Preservation and Renewal of Civil Engineering Infrastructure Using FRP Composites

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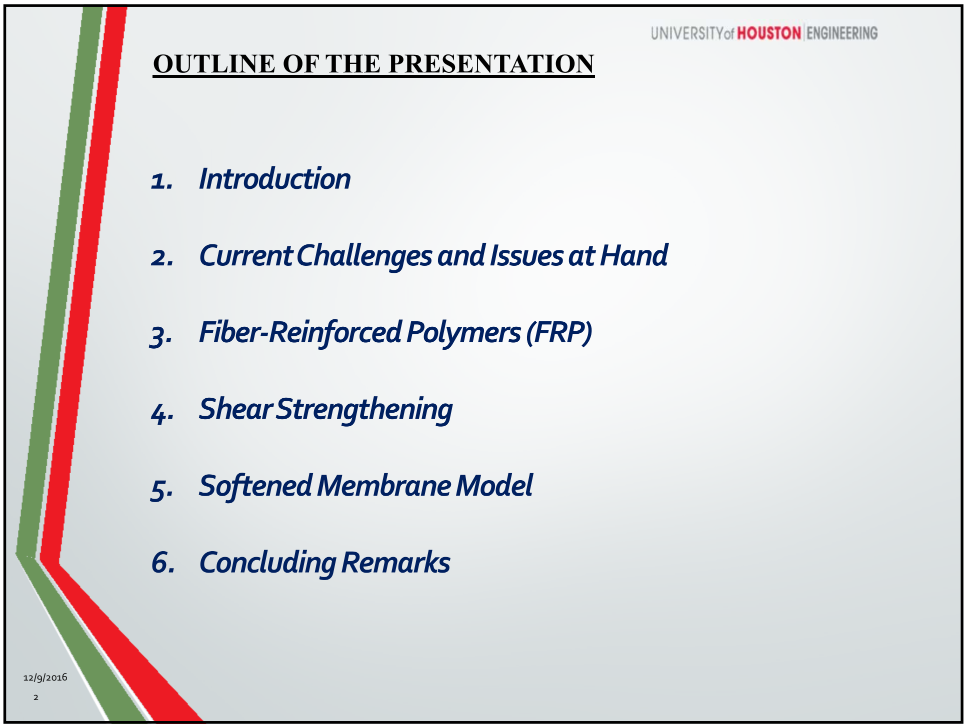
London, UK
December 7, 2016



OUTLINE OF THE PRESENTATION

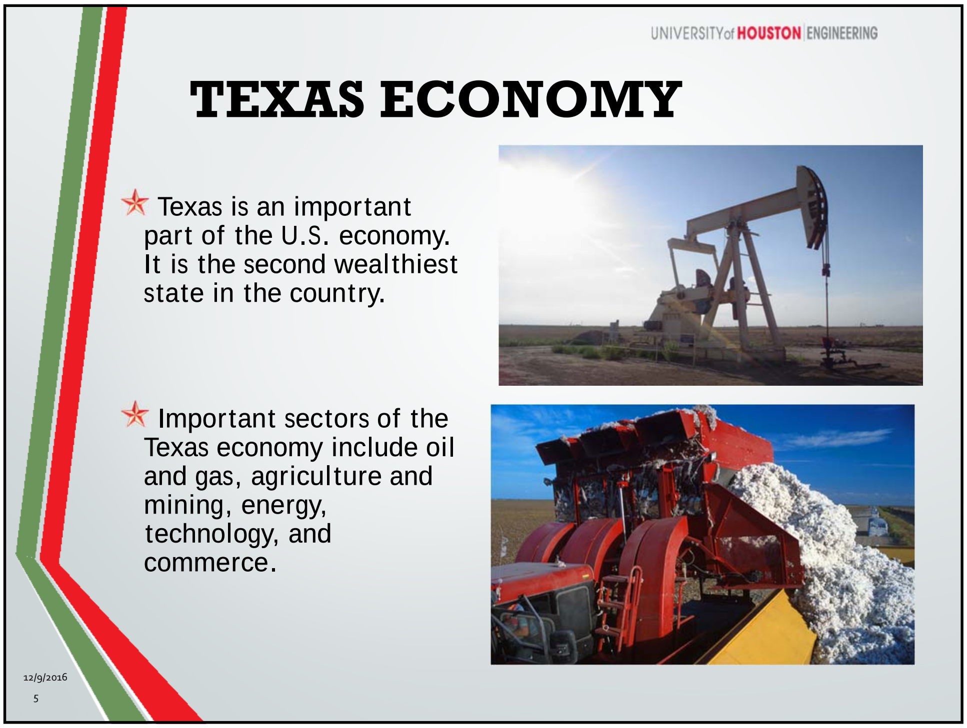
1. *Introduction*
2. *Current Challenges and Issues at Hand*
3. *Fiber-Reinforced Polymers (FRP)*
4. *Shear Strengthening*
5. *Softened Membrane Model*
6. *Concluding Remarks*

