

- Introduction: *What are Composite Materials?*
- Bridge Applications
- Final Remarks

What are Composite Materials?

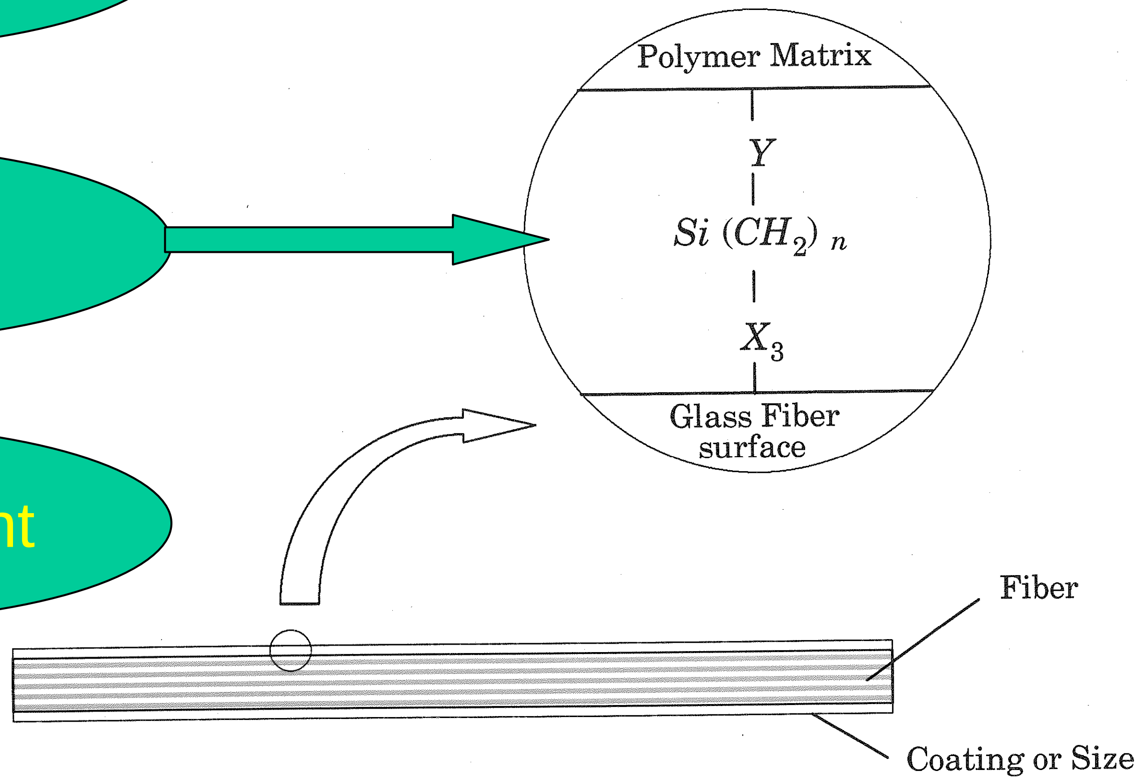
- Composite structures are often called fiber reinforced polymer (FRP) structures, and polymer matrix composites (PMC).
- Composite materials are man-made, and must contain at least two constituents that are distinct chemically and physically.
- Intended to achieve an increase in certain properties such as stiffness, strength, fracture toughness among others, or decrease certain properties such as weight and corrosion. Composites in general can be categorized in two groups as follows:

Composites Architecture

Matrix

Interface

Reinforcement



Reinforcement

- Long continuous bundles

  l/d > 10 by definition, (typical dia for a fiber ~ 6-15 μm)
  unidirectional
  multidirectional
  woven or braided Continuous fibers

- Short chopped fibers

  randomly oriented

- Whiskers

  long thin crystals d< 1 micron length in the order of 100 microns used in ceramic matrix composites (CMC) and metal matrix composites (MMC)

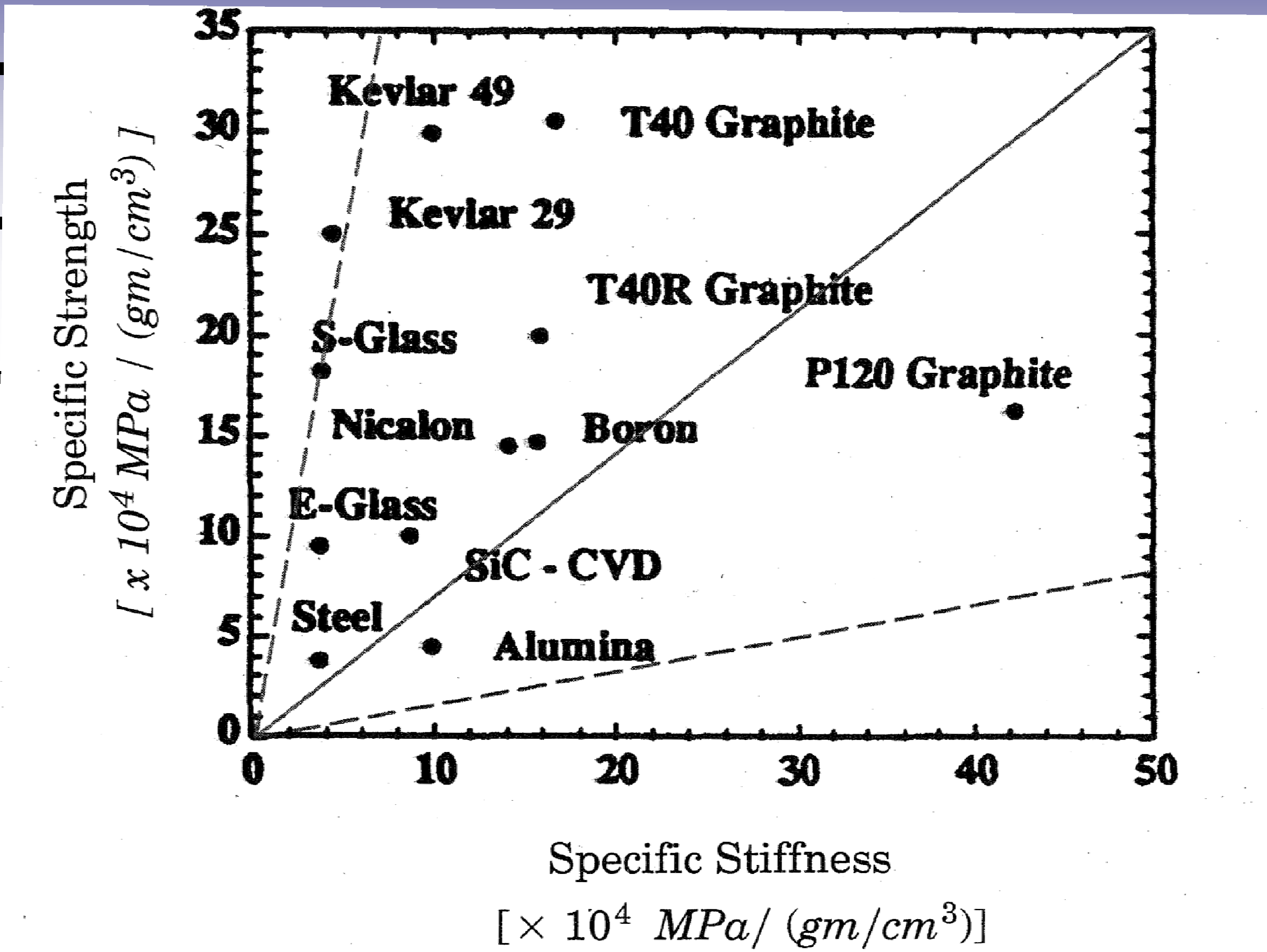
- Particulates

  Near spherical
  not usually used for strength
  increase the toughness of the material

- Flakes

  metallic, electrical/heating applications
  2-D in nature, not usually used for strength

Reinforcement (cont'd)



Matrix

- Metallic
- Ceramic
- Polymeric
  - Thermoplastic
  - Thermoset

Polymer Matrix

Poly mer

Linear

Branched

Some Properties of Thermoset & Thermoplastic		
	Epoxy	Polycarbonate
ρ (g/cm^3)	1.2	1.0
σ_u (MPa)	50-130	60
E (GPa)	3-4	2.2
α_L $(10^{-6}/{}^oC)$	60	70
Elongation (%)	1-8	50-100

(c)

Network

Composites Categories

Reinforced Plastics

- Low strength and stiffness
- Inexpensive
- Glass fibers is primary reinforcement
- Applications:
  - Boat Hulls
  - Corrugated sheets
  - Piping
  - Automotive panels
  - Sporting goods

Advanced Composites

- High strength and stiffness
- Expensive
- High performance reinforcement such as: graphite, aramid, kevlar
- Applications:
  Aerospace industry

Typical Applications in Structural Engineering

- Retrofitting of beams and columns
- Seismic Retrofitting
- New applications
  - Bridge Deck
  - Bridge Superstructure

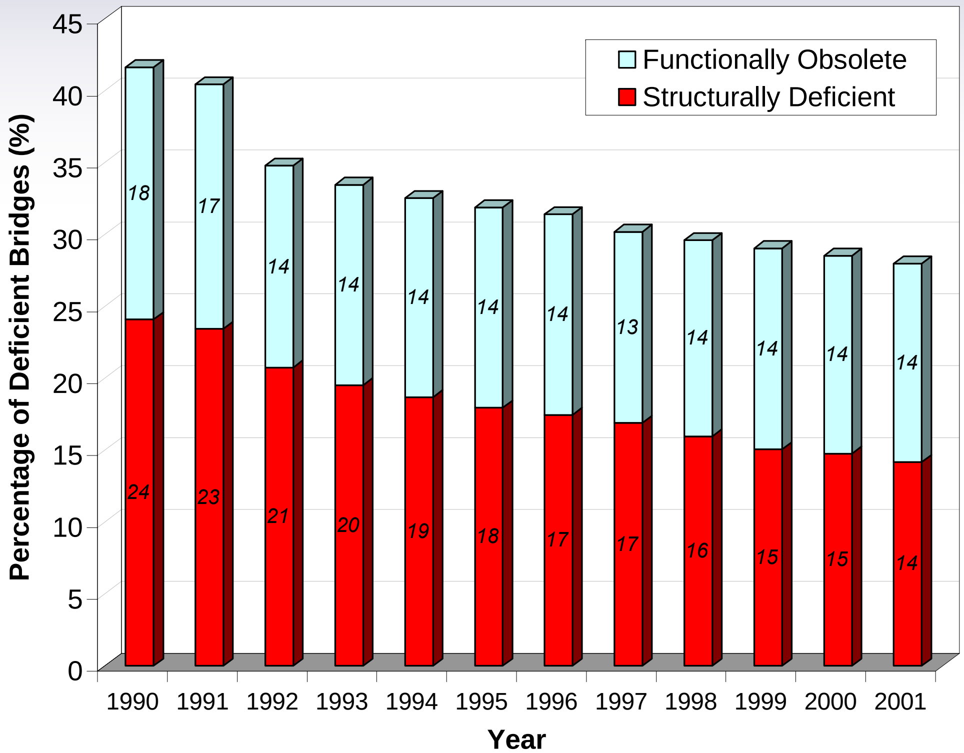
FRP COMPOSITES IN STRUCTURAL APPLICATIONS

- Advantages
  - High specific strength and stiffness
  - Corrosion resistance
  - Tailored properties
  - Enhanced fatigue life
  - Lightweight
  - Ease of installation
  - Lower life-cycle costs
- Factors preventing FRP from being widely accepted
  - High initial costs
  - No specifications
  - No widely accepted structural components and systems
  - Insufficient data on long-term environmental durability

CONDITIONS OF U.S. HIGHWAY BRIDGES

- **28%** of 590,000 public bridges are classified as "deficient".
- The annual cost to improve bridge conditions is estimated to be **$10.6 billion**.

Need for bridge systems that have long-term durability and require less maintenance



(Source: National Bridge Inventory)

Demand for FRP in Bridge Applications

Is it necessary to use expensive FRP materials for bridge renewal?

Given the massive investment to renew deficient bridges (28% of all bridges are deficient), repeating the same designs, materials, etc. may not be a prudent approach.

Consider the fact that the average life span of a bridge in the U.S. is less than 50 years.

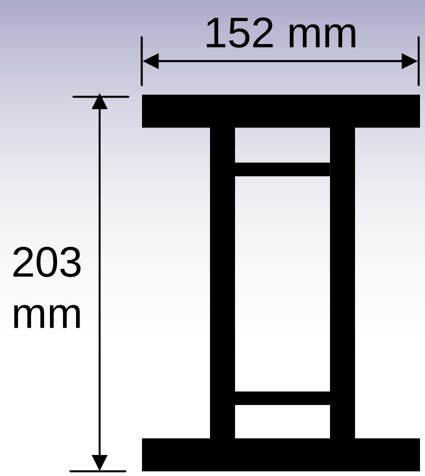
FRP materials, if designed properly, could provide new bridges that last over 100 years.

Glass Fiber Reinforced Polymer (GFRP) Box Sections

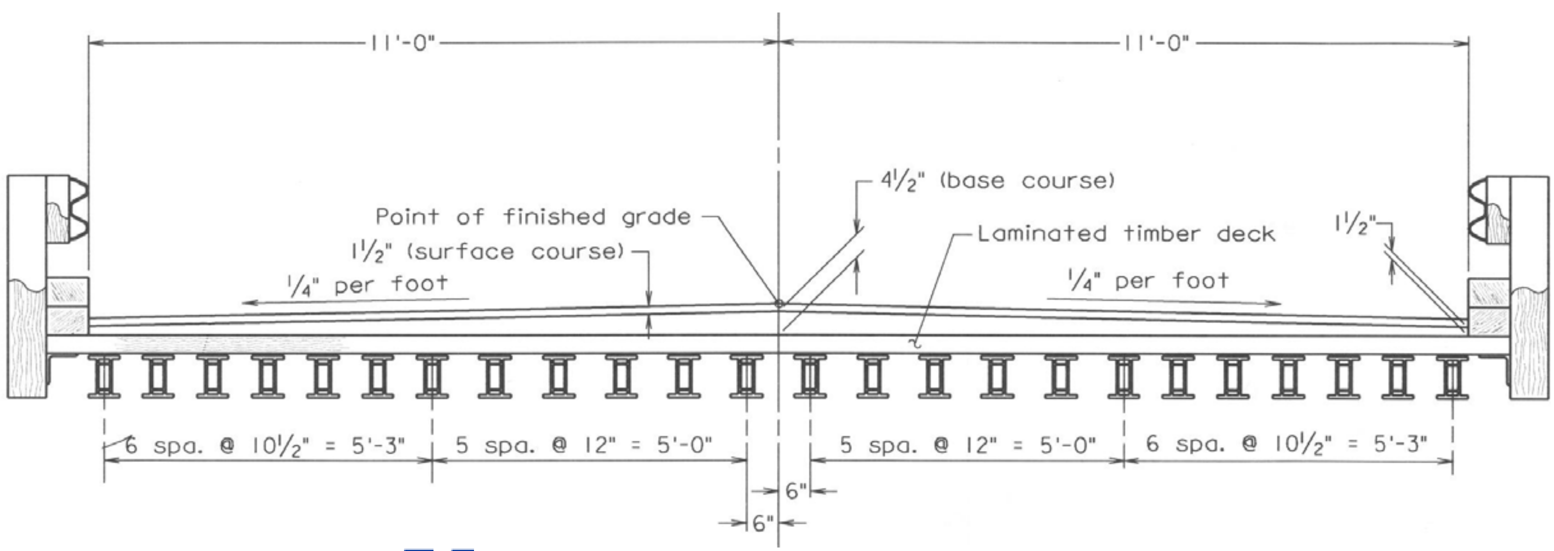
- The compressive flange is weaker than the tensile flange.
- A failure of a GFRP box section usually occurs in a catastrophic manner.
- The design of a GFRP box section is usually governed by stiffness instead of strength.

Hybrid design
or
Special structural system

BRIDGE APPLICATIONS – 1 (TOM'S CREEK BRIDGE)



- Virginia Tech and Strongwell
- Pultruded composite beam (hybrid design of glass and carbon fibers and vinyl ester matrix)
- Span : 5.33 m , Width : 7.32 m

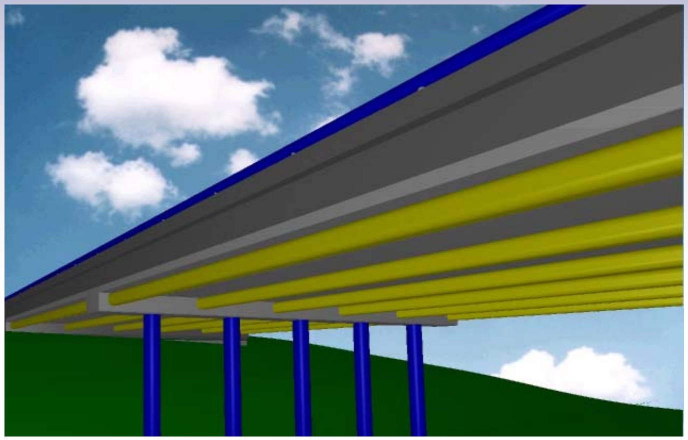


BRIDGE APPLICATIONS – 2 (TECH 21 BRIDGE)

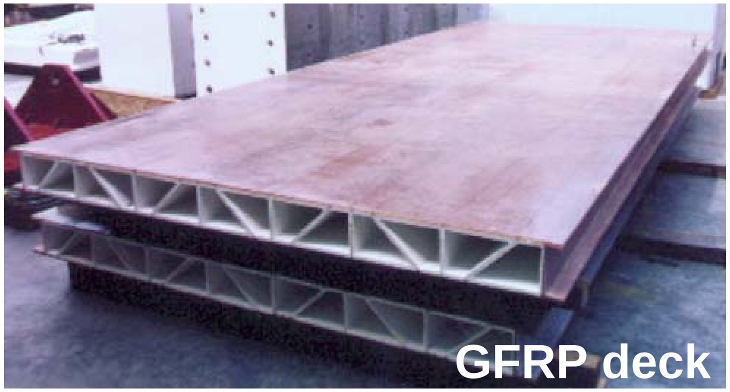
- LJB Engineers & Architects, Inc. and Martin Marietta Materials
- Length : 10.1 m, Width : 7.3 m
- E-glass fiber reinforcement and polyester matrix
- Deck : pultruded trapezoidal tubes between two face sheets (tubes run parallel with the traffic direction)
- Stringer : three U-shaped structural beams

BRIDGE APPLICATIONS – 3
(KINGS STORMWATER CHANNEL BRIDGE)

- UC San Diego, Alliant TechSystems, Inc., and Martin Marietta
- Span: 2 x 10 m, Width: 13 m
- Six longitudinal concrete filled carbon tube girders (carbon/epoxy system)
- GFRP deck panel (pultruded trapezoidal E-glass/epoxy tubes with a top skin layer