WHERE IN THE WORLD ARE HOUSTON AND TEXAS?

- Texas is the second largest state in the USA.
- It shares border with Mexico.
- The capital city is Austin
- 26 million people live in Texas.

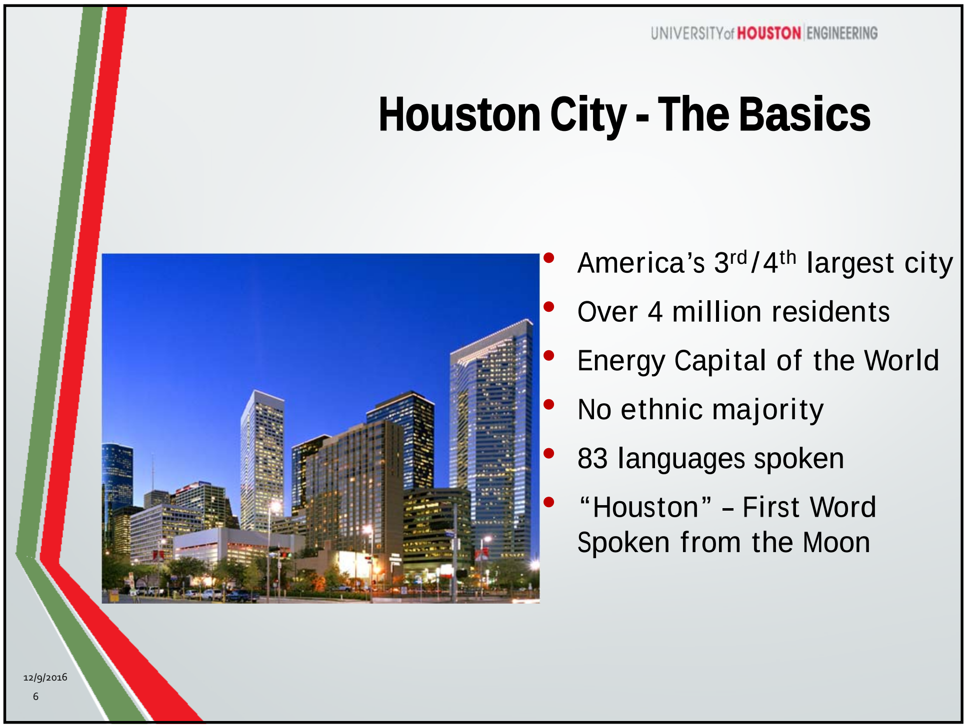
TEXAS LANDSCAPE

- Texas has a wide variety of landscapes, including coastal, mountains, planes, and desert.



TEXAS ECONOMY

- Texas is an important part of the U.S. economy. It is the second wealthiest state in the country.
- Important sectors of the Texas economy include oil and gas, agriculture and mining, energy, technology, and commerce.



Houston City - The Basics

- America’s 3rd/4th largest city
- Over 4 million residents
- Energy Capital of the World
- No ethnic majority
- 83 languages spoken
- “Houston” – First Word Spoken from the Moon

1873

21st Century

UNIVERSITY OF HOUSTON

The University of Houston (UH) is a state research university and the flagship institution of the University of Houston System

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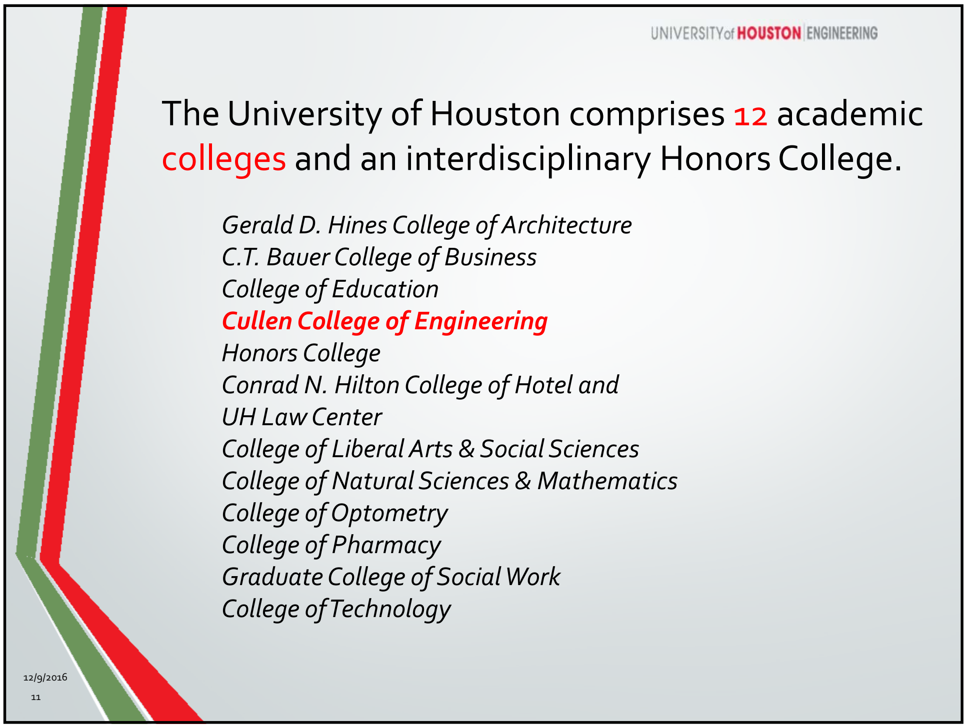
Founded in 1927
UH is the third largest university in Texas with more than 41,000 students.

UH is the second most ethnically diverse major research university in the United States.

Students come to UH from more than 137 nations

UH offers more than 120 undergraduate majors, 139 master's, and 54 doctoral degrees.

UH has 980 ranked faculty, 1340 non-ranked faculty, and 1450 student teaching assistants



The University of Houston comprises 12 academic colleges and an interdisciplinary Honors College.

Gerald D. Hines College of Architecture
C.T. Bauer College of Business
College of Education
Cullen College of Engineering
Honors College
Conrad N. Hilton College of Hotel and
UH Law Center
College of Liberal Arts & Social Sciences
College of Natural Sciences & Mathematics
College of Optometry
College of Pharmacy
Graduate College of Social Work
College of Technology