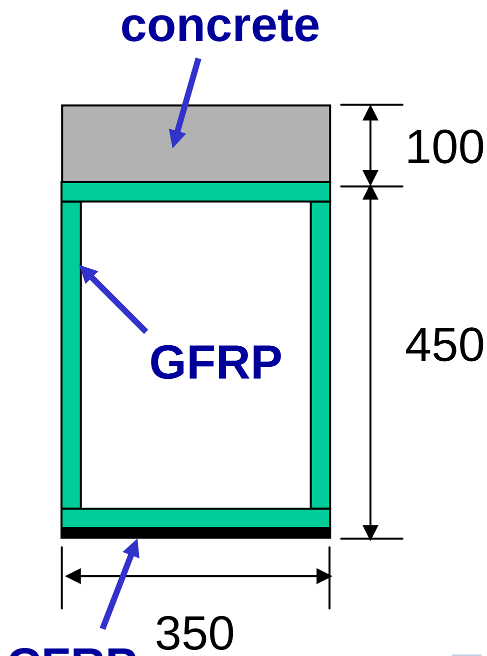
Filament wound CFRP tube



GFRP deck

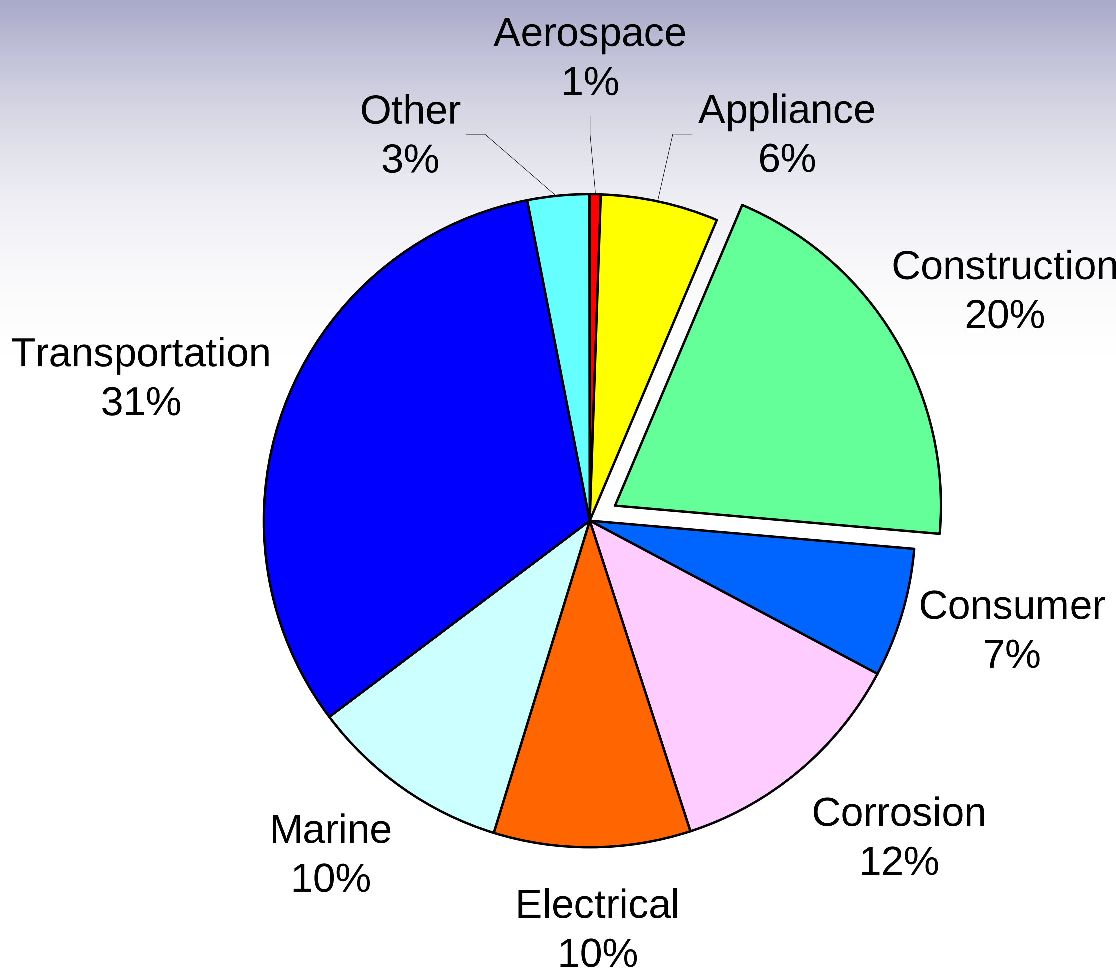
BRIDGE APPLICATIONS – 4 (TOOWOOMBA BRIDGE)

- University of Southern Queensland, Wagners Composite Fibre Technologies, and Huntsman Composites
- Span : 10 m, Width : 5.0 m
- Hybrid box beams : prefabricated concrete, GFRP, and CFRP

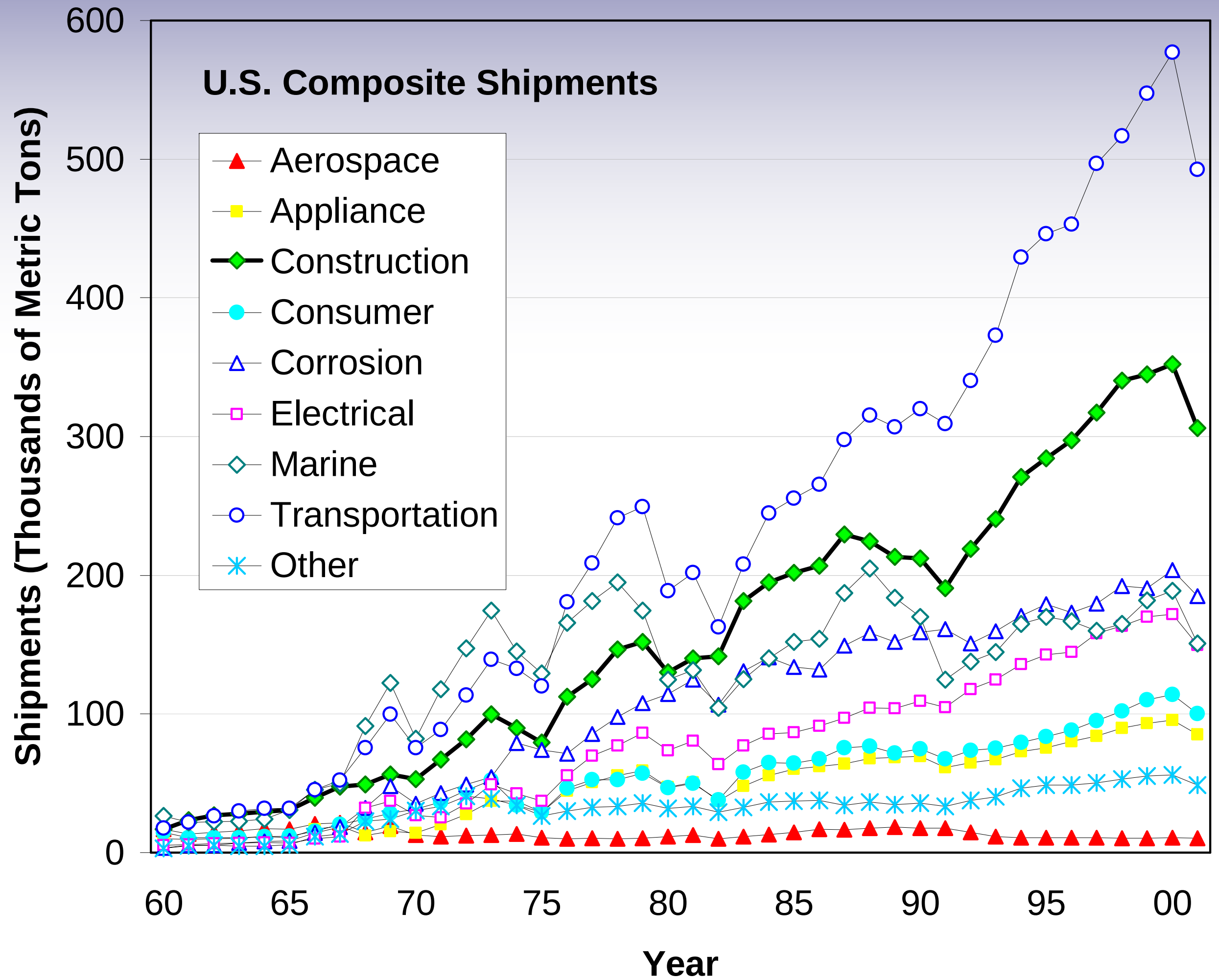


(dimensions in mm)

MARKET SHARE (FRP COMPOSITES)



FRP COMPOSITE SHIPMENTS



Recent Development of FRP Bridge Deck and Superstructure Systems

Hybrid-FRP-Concrete Bridge Deck and Superstructure System

- The system is developed at UB by an optimum selection of concrete and FRP.
- The system is validated analytically and experimentally to assess the feasibility of the proposed hybrid bridge superstructure and deck.
- Simple methods of analysis for the proposed hybrid bridge superstructure were developed.

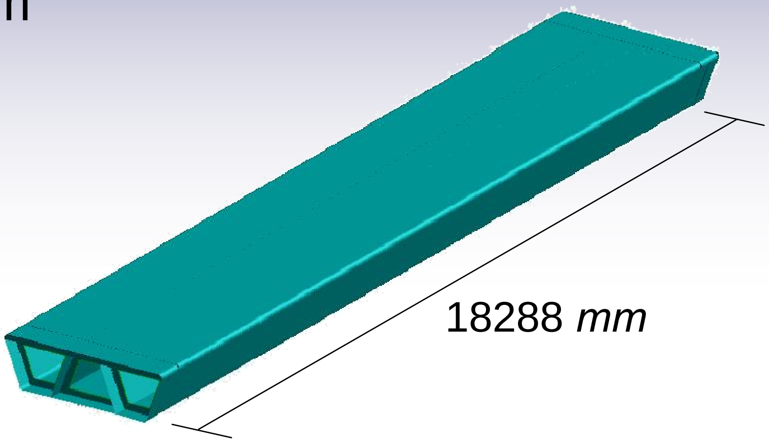
BASIC CONCEPT OF PROPOSED HYBRID FRP-CONCRETE BRIDGE

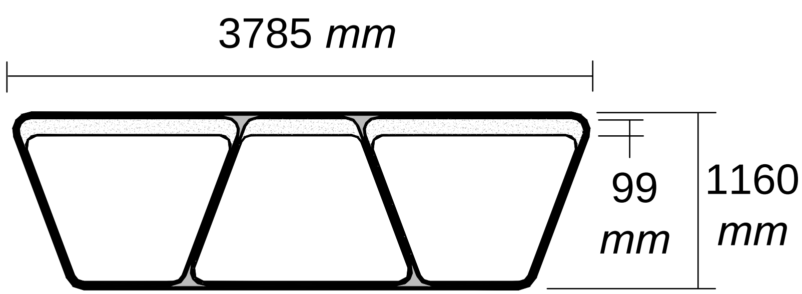
- Single span with a span length of 18.3 m
- AASHTO LRFD Bridge Specifications
  - Live load deflection check

    d_{LL}*<L/800 under (1+IM)Truck*
  - Service I limit

    DC+DW+Lane+(1+IM)Truck
  - Strength I limit

    1.25DC+1.5DW+1.75[Lane+(1+IM)Truck]
- Concrete should fail first in flexure.
- A strength reduction factor for GFRP was taken as 0.4.





Simple-span one-lane hybrid bridge

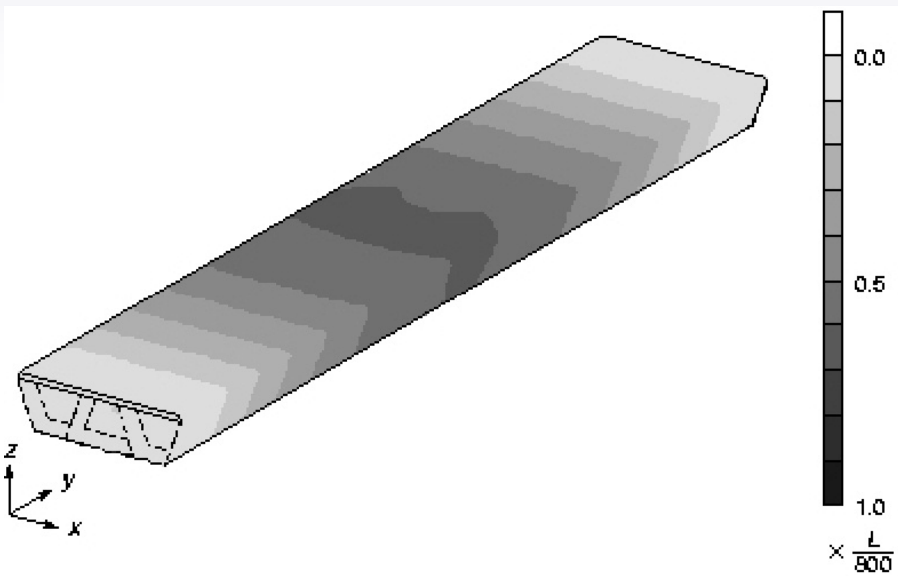
PROPOSED HYBRID BRIDGE SUPERSTRUCTURE

Advantages include:

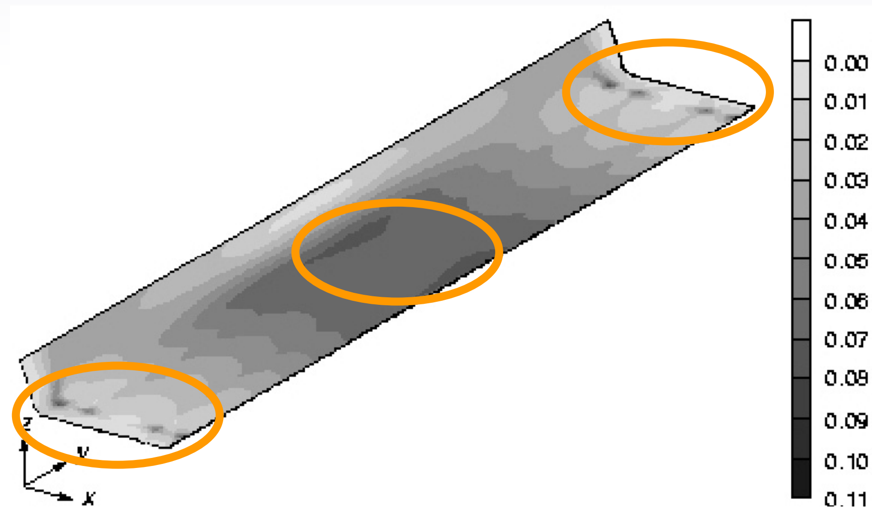
- Increase in stiffness
- Corrosion resistance
- Cost-effectiveness
- Lightweight
- Local deformation reduction
- High torsional rigidity
- Pre-fabrication
- Short construction period

DISPLACEMENT AND STRENGTH CHECKS

- Deflection check: 0.61 x L/800
- Max. failure index : 0.107 (safety factor=3.1)



(a) Live load deflection check



(b) Tsai-Hill Failure index under Strength I limit

TSAI-HILL FAILURE INDEX

$$\boxed{I_{TH} = \frac{\sigma_1^2}{X^2} - \frac{\sigma_1 \sigma_2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\sigma_6^2}{S^2}}$$

Failure condition : $\underline{I_{TH} = 1.0}$

where

$$\{\sigma_1\ \sigma_2\ \sigma_6\} = \{\sigma_{11}\ \sigma_{22}\ \tau_{12}\}$$

$$X = \begin{cases} X^T & \text{for} \quad \sigma_1 > 0 \\ X^C & \text{otherwise} \end{cases} \qquad Y = \begin{cases} Y^T & \text{for} \quad \sigma_2 > 0 \\ Y^C & \text{otherwise} \end{cases}$$

$X,\ Y,$ and S : Strengths in the principal 1 and 2 directions and in-plane shear

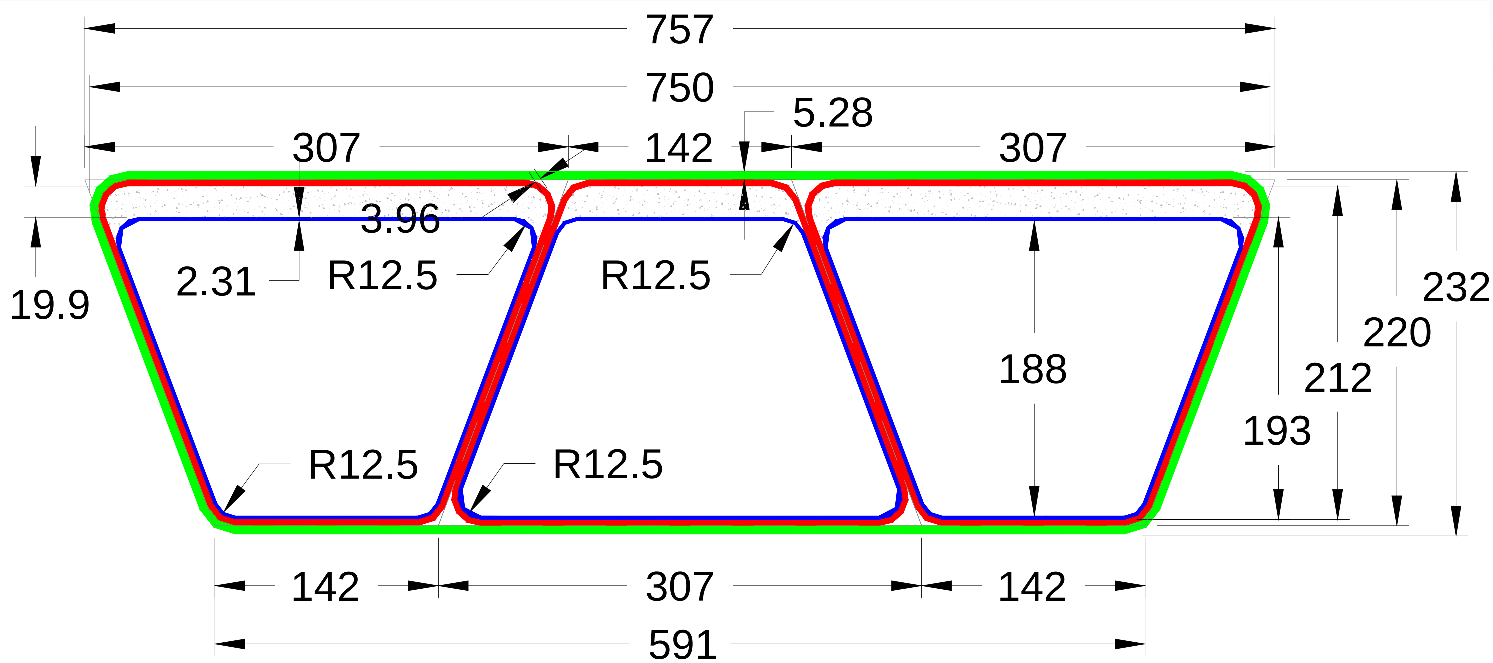
T and C : Tensile and compressive directions

EXPERIMENTAL PROGRAM

- Materials
  - GFRP
  - Concrete
- Non-destructive tests
  - Flexure
  - Off-axis flexure
- Fatigue test
- Destructive tests
  - Flexure
  - Shear
  - Bearing

TEST SPECIMEN

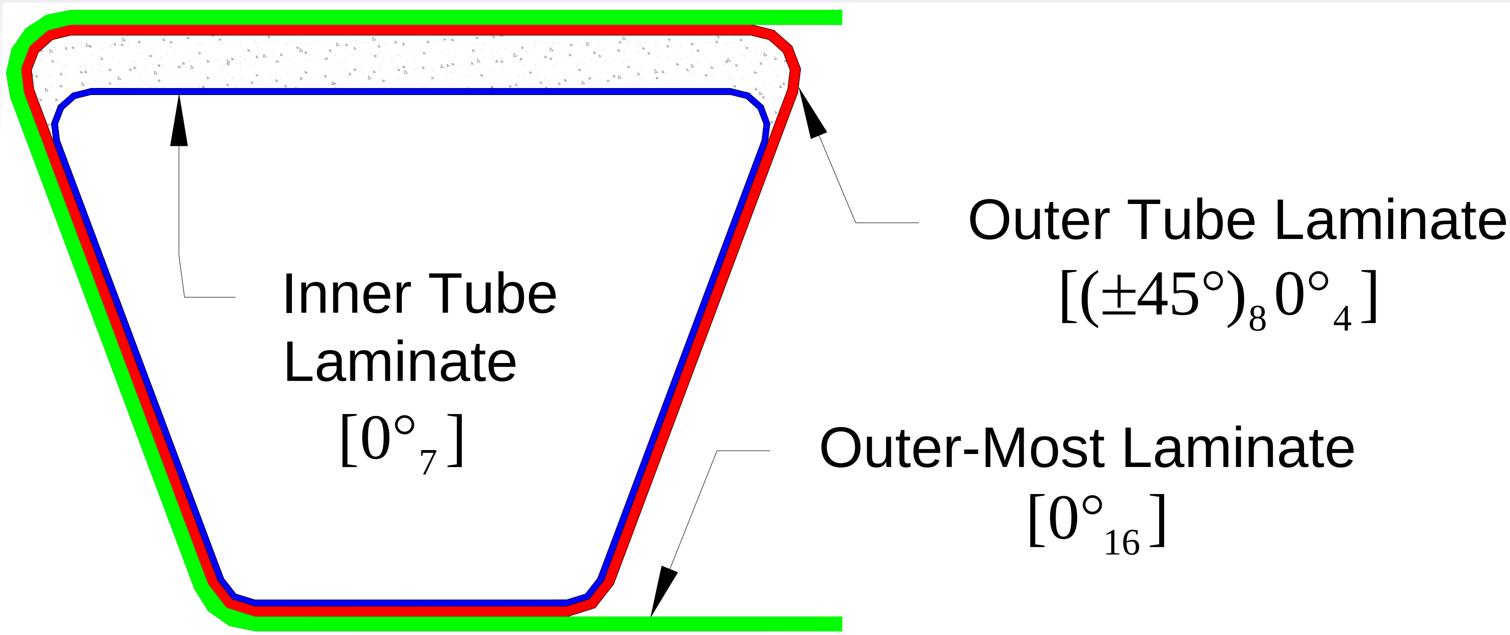
- One-fifth scale model
- Span length = 3658 mm