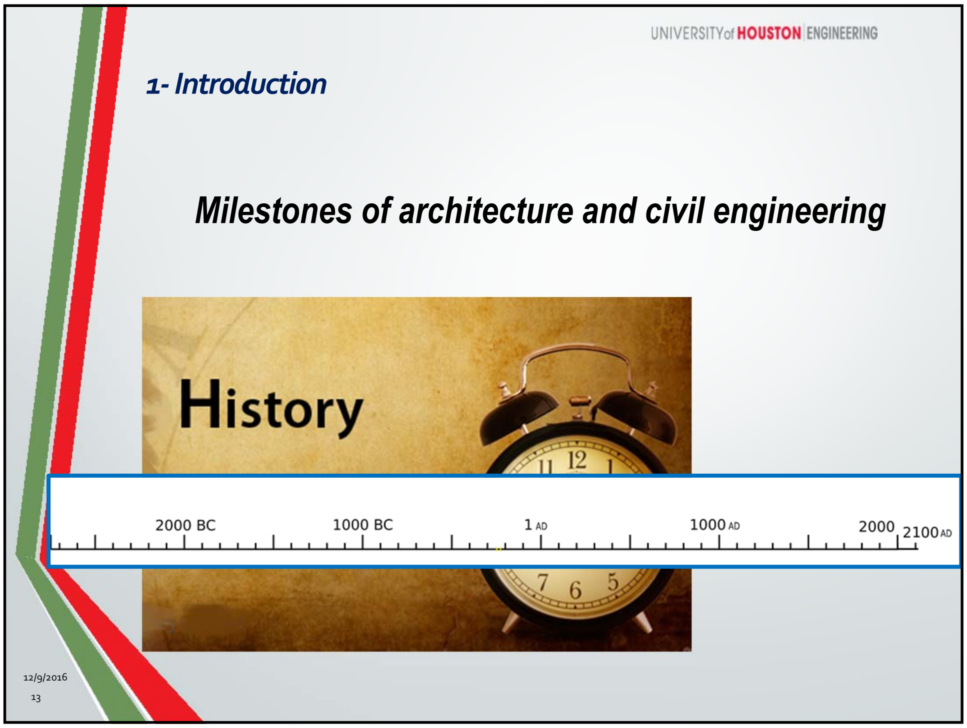
UH *Cullen College of Engineering*

- *Dept. of Civil and Environmental Engineering*
- *Dept. of Electrical and Computer Engineering*
- *Dept. of Chemical Engineering*
- *Dept. of Petroleum Engineering*
- *Dept. of Biomedical Engineering*
- *Dept. of Industrial Engineering*

Interdisciplinary Graduate Programs in

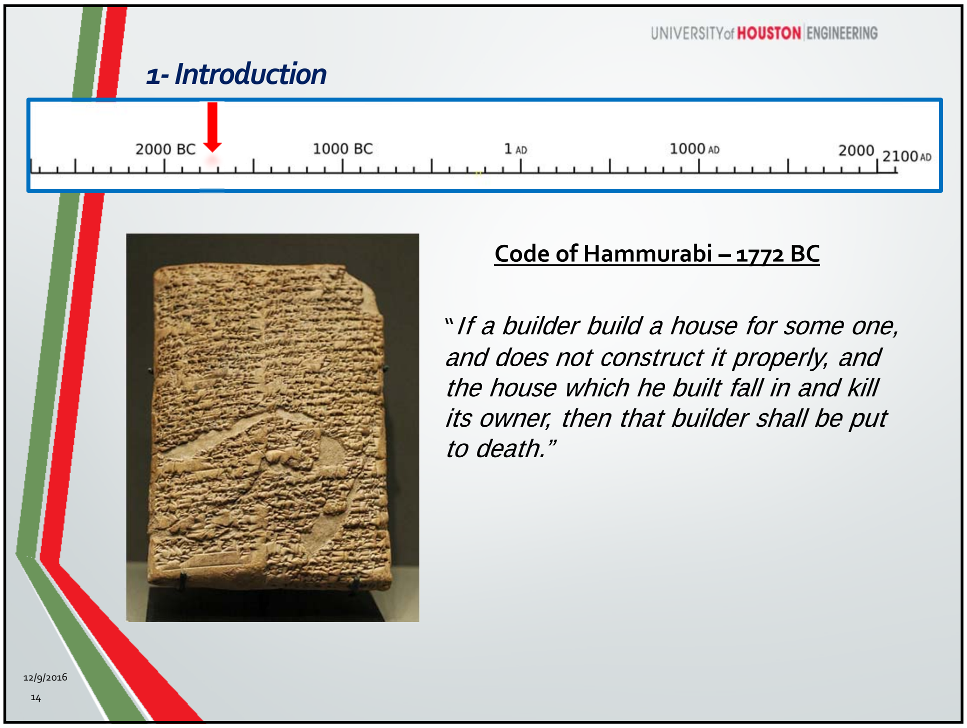
- *Materials engineering*
- *Subsea Engineering*
- *Aerospace Engineering*
- *Geosensing Engineering*
- *Environmental Engineering*