(dimensions in *mm*)

STACKING SEQUENCES

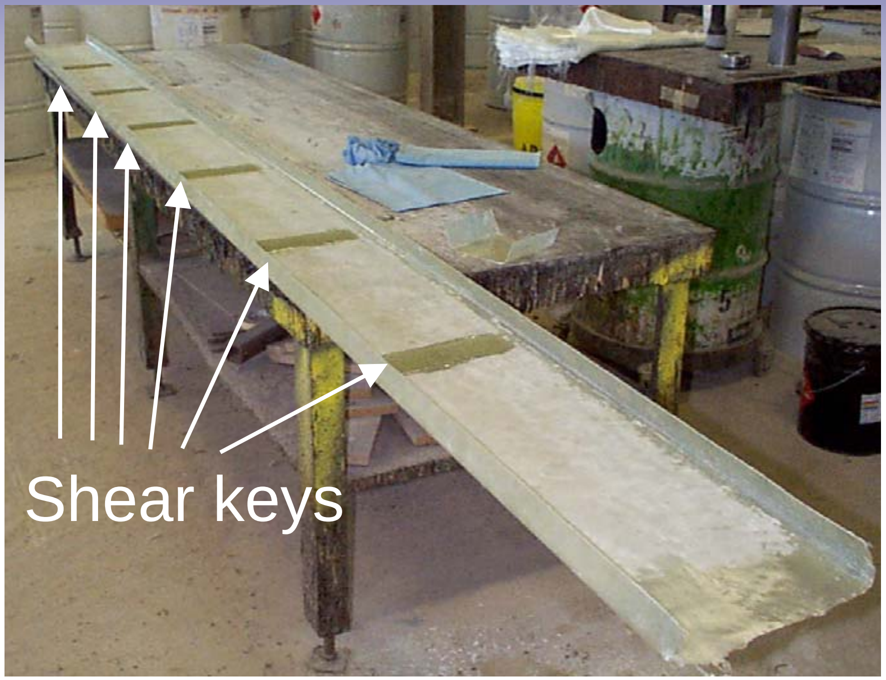
- Thickness of one layer = 0.33-0.40 mm

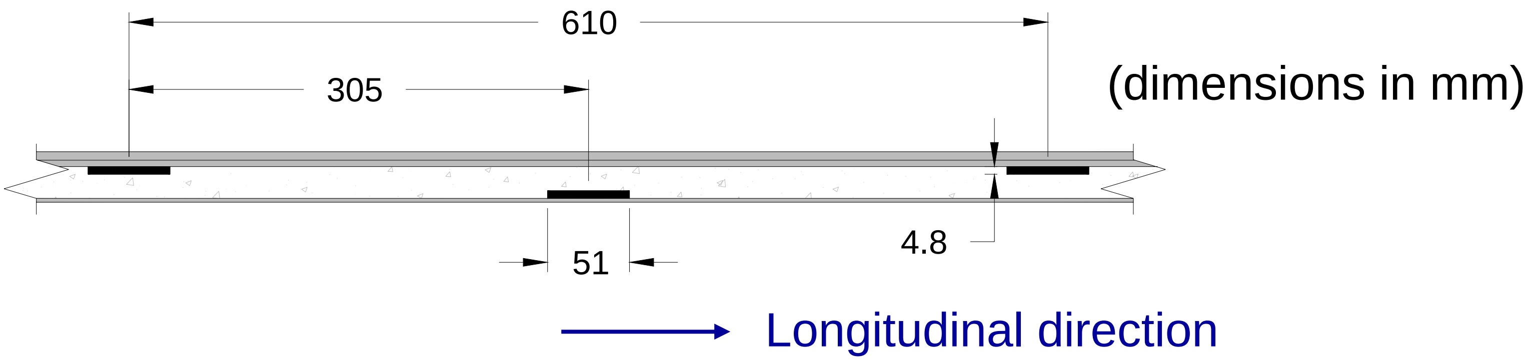


FABRICATION – 1

FABRICATION – 2

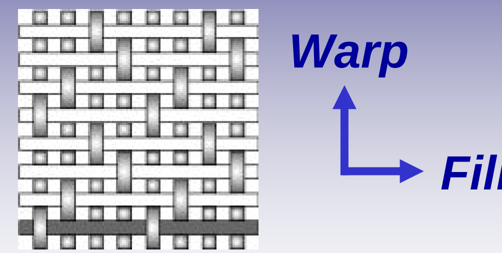
SHEAR KEYS


Shear keys


610
305
(dimensions in mm)
4.8
51
Longitudinal direction

MATERIALS – GFRP

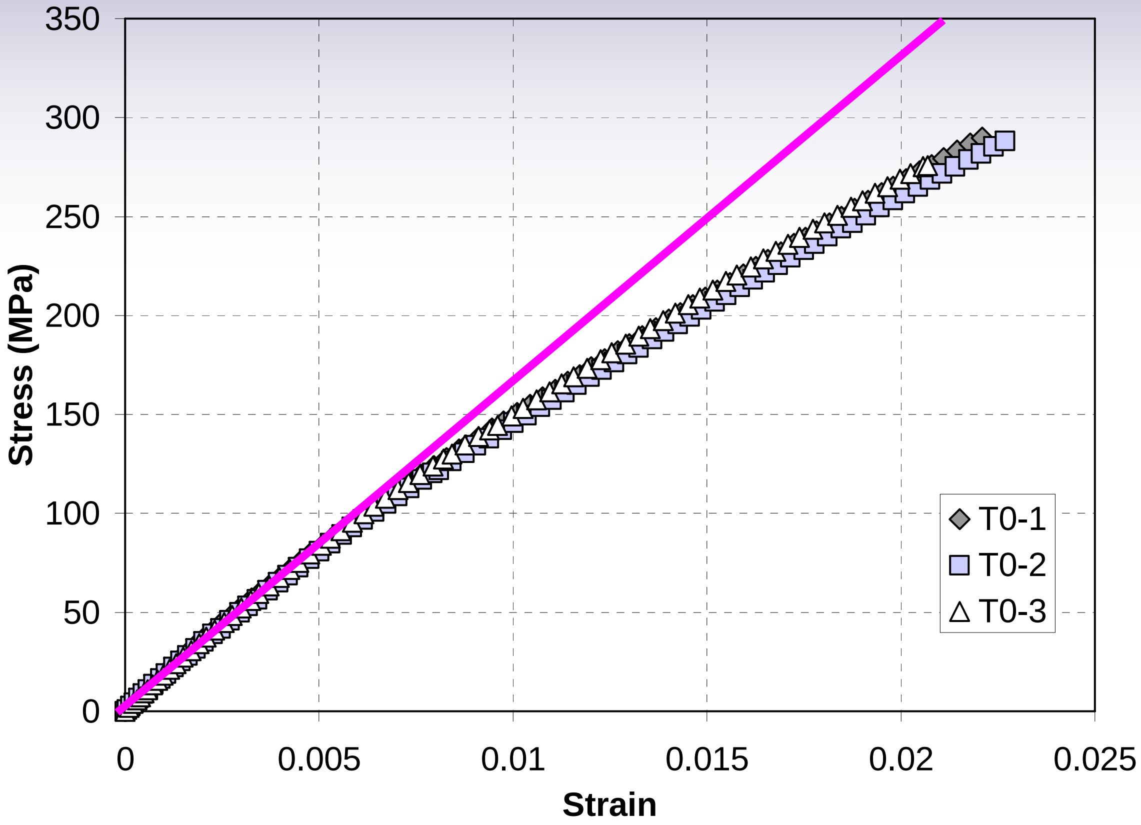
- E-glass woven fabric reinforcement
  - Cheaper than carbon fiber reinforcement
  - Impact resistance
- Vinyl ester
  - High durability
  - Extremely high corrosion resistance
  - Thermal stability



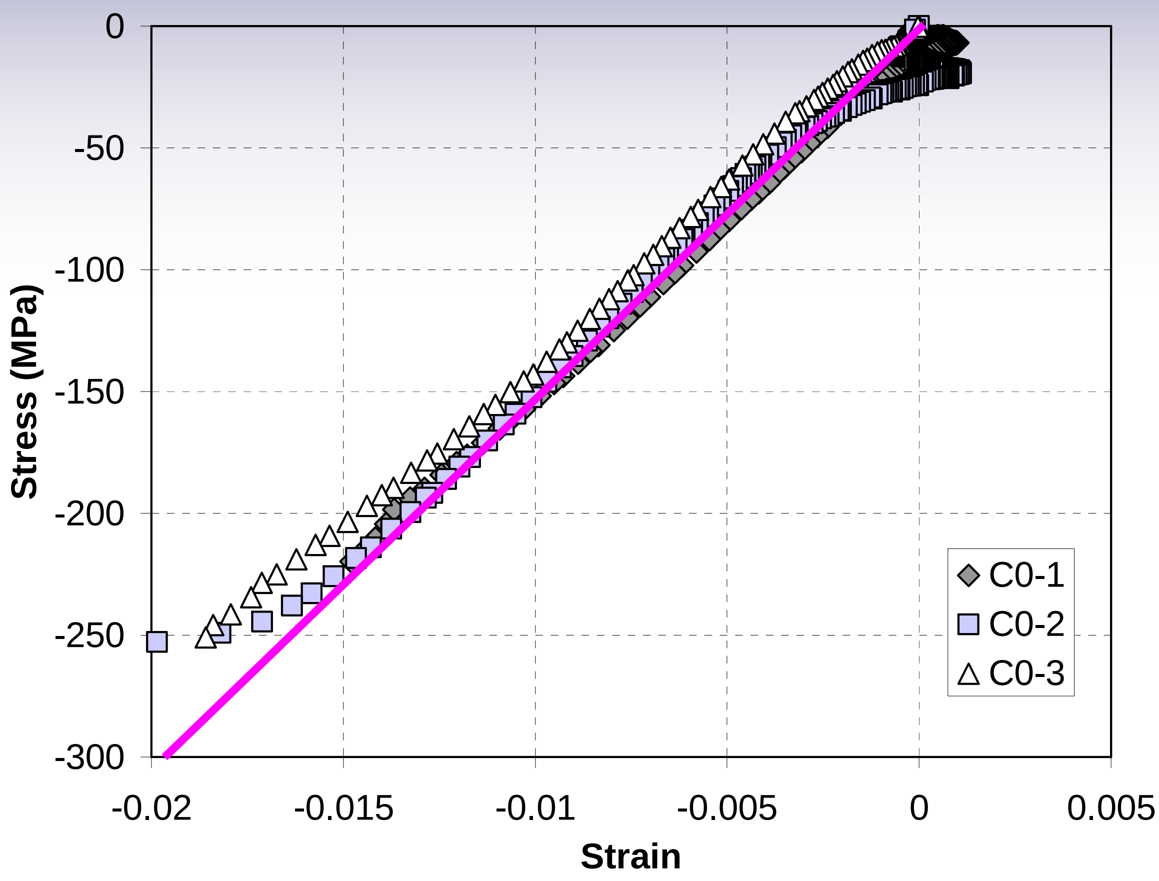
Material Properties

Test	Dir.	E or G (GPa)	ν	Strength (MPa)
Tens	Fill	16.6	0.129	285
	Warp	17.9	0.131	335
Comp	Fill	15.9	0.099	-241
	Warp	22.5	0.254	-265
Shear	Fill	2.72	--	56.1
	Warp	2.45	--	63.8

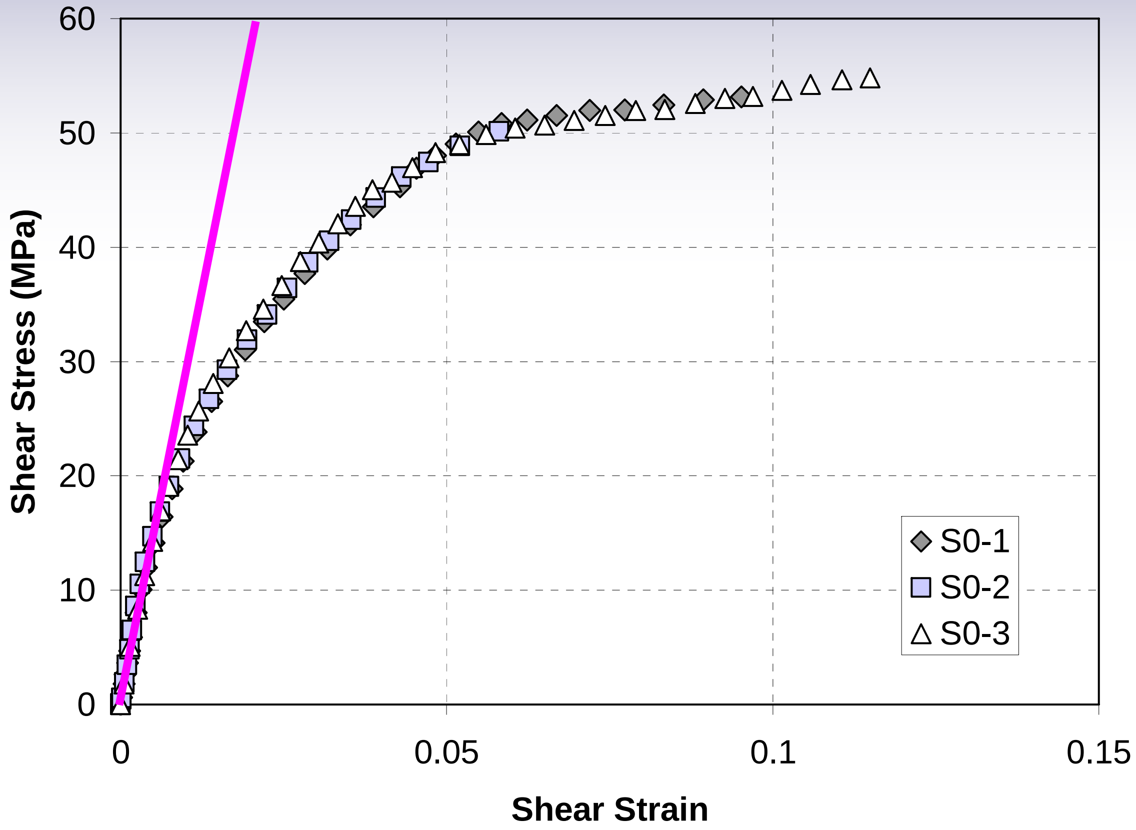
GFRP – TENSION



GFRP – COMPRESSION



GFRP – SHEAR

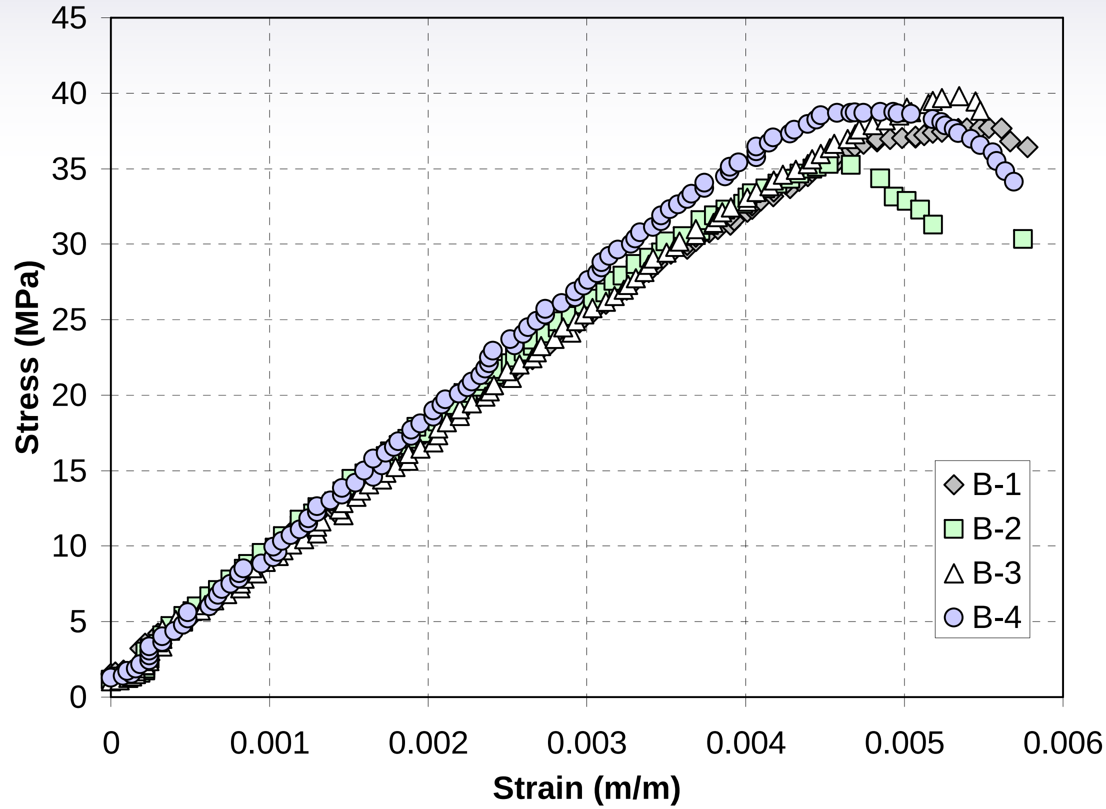

Shear Stress (MPa)
60
50
40
30
20
10
0
0
0.05
0.1
0.15
Shear Strain
S0-1
S0-2
S0-3

MATERIALS - CONCRETE

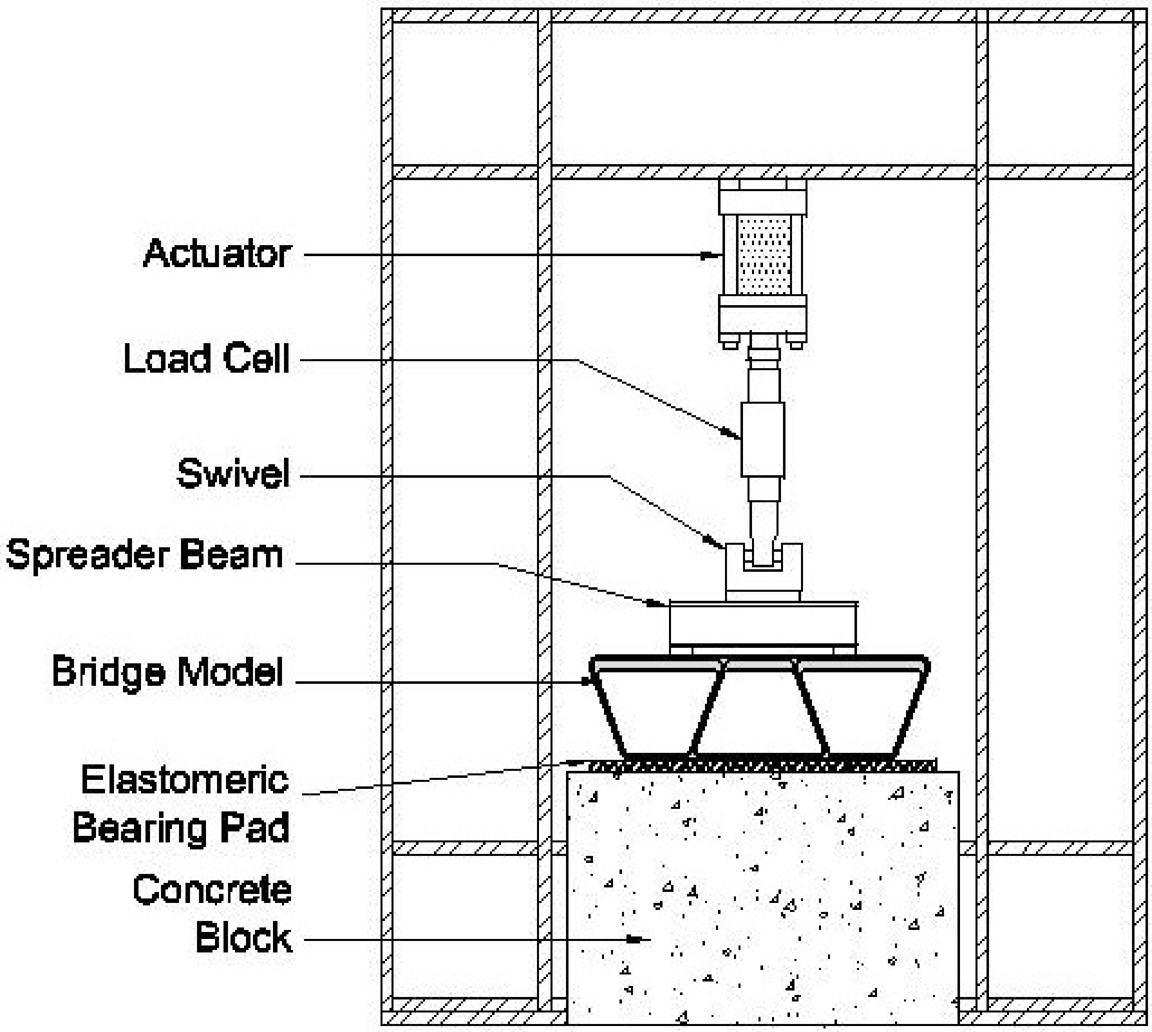
- No coarse aggregates
- water : cement : aggregate = 0.46 : 1.0 : 3.4 by weight