www.uh.edu



1- Introduction

Milestones of architecture and civil engineering



1- Introduction

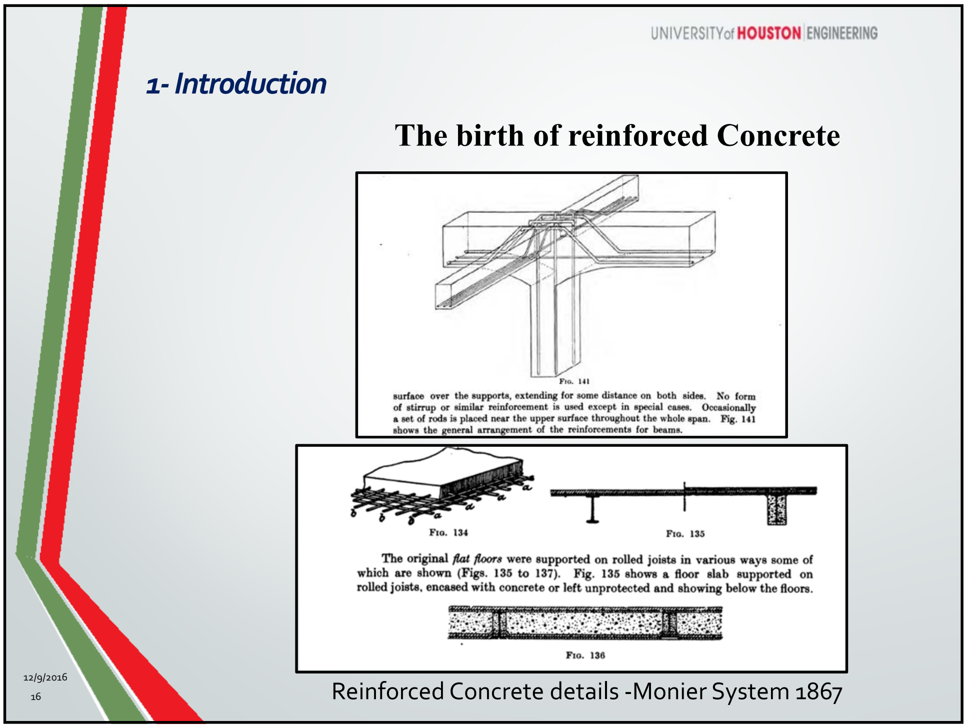
Code of Hammurabi – 1772 BC

"*If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.*"

1- Introduction

Conventional construction materials of today started to appear.

- *Portland cement concrete*
- *Reinforced concrete*
- *Prestressed concrete*
- ***Advanced composites and plastics***
- ***What is next???***



1- Introduction

The birth of reinforced Concrete

Fig. 141

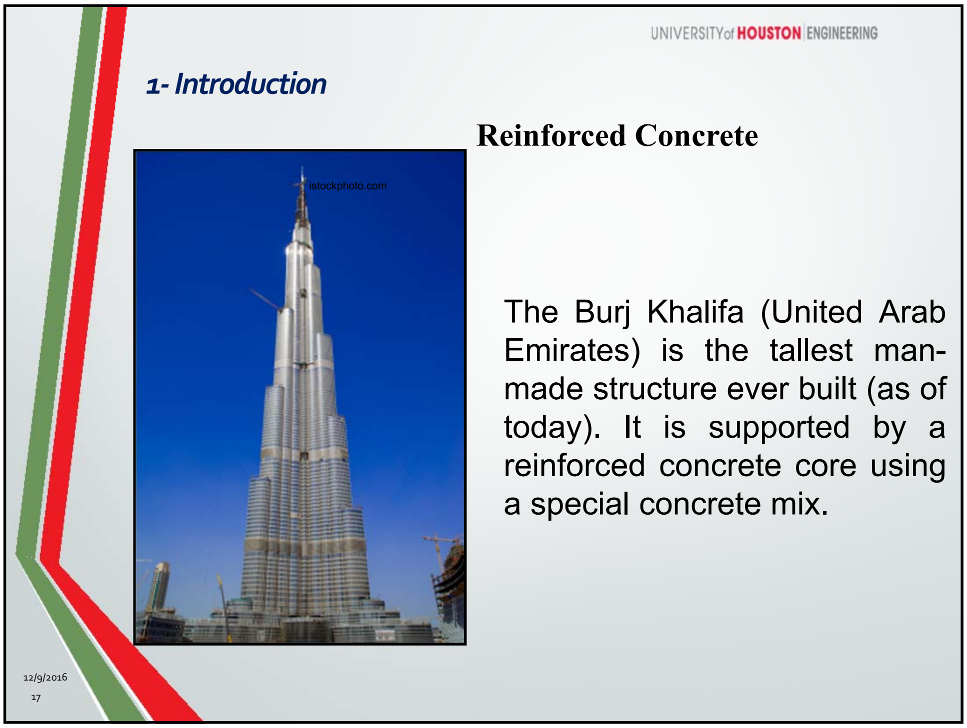
surface over the supports, extending for some distance on both sides. No form of stirrup or similar reinforcement is used except in special cases. Occasionally a set of rods is placed near the upper surface throughout the whole span. Fig. 141 shows the general arrangement of the reinforcements for beams.