Compressive Properties

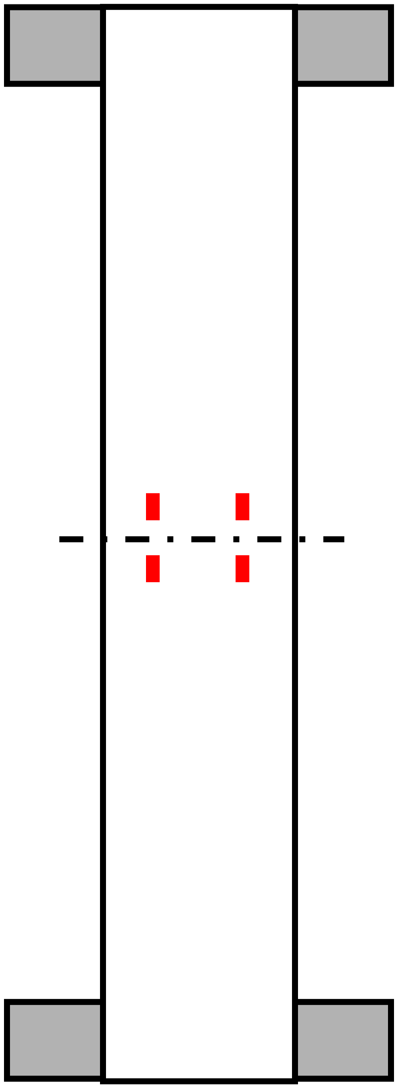
Young's Modulus (GPa)	Strength (MPa)
8.38	**37.9**



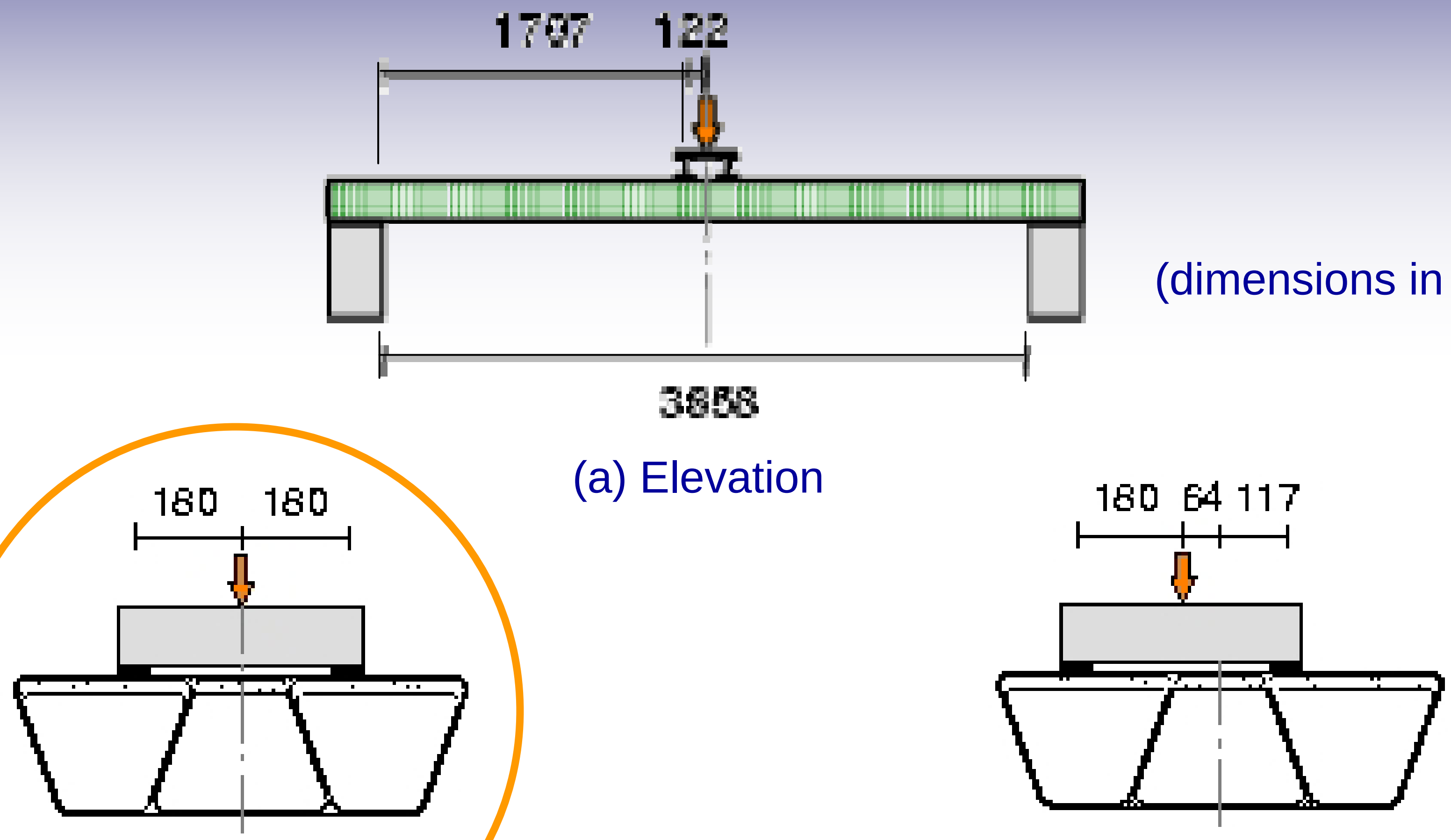
TEST SETUP



Actuator
Load Cell
Swivel
Spreader Beam
Bridge Model
Elastomeric Bearing Pad
Concrete Block



FLEXURAL LOADING CONFIGURATION



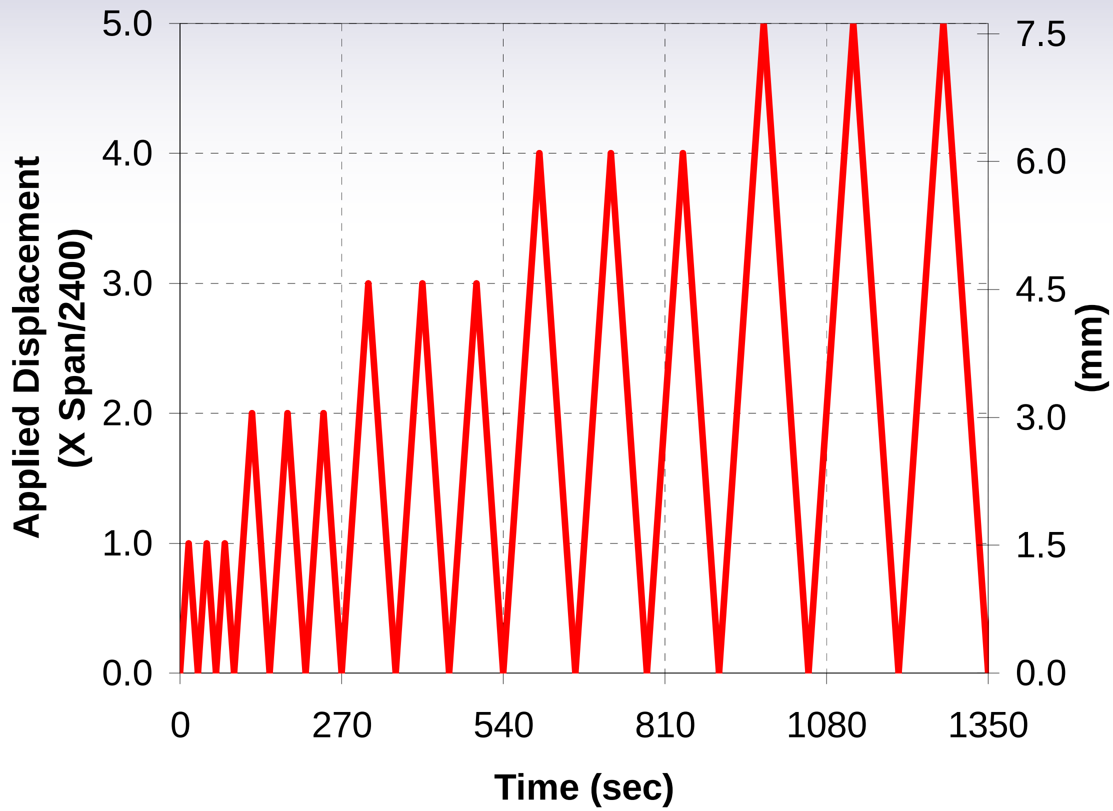
(a) Elevation

(b) Cross section (flexure)

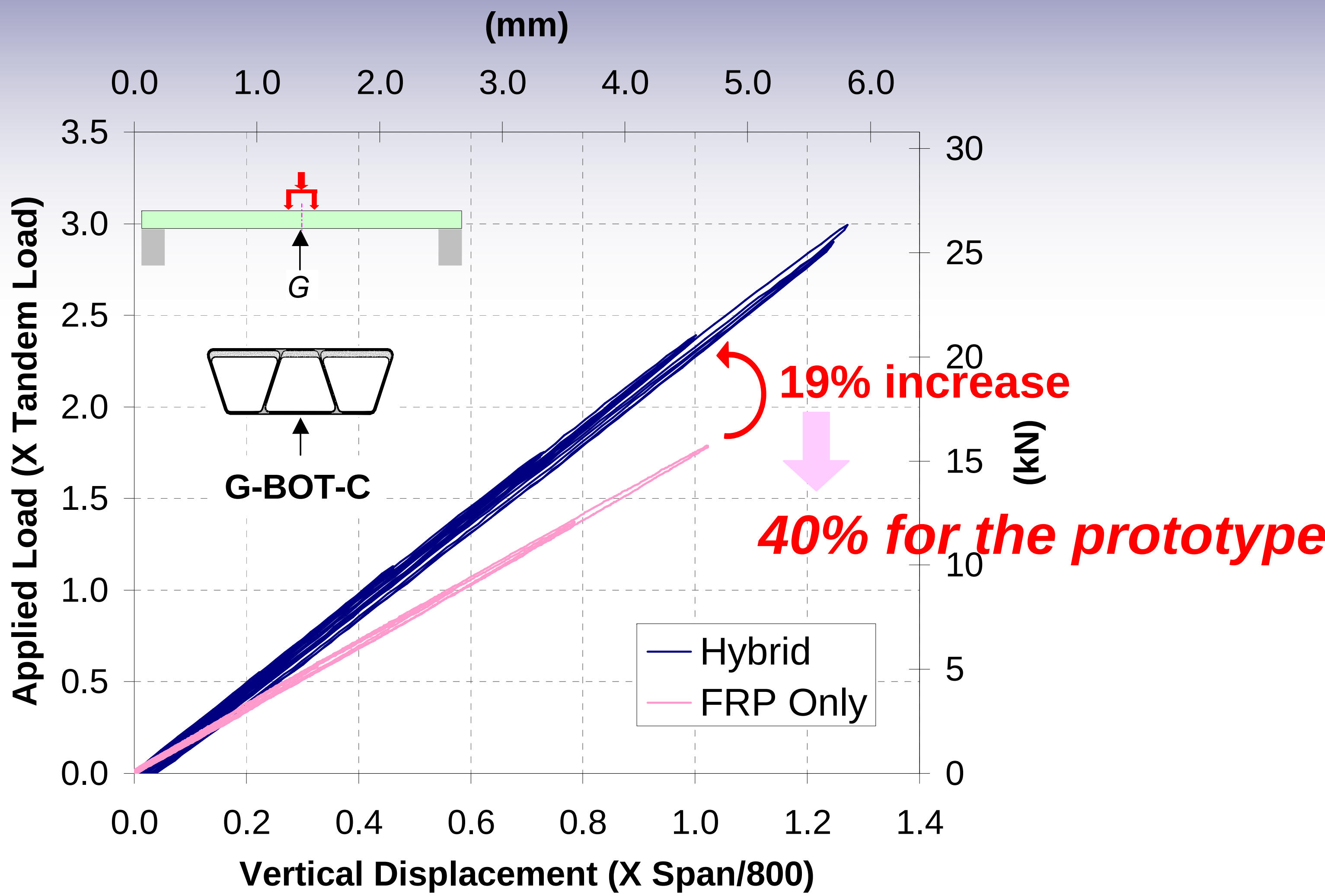
(c) Cross section (off-axis flexure)

NONDESTRUCTIVE FLEXURE (TEST PROTOCOL)

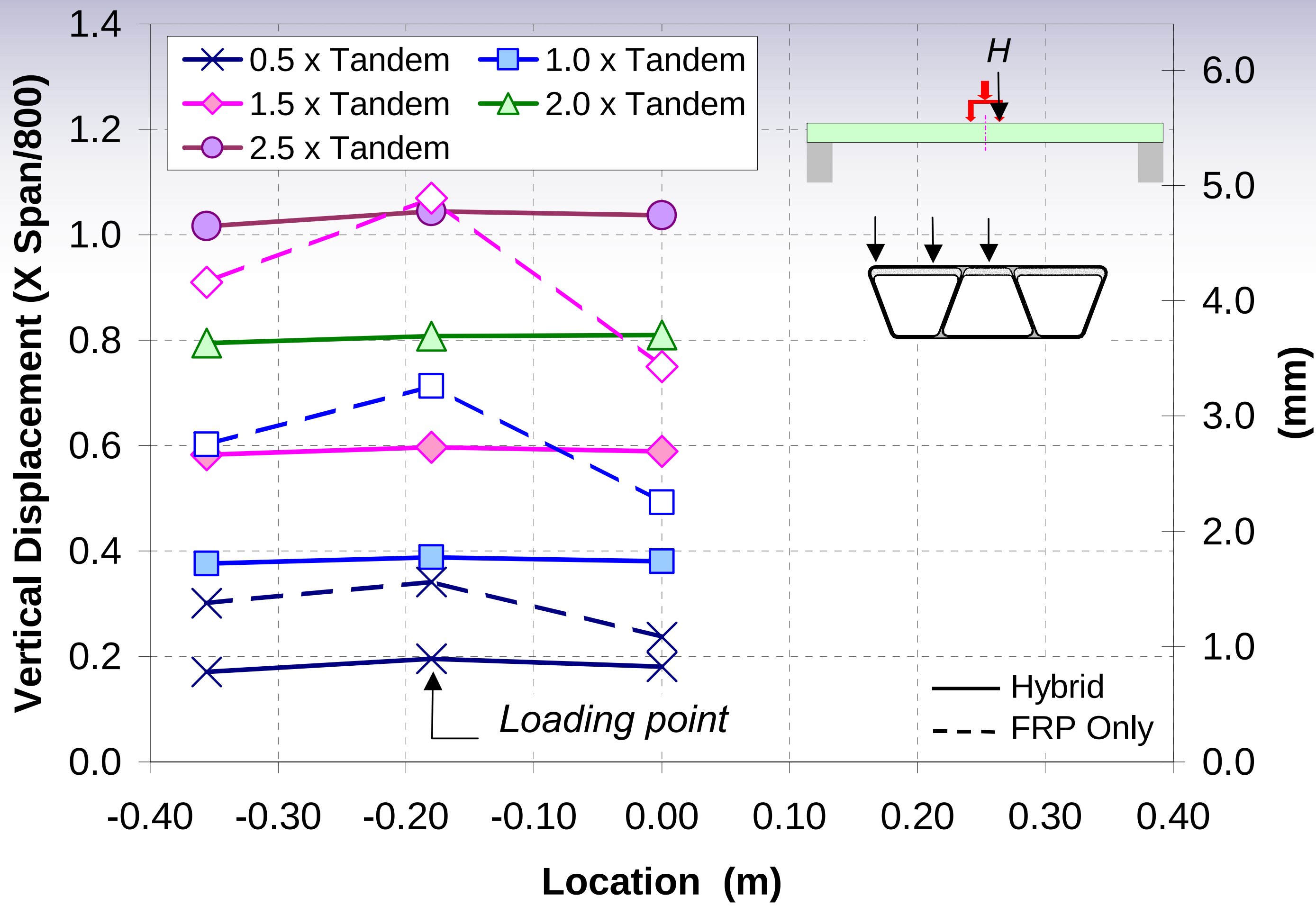
- To examine elastic behavior of the bridge under the flexural loading
- Displacement control
- Max applied displ. = L/480 (L: span length)



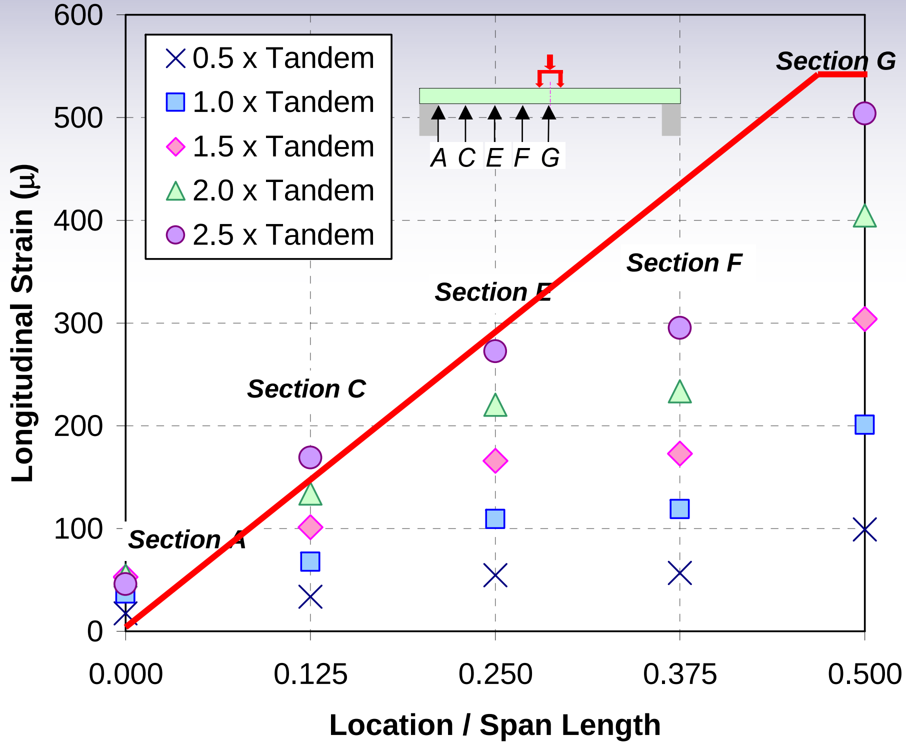
NONDESTRUCTIVE FLEXURE (FORCE-DISPLACEMENT)



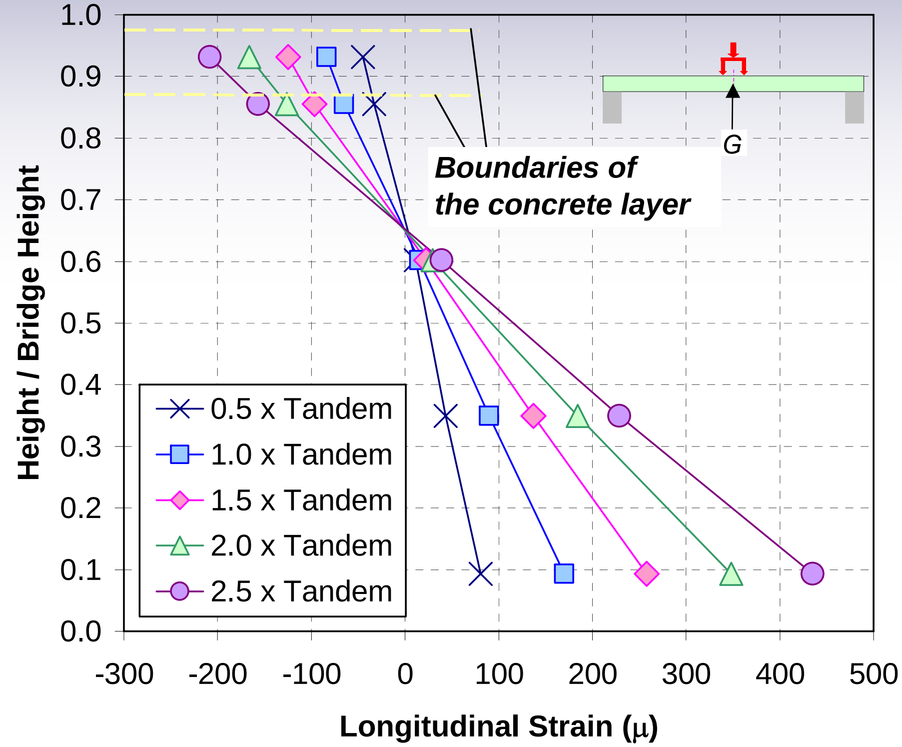
NONDESTRUCTIVE FLEXURE (TOP SURFACE DEFORMATION)



NONDESTRUCTIVE FLEXURE (STRAIN RESULTS)



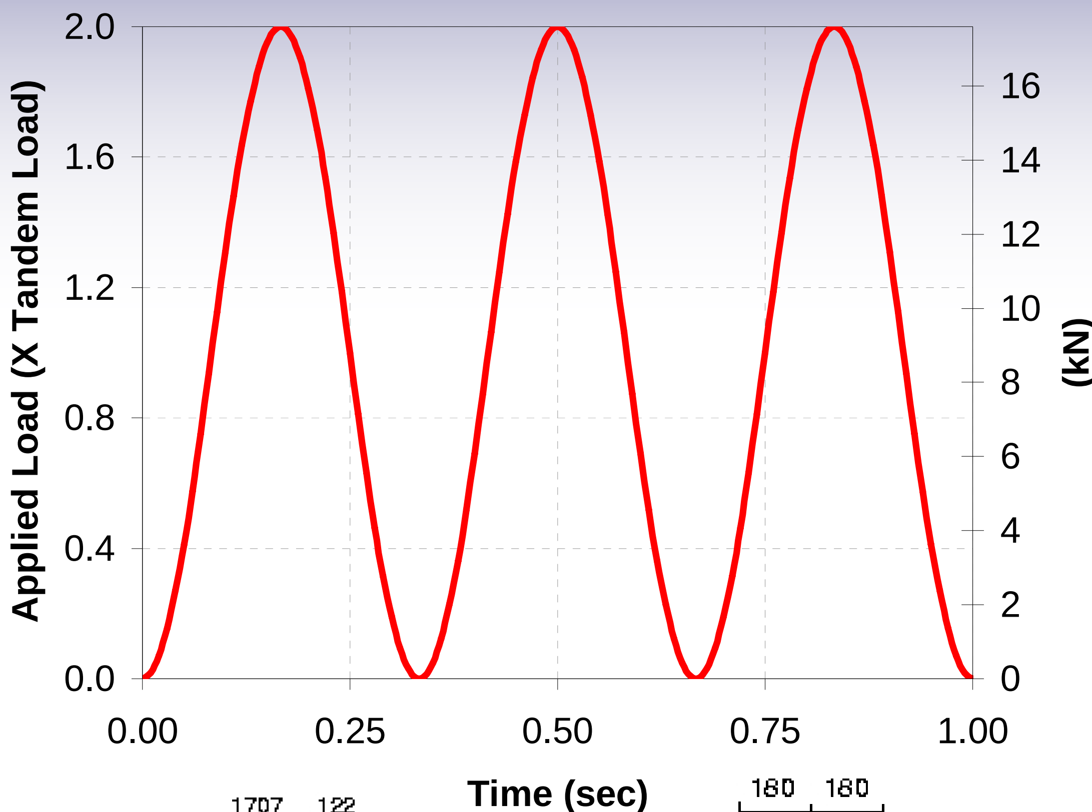
(a) Bottom surface along the center-line

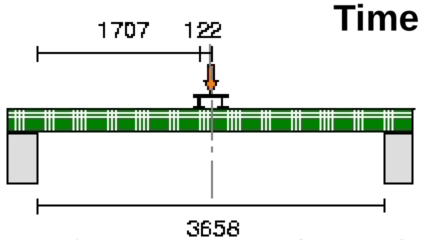


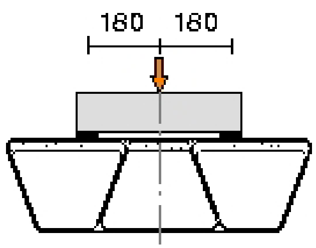
(b) Exterior web over height

FATIGUE LOADING (TEST PROTOCOL)

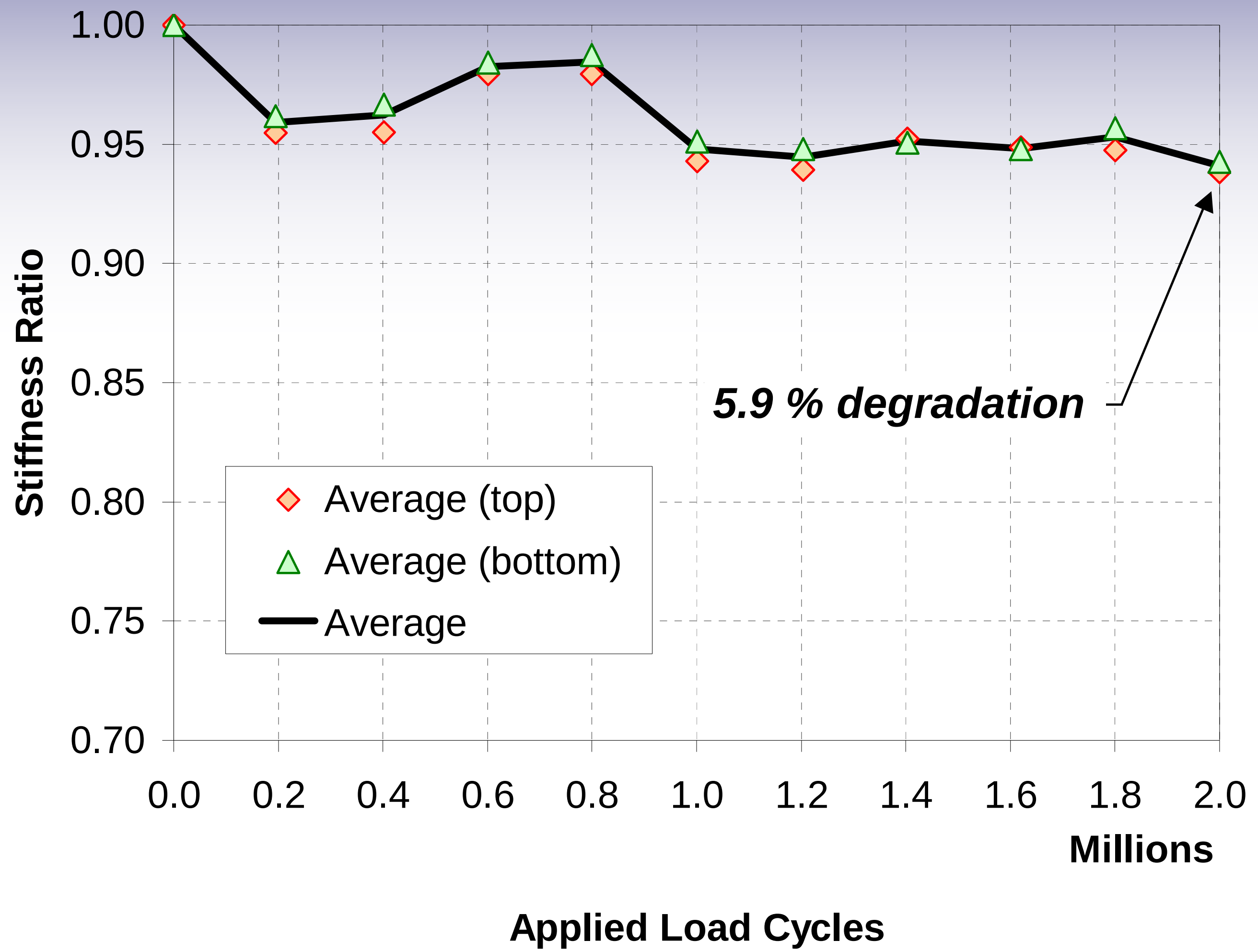
- To examine fatigue characteristics
- Flexural loading
- Force control
- 2×10^6 cycles
- Freq.= 3.0 Hz
- Max. load = 2.0 x Tandem
- Stiffness evaluation every 0.2 million cycles





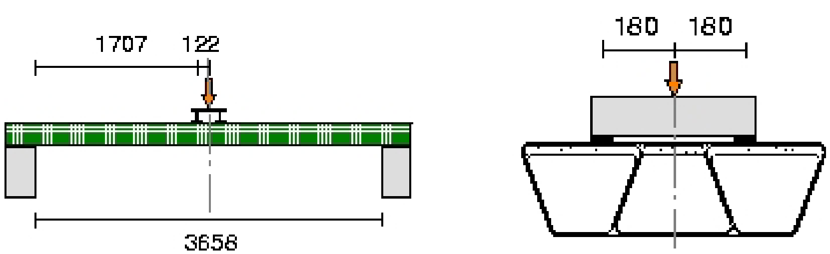


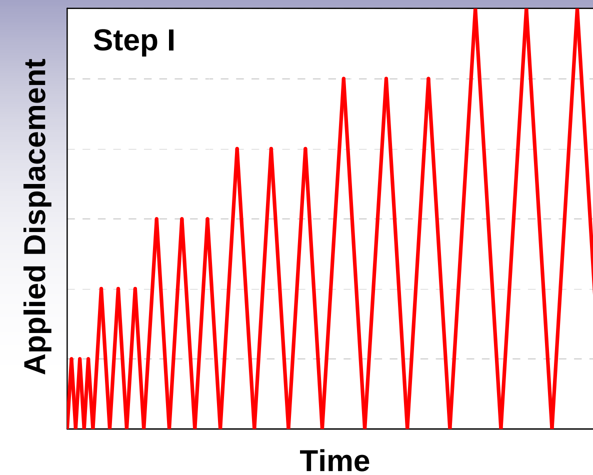
FATIGUE LOADING (TEST RESULTS)



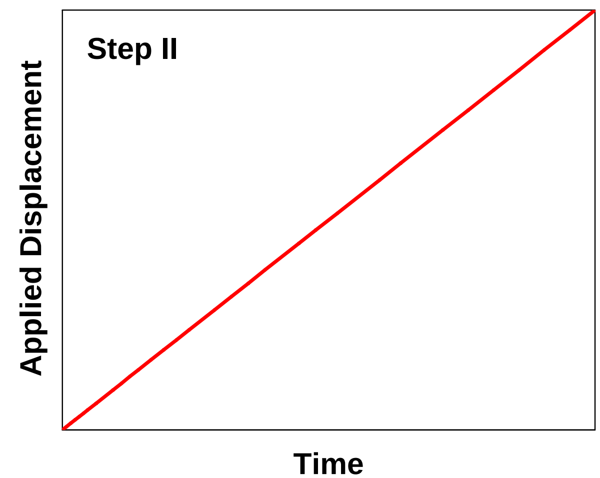
DESTRUCTIVE FLEXURE (TEST PROTOCOL)

- To examine the strength of the bridge and failure modes
- Flexural loading
- Displacement control
- Two stages
  - Step I (displacement history #1)
  - Step II (displacement history #2)





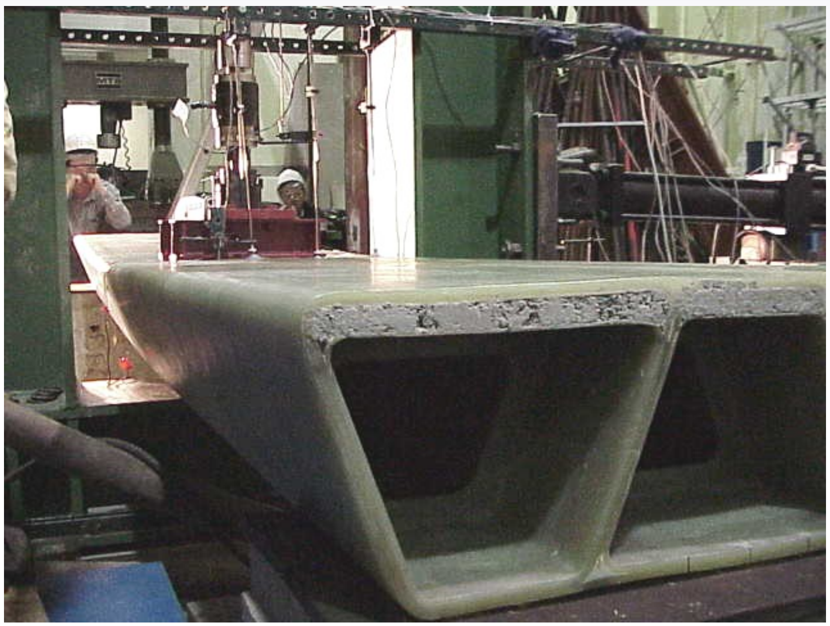
(a) Displacement history #1

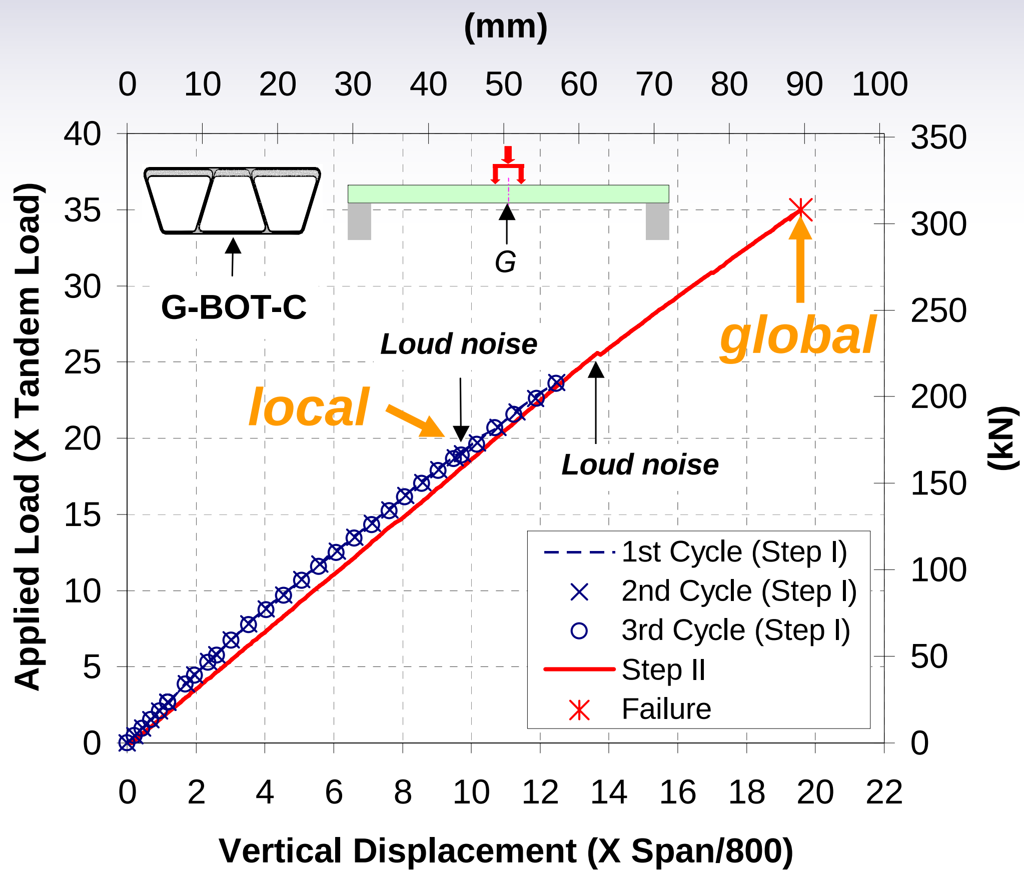


(b) Displacement history #2

DESTRUCTIVE FLEXURE (TEST RESULTS – 1)

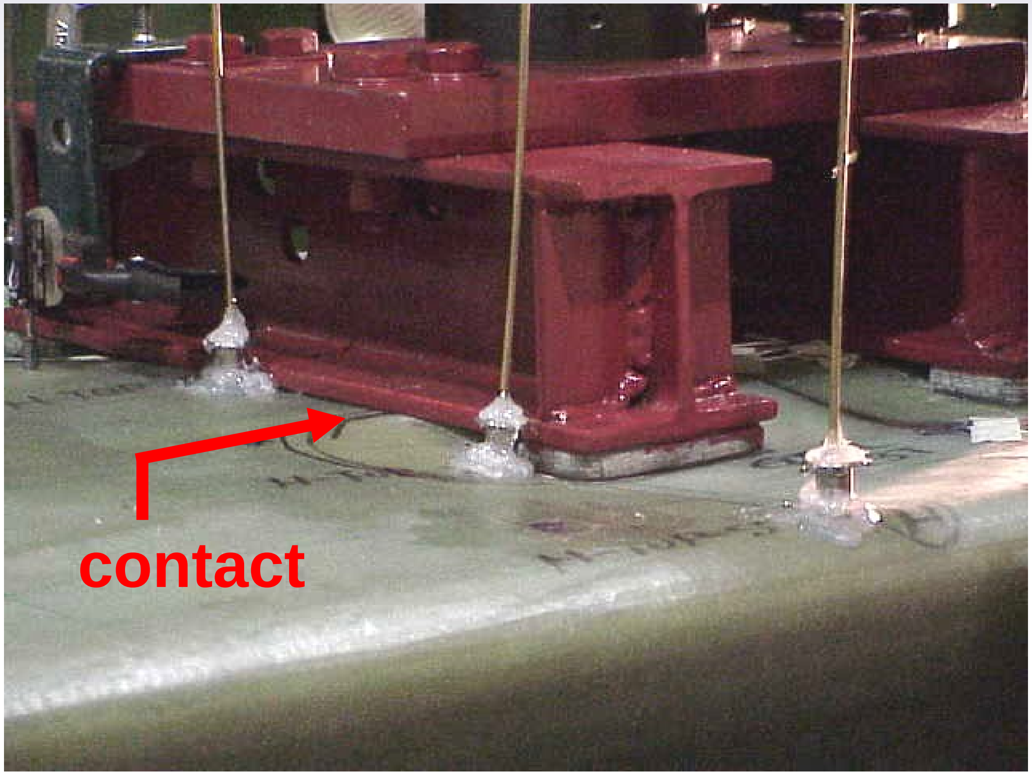
- Failure load = 35 x Tandem load





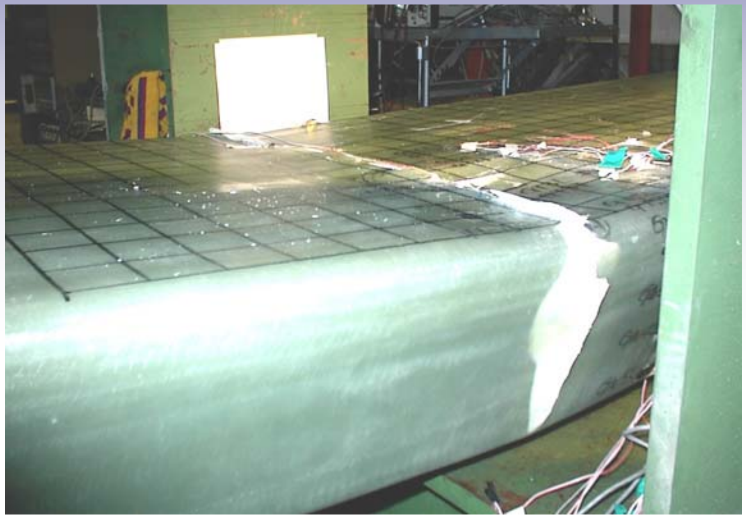
CHANGE OF A LOADING CONDITION

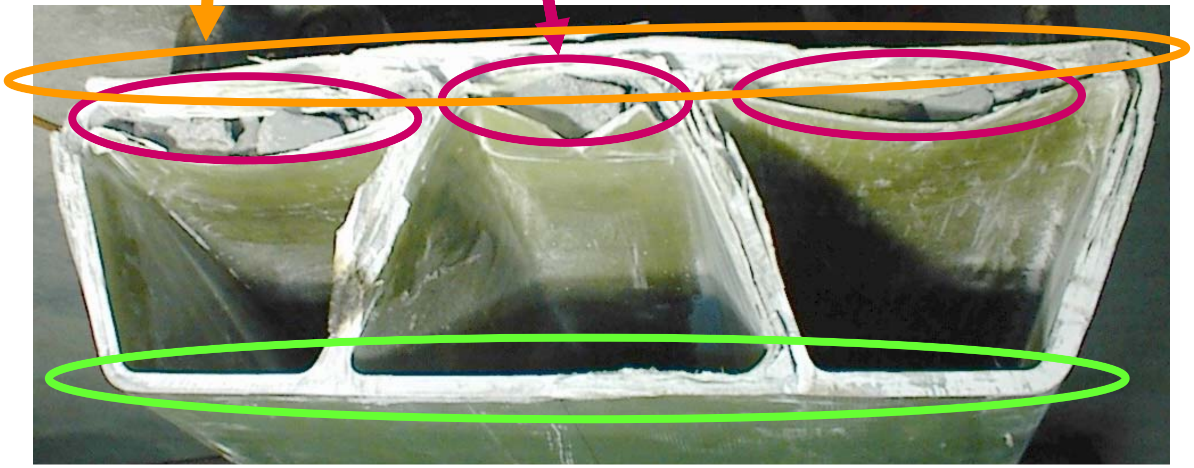
- From four point loads to two line loads