Fig. 134 Fig. 135

The original *flat floors* were supported on rolled joists in various ways some of which are shown (Figs. 135 to 137). Fig. 135 shows a floor slab supported on rolled joists, encased with concrete or left unprotected and showing below the floors.

Fig. 136

Reinforced Concrete details -Monier System 1867



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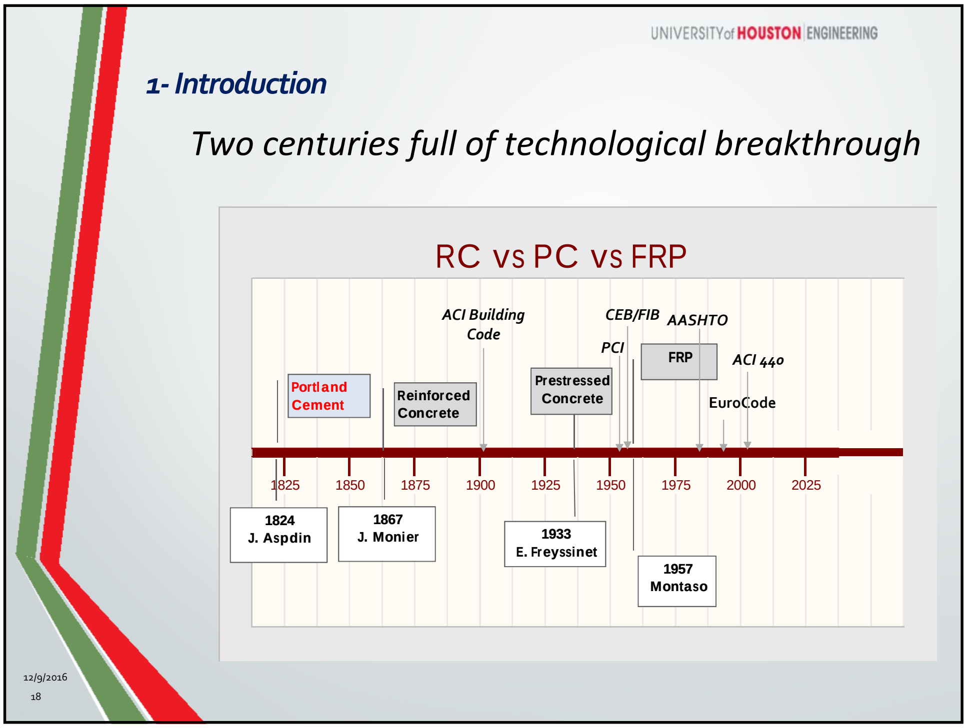
1- Introduction

Reinforced Concrete

istockphoto.com

The Burj Khalifa (United Arab Emirates) is the tallest man-made structure ever built (as of today). It is supported by a reinforced concrete core using a special concrete mix.



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1- Introduction

Two centuries full of technological breakthrough

RC vs PC vs FRP

2- Current Challenges and Issues at Hand

Man constructs,
Man destructs,
Man constructs…

Source: http://whateverhappensny.bandcamp.com/releases

2- Current Challenges and Issues at Hand

WW II – Mass destruction of built environment and infrastructure of cities all around the world.