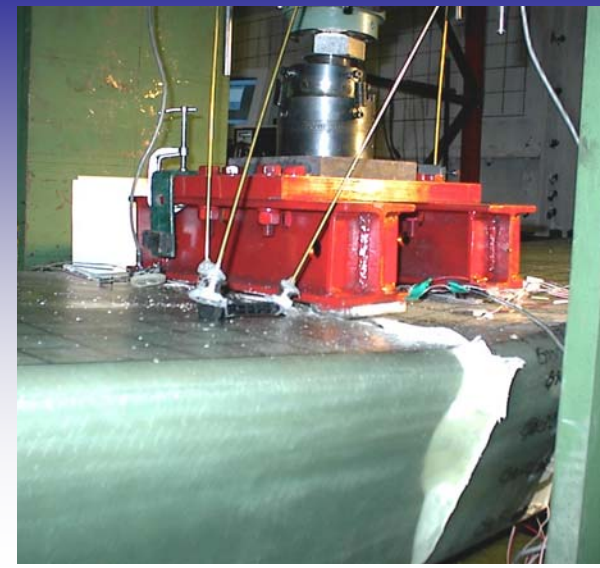
DESTRUCTIVE FLEXURE (TEST RESULTS – 2)

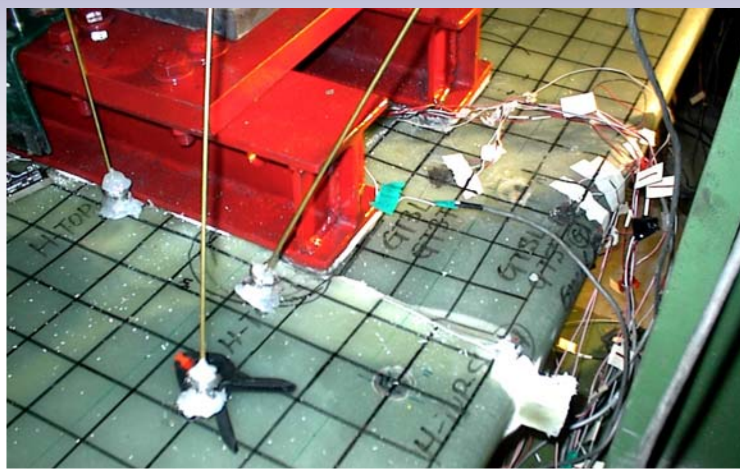
- Failure modes
  - Concrete crushing
  - Failure of GFRP in compression

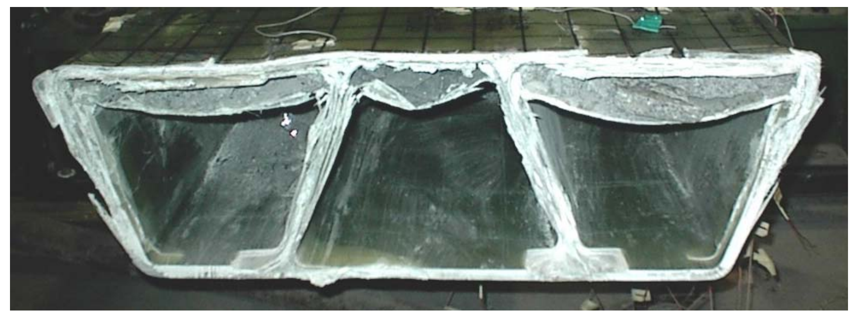


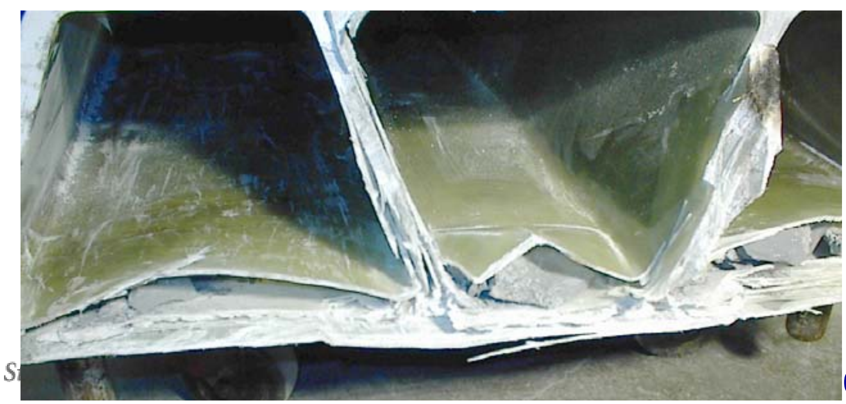


DESTRUCTIVE FLEXURE (FAILURE MODES)

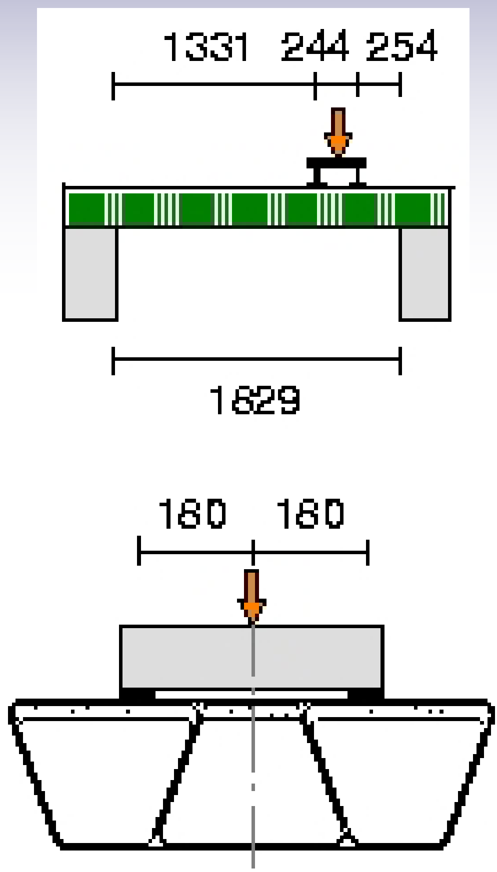




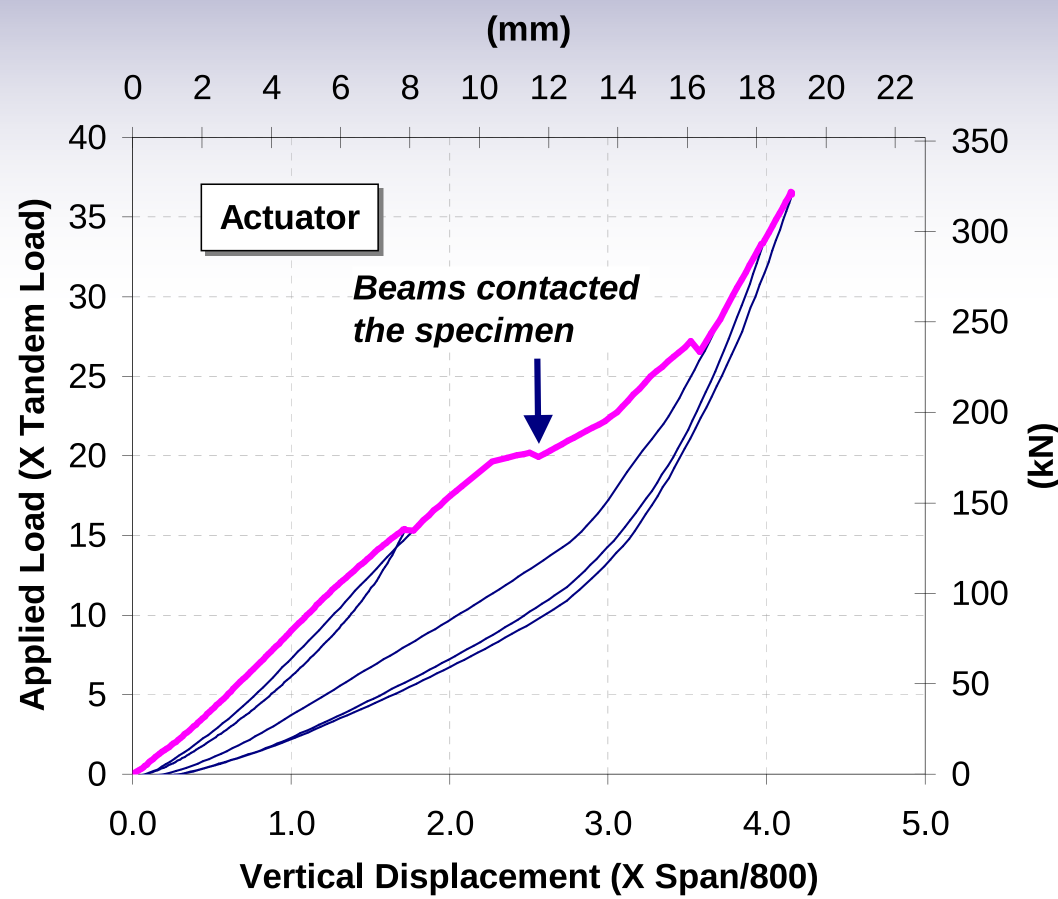




SHEAR TEST

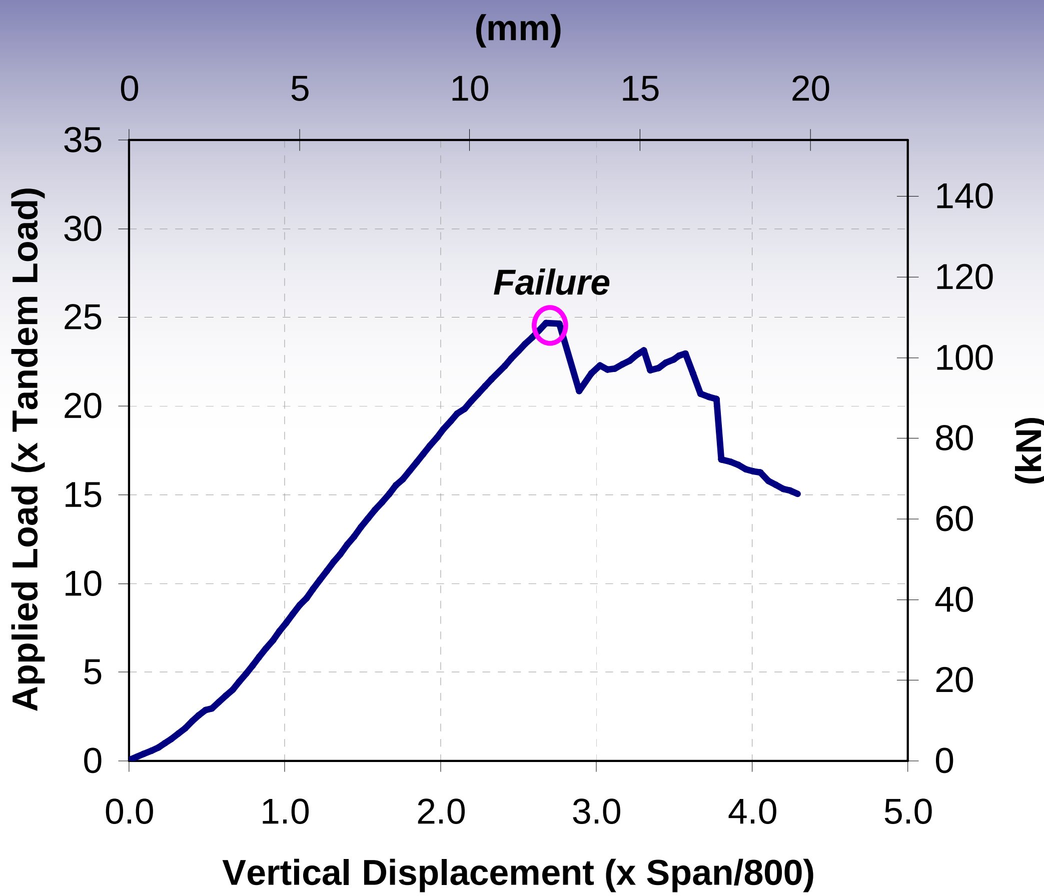


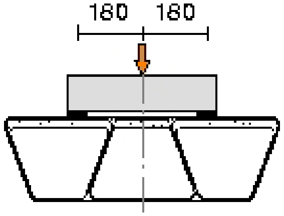
1331 244 254
1829
180 180



(mm)
0 2 4 6 8 10 12 14 16 18 20 22
Actuator
Beams contacted
the specimen
Applied Load (X Tandem Load)
(kN)
Vertical Displacement (X Span/800)
0 5 10 15 20 25 30 35 40
0 50 100 150 200 250 300 350
0.0 1.0 2.0 3.0 4.0 5.0

BEARING TEST

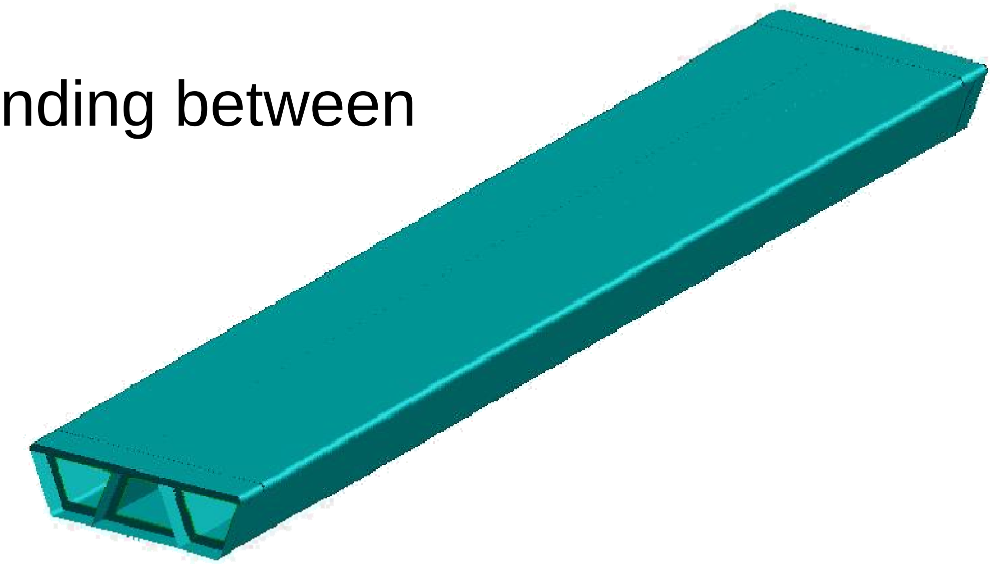




BEARING TEST (FAILURE MODE)

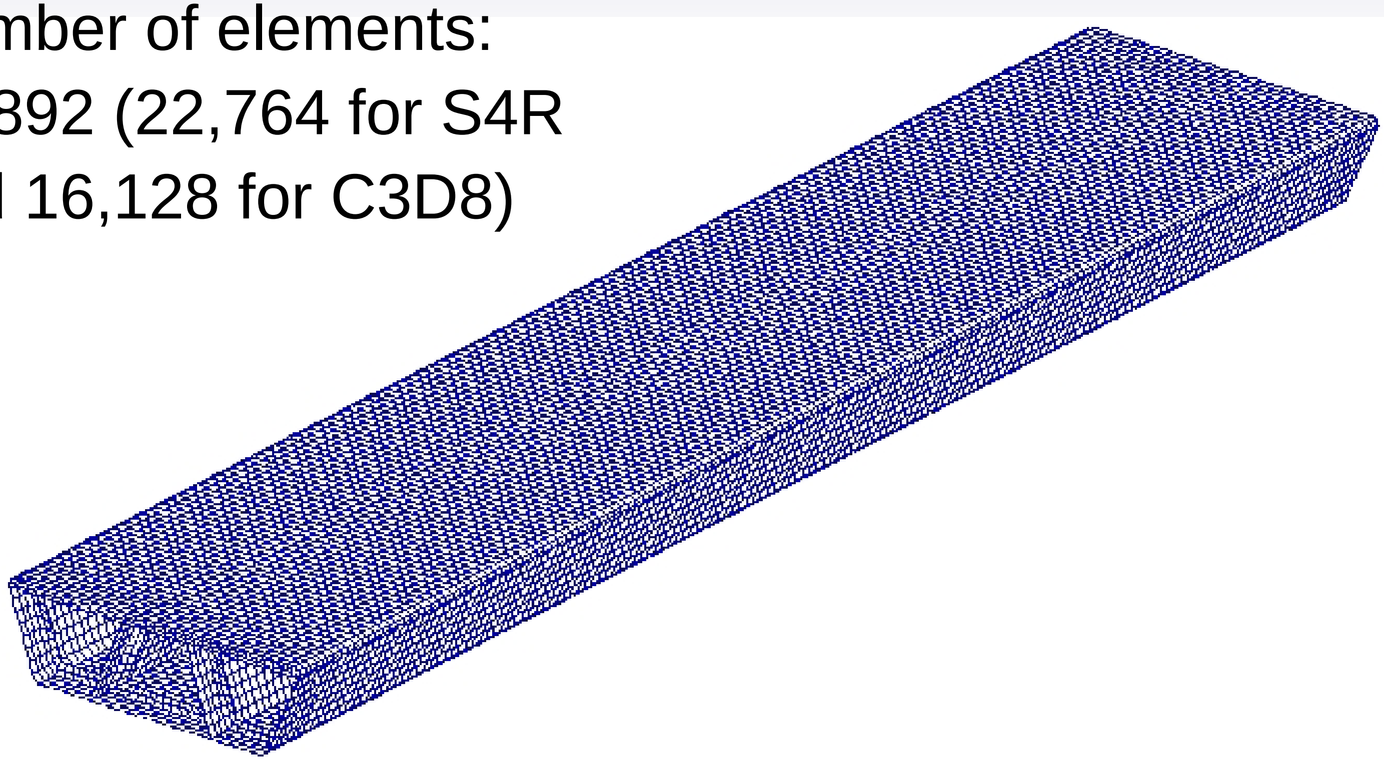
FINITE ELEMENT ANALYSIS

- ABAQUS
- Four-noded general shell element, S4R, for GFRP laminates
- Eight-noded general 3D solid element, C3D8, for concrete
- Assumed a perfect bonding between concrete and GFRP
- Linear analysis
- Nonlinear analysis