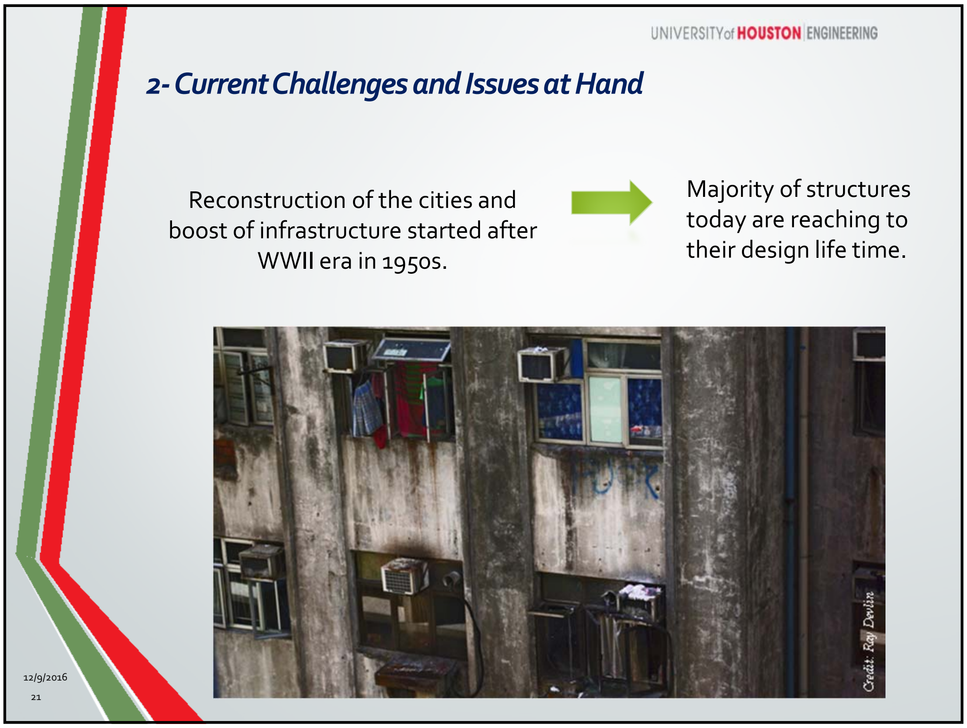
Hiroshima – Japan, 1945

1935

1945

2009

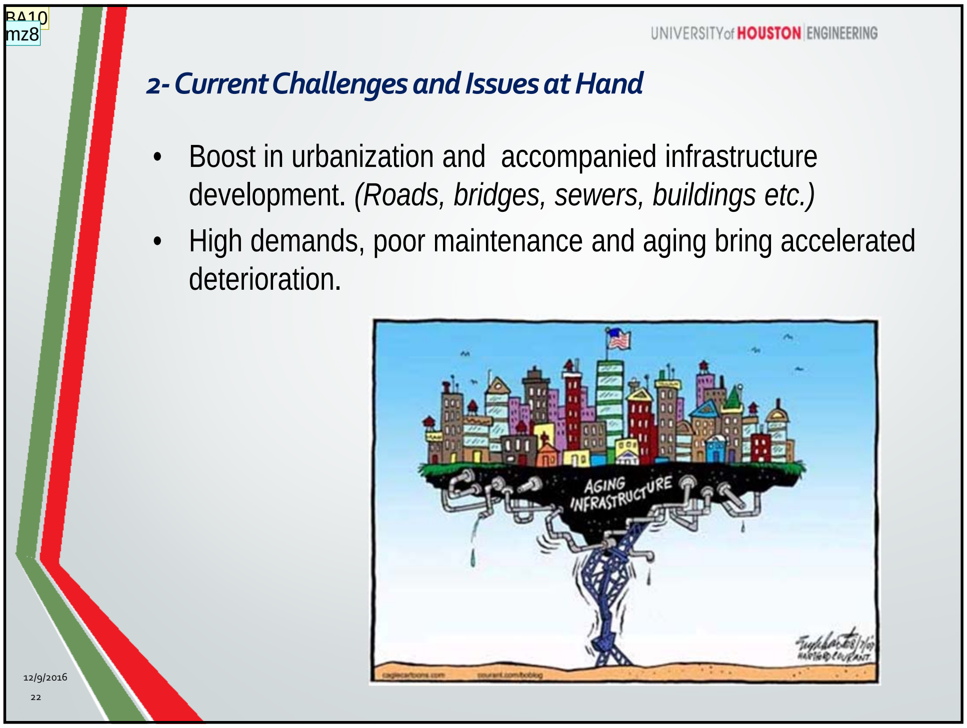
Warsaw, Poland



2- Current Challenges and Issues at Hand

Reconstruction of the cities and boost of infrastructure started after WWII era in 1950s. → Majority of structures today are reaching to their design life time.