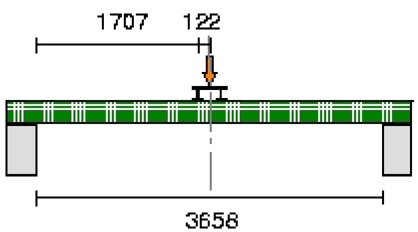
FINITE ELEMENT DISCRITIZATION (LINEAR ANALYSIS)

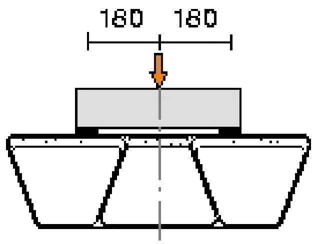
- Number of nodes: 31,857
- Number of elements: 38,892 (22,764 for S4R and 16,128 for C3D8)

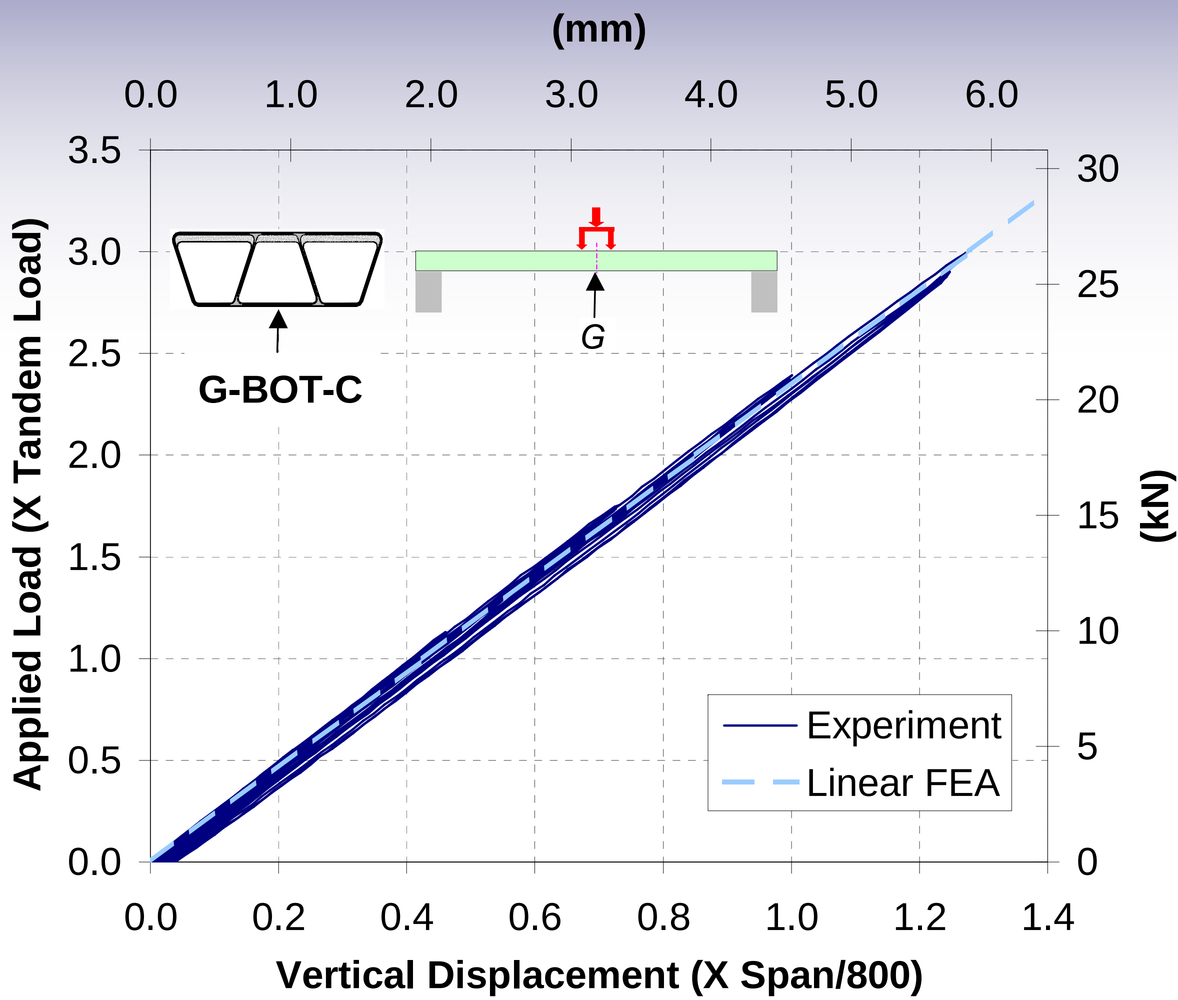


LINEAR FEA RESULTS (FLEXURE – 1)

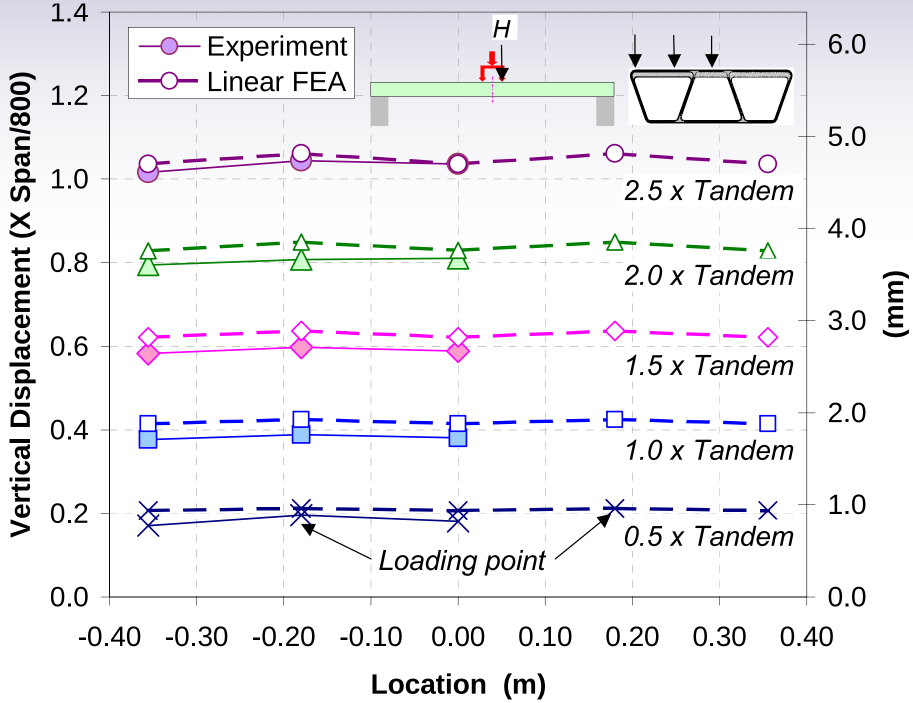
- Stiffness was predicted by FEA within 5% error.



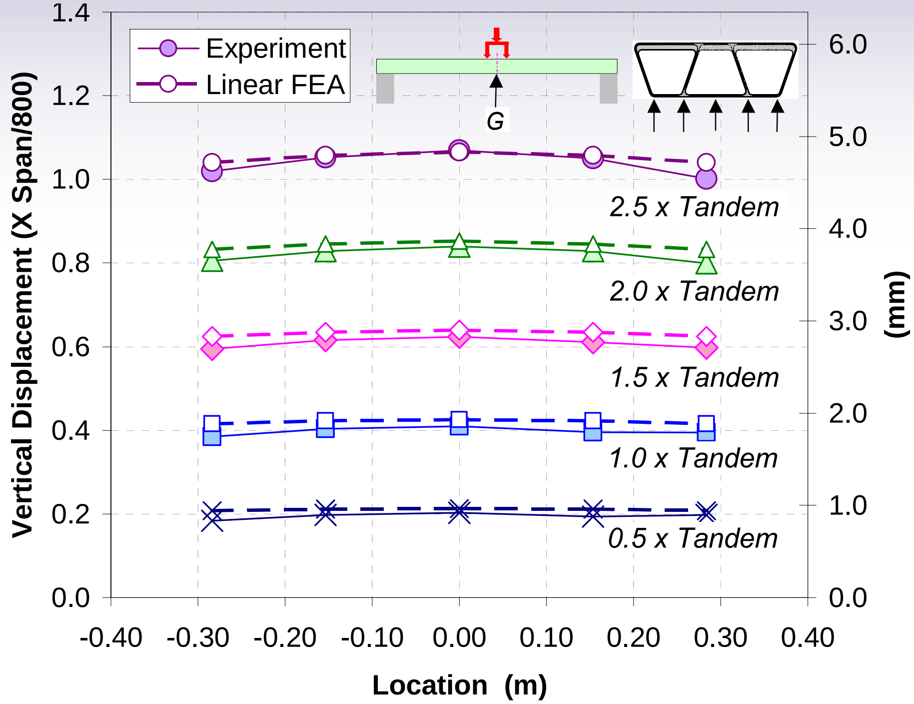




LINEAR FEA RESULTS (FLEXURE – 2)

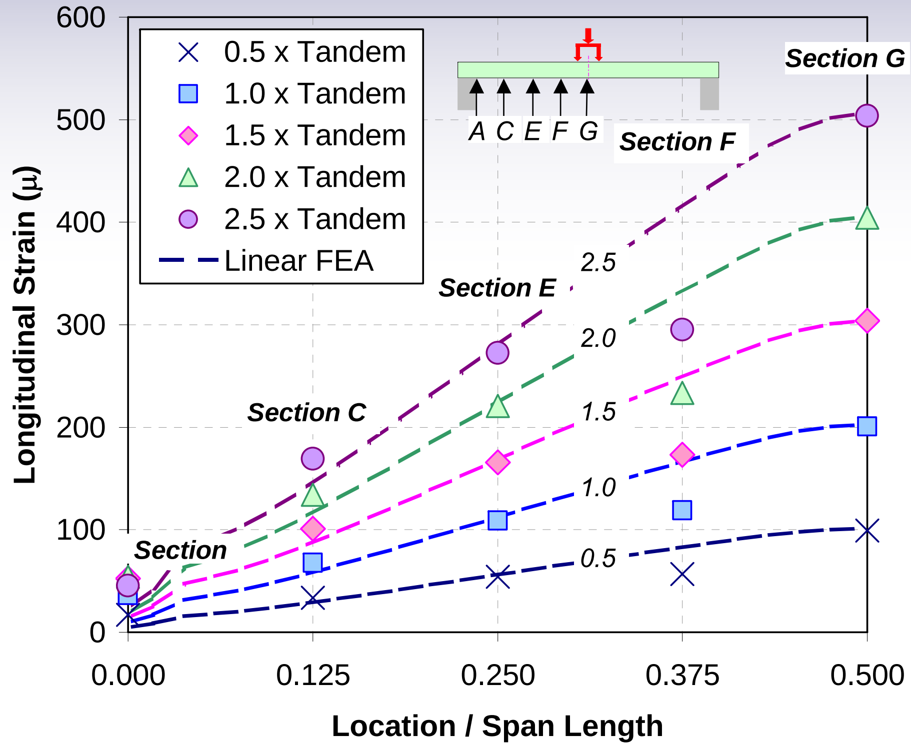


(a) Top surface

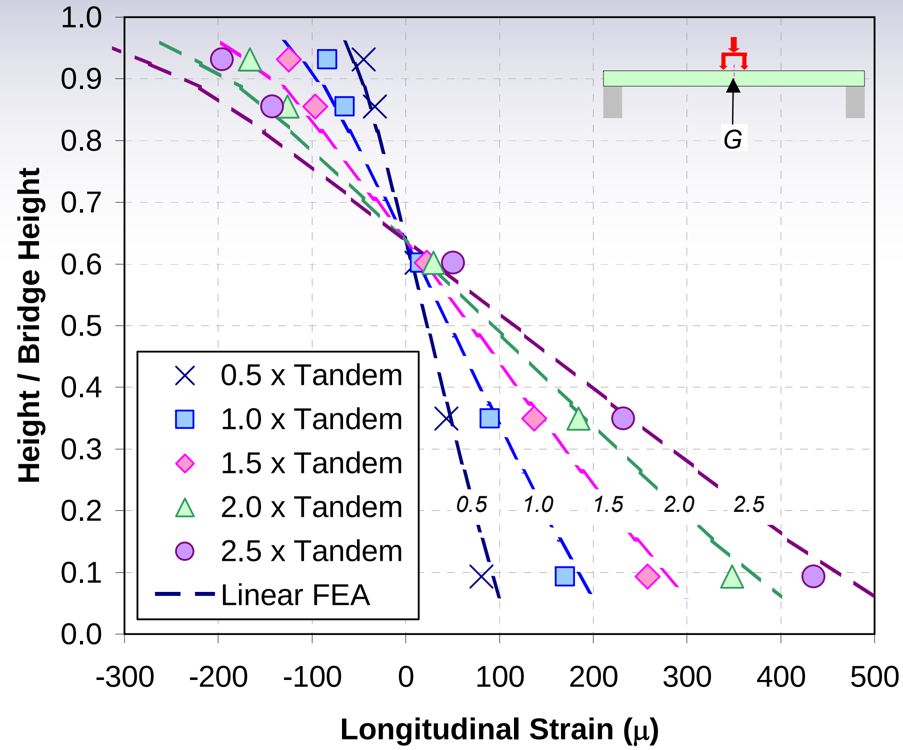


(b) Bottom surface

LINEAR FEA RESULTS (FLEXURE – 3)



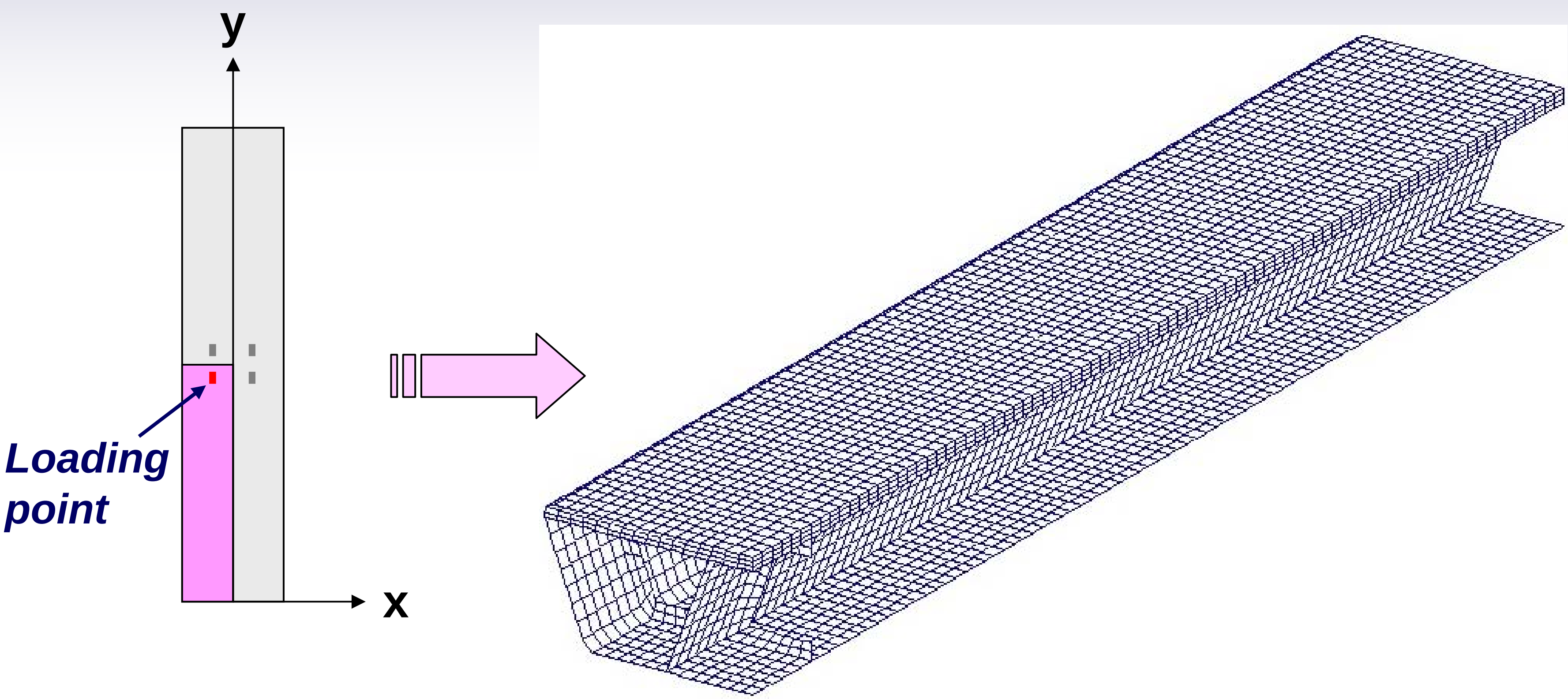
(a) Bottom surface along the center-line



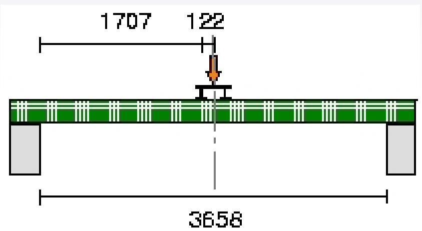
(b) Exterior web over height

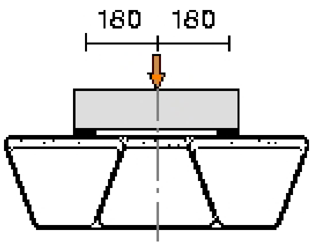
Finite Element Discretization (Nonlinear Analysis)

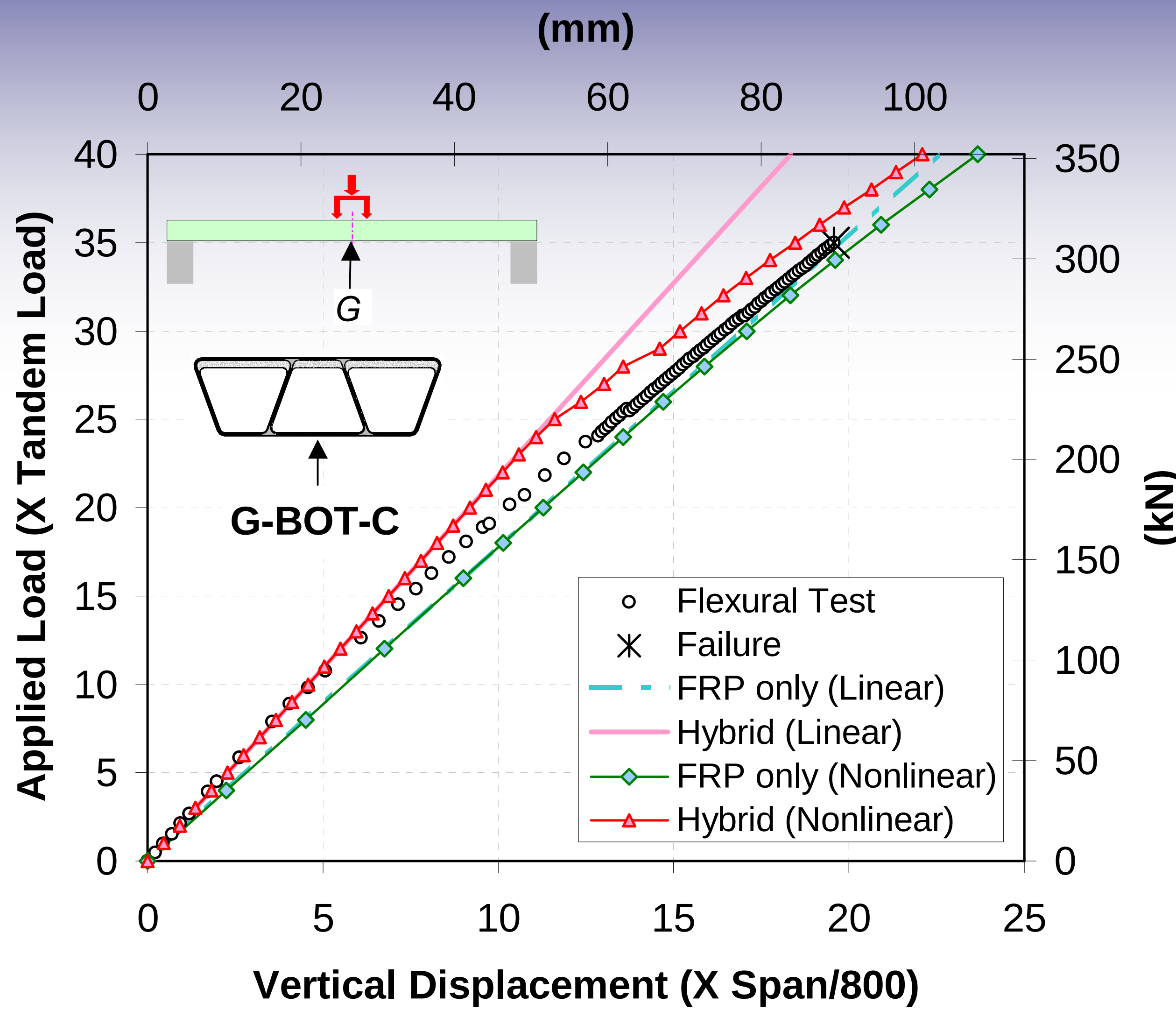
- A quarter model



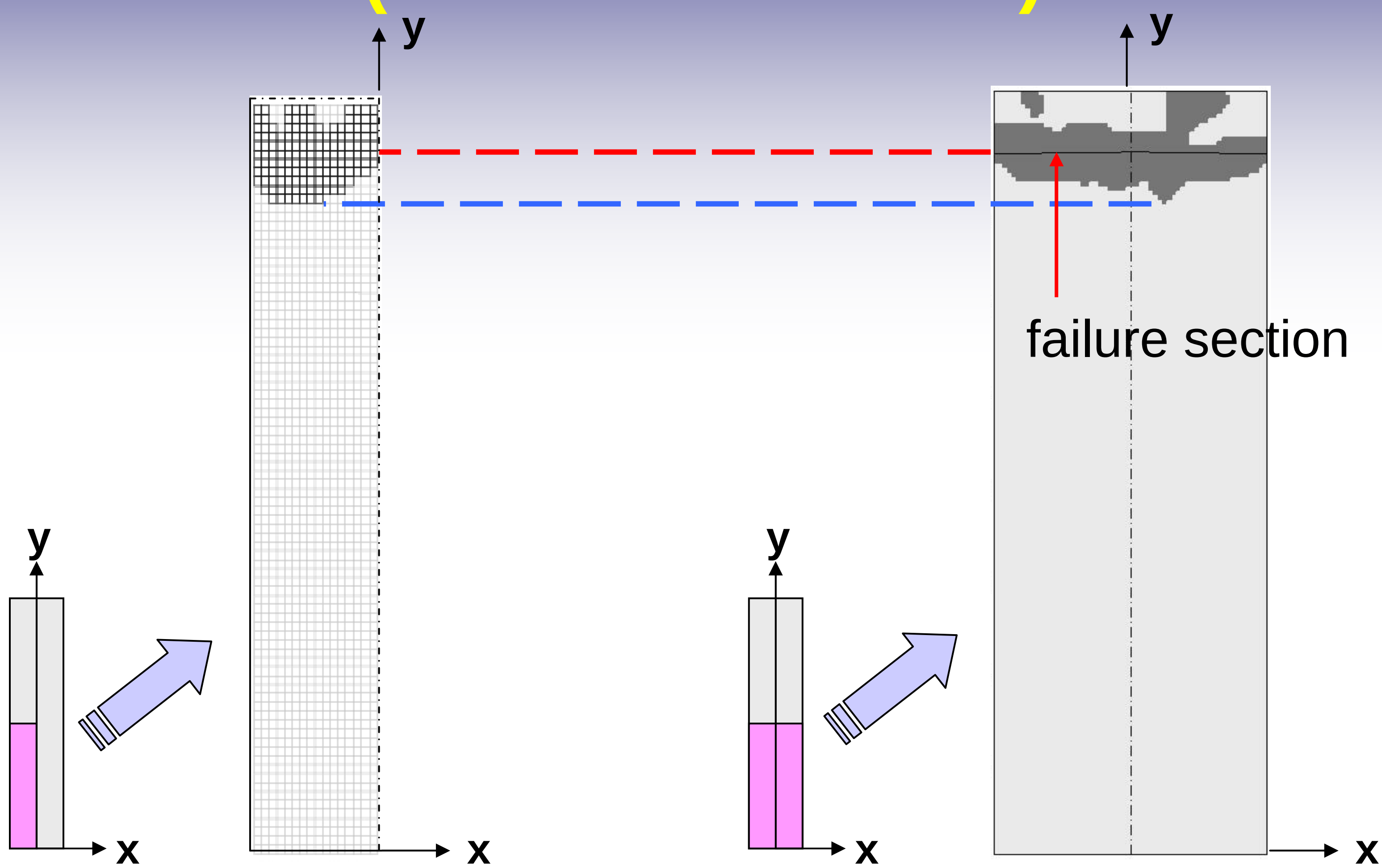
NONLINEAR FEA RESULTS – 1







NONLINEAR FEA RESULTS – 2 (DAMAGED AREA)



(a) FEA (b) Experiment

SIMPLE METHODS OF ANALYSIS

- Simple methods
  - Beam analysis
  - Orthotropic plate analysis
- Classical lamination theory
- Use of effective engineering properties of laminates
- Perfect bonding between concrete and GFRP was assumed.
- Shear deformation was neglected
- Primary objective is to obtain deflection under design loads.

BEAM ANALYSIS

- The bridge is modeled as a beam with a span length, *L*, effective flexural rigidity, EI_{eff}, and effective torsional rigidity, GJ_{eff}.

$$EI_{eff} = \int_{Ay} \overline{E}_y \overline{z}^2 dA \qquad GJ_{eff} = \frac{4A_{encl}^2}{\displaystyle\int \frac{1}{\int \overline{G}_{xy} dz} ds}$$

where

$\overline{E}_y$: Effective modulus

$\overline{G}_{xy}$: Effective shear modulus

$\overline{z}$: Vertical coord. from the neutral axis

A_{encl} : Area enclosed by median lines of the top and bot. flanges and exterior webs

s : Axis along the median line of a component

ORTHOTROPIC PLATE ANALYSIS

- The bridge is modeled as an orthotropic plate with span length of *L* and width of *W*.

$$D_x \frac{\partial^4 w_0}{\partial x^4} + 2H \frac{\partial^4 w_0}{\partial x^2 \partial y^2} + D_y \frac{\partial^4 w_0}{\partial y^4} = q(x, y)$$

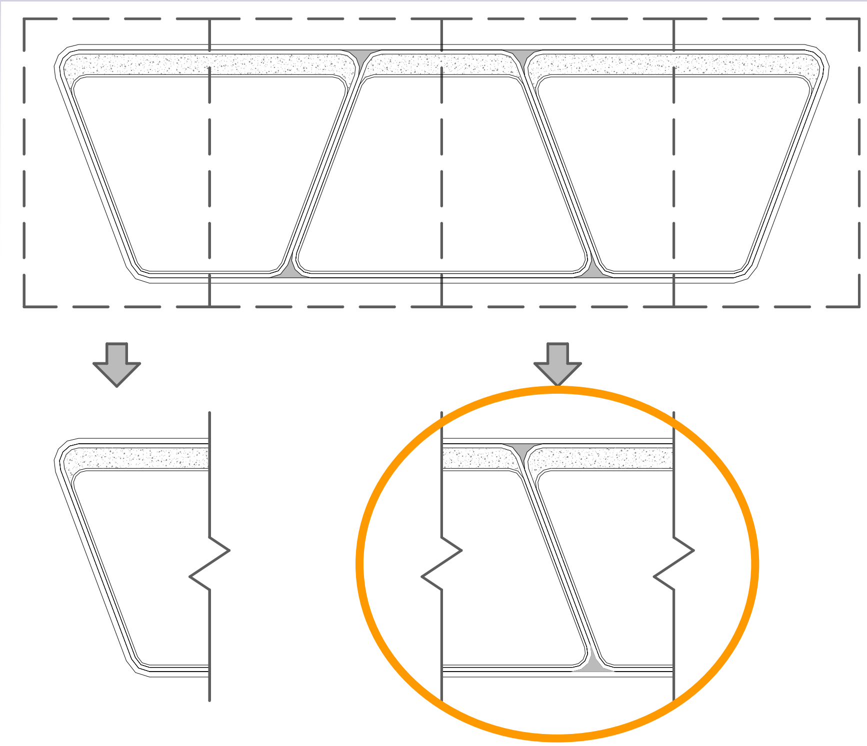
where

w_0 : Vertical displacement

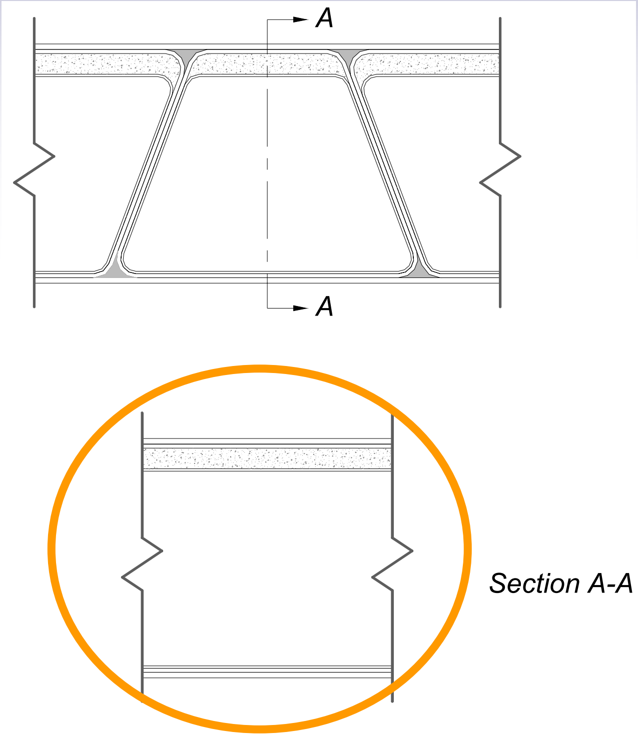
q : Distributed load on the plate

D_x, D_y, and H : Rigidities that can be obtained by using the classical lamination theory

REPRESENTATIVE UNITS FOR THE PLATE ANALYSIS

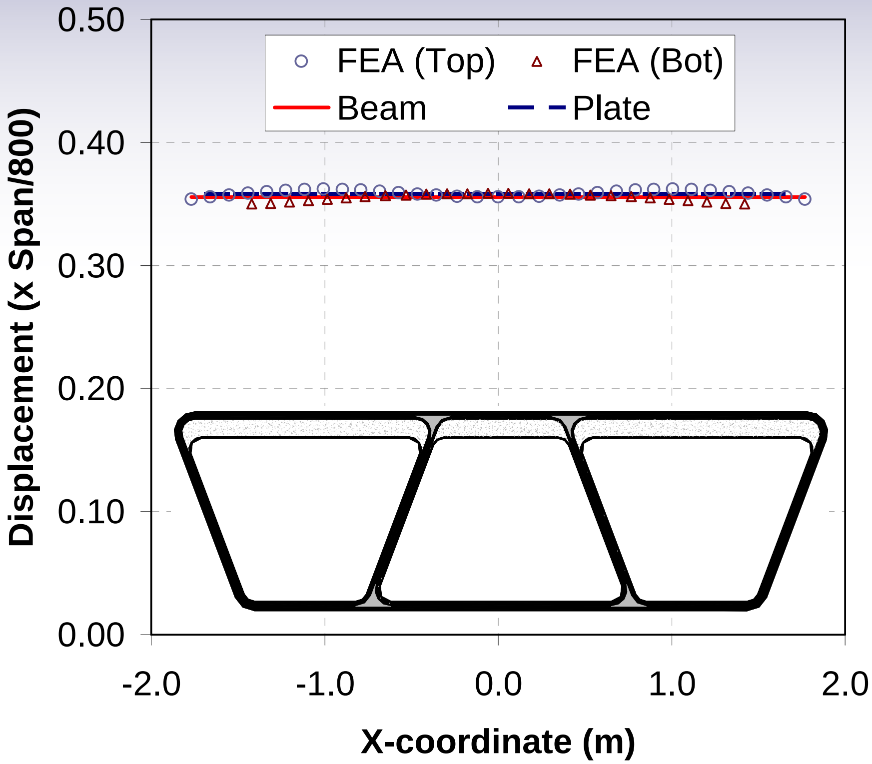


(a) Longitudinal direction

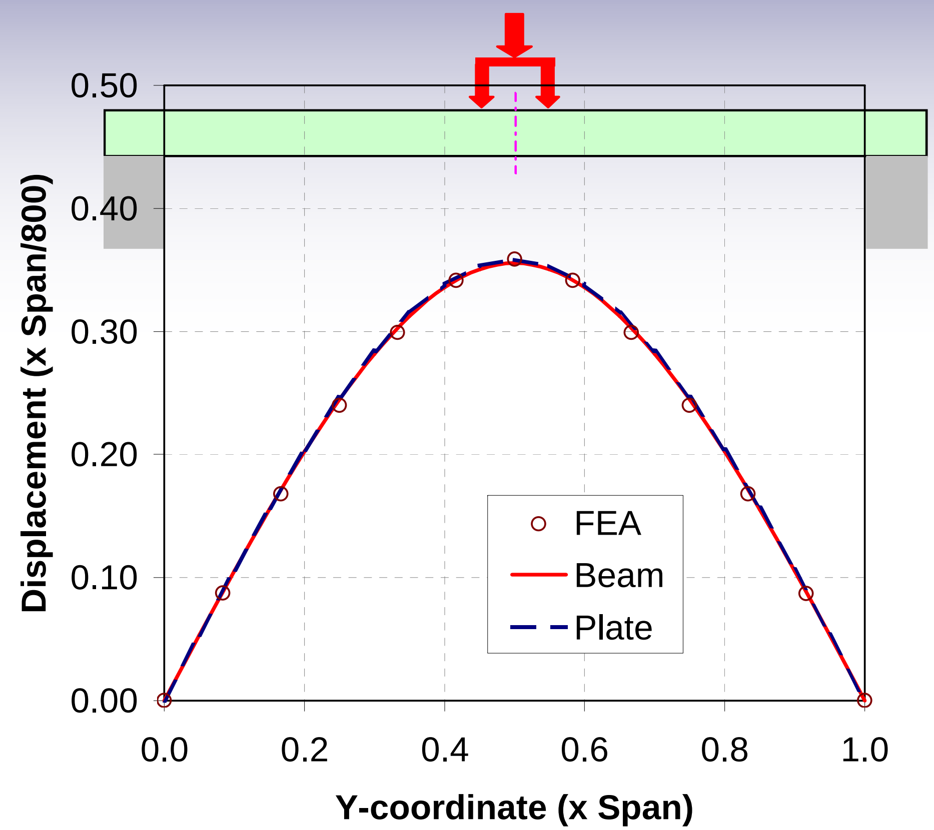


(b) Transverse direction

SIMPLE METHODS OF ANALYSIS (UNDER TANDEM LOAD ONLY)



(a) Transverse direction



(b) Longitudinal direction

Summary

- Composite materials hold great promise for effective renewal of deficient bridges.
- The hybrid FRP-concrete bridge superstructure is highly feasible from the structural engineering point of view.
- GFRP used in this study has revealed that its stress-strain relationship is not perfectly linear-elastic. However, for design purposes, the equivalent linear model can be used.

Summary (CONT'D)

- As is often the case with all-composite bridges, the design of the hybrid bridge superstructure is also stiffness driven.
- Results from a series of quasi-static tests have shown an excellent performance of the proposed hybrid bridge under live loads.
- The beam and orthotropic plate simplified analyses have proven to be effective to accurately predict the deflection of the hybrid bridge under design loads.

Challenges

- A systematic way to determine design parameters should be developed. It is also important to propose and optimize the design based on life-cycle cost as well as performance.
- Long-term performance of FRP bridges is not yet established and should be investigated:

  creep, fatigue, and material degradation.

- Thermal effects on FRP bridges is still unknown and should be investigated.
- Quality control concerns— the material properties are highly dependent on the manufacturing process.

Challenges (CONT'D)

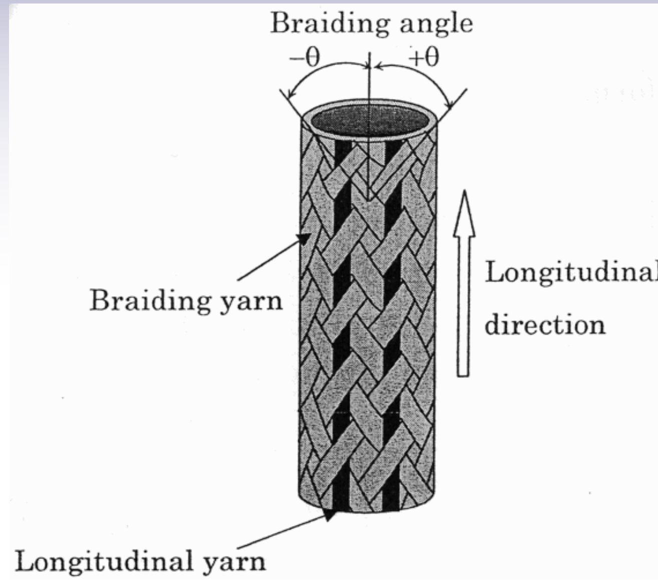
- Several practical aspects of FRP applications in bridges need to be addressed by researchers. The following are some of the outstanding issues:
  - Methods to expand lanes
  - Methods to cast concrete
  - Considerations for negative moments
  - Concrete barrier or steel parapet
  - Support conditions

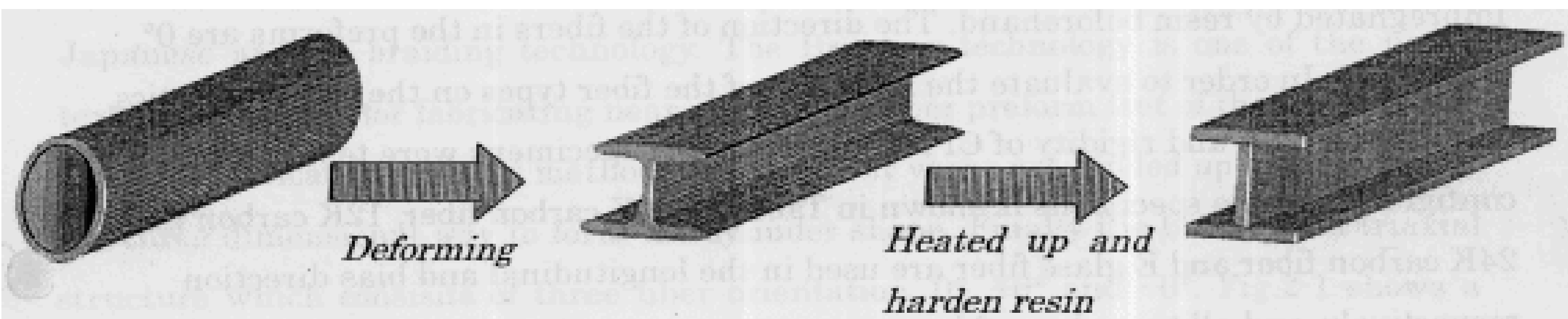
Challenges (CONT'D)

- There are benefits in using light FRP deck or superstructure in bridges located in moderate and seismic regions.
- Automated fabrication process must be used to fabricate the FRP parts of the superstructure or deck.

AUTOMATED FABRICATION PROCESSES

- Pultrusion
- RTM
- VARTM
- Use of braided fabrics
- Filament Winding





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THANK YOU