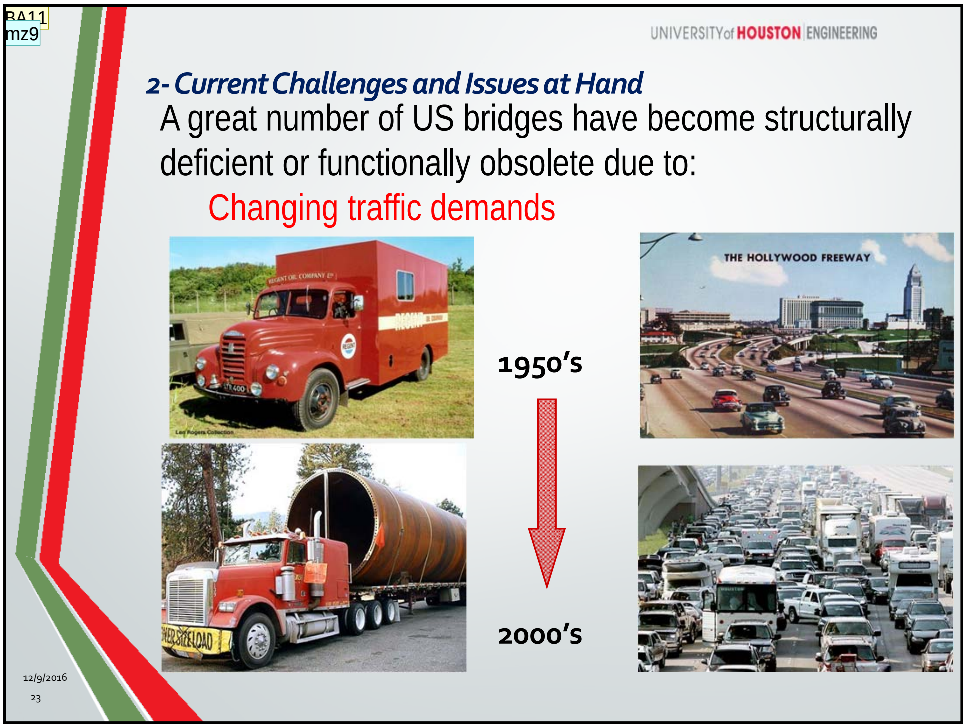
Credit: Ray Devlin



RA10
mz8

2- Current Challenges and Issues at Hand

- Boost in urbanization and accompanied infrastructure development. *(Roads, bridges, sewers, buildings etc.)*
- High demands, poor maintenance and aging bring accelerated deterioration.



BA11
mz9

2- Current Challenges and Issues at Hand

A great number of US bridges have become structurally deficient or functionally obsolete due to:

Changing traffic demands

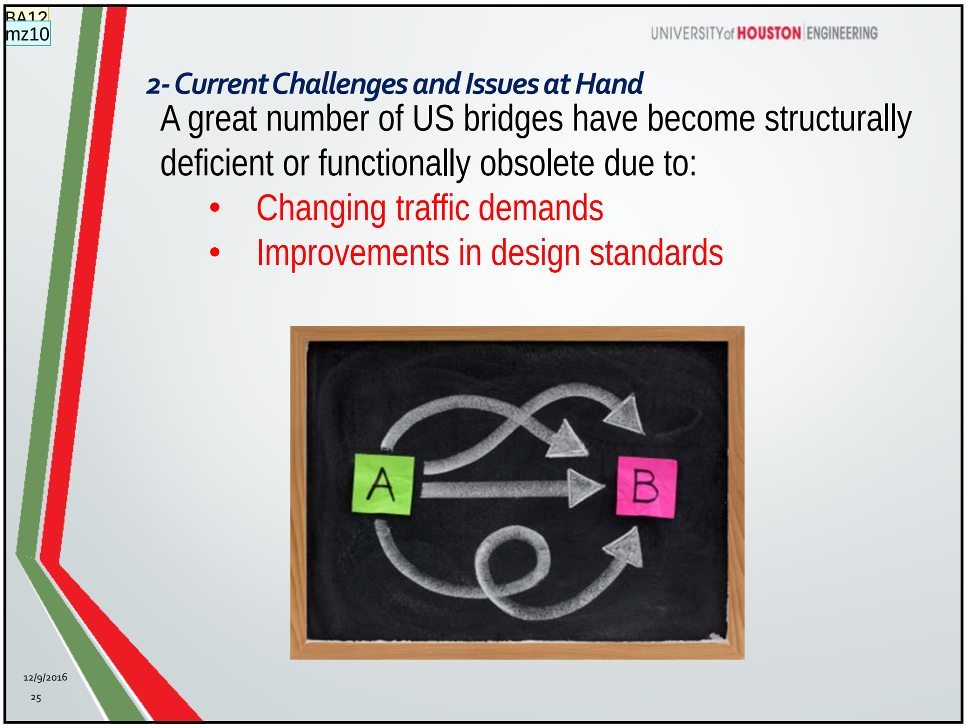
1950's

2000's

BA17
mz13

2- Current Challenges and Issues at Hand

Change of use: Higher loads than originally designed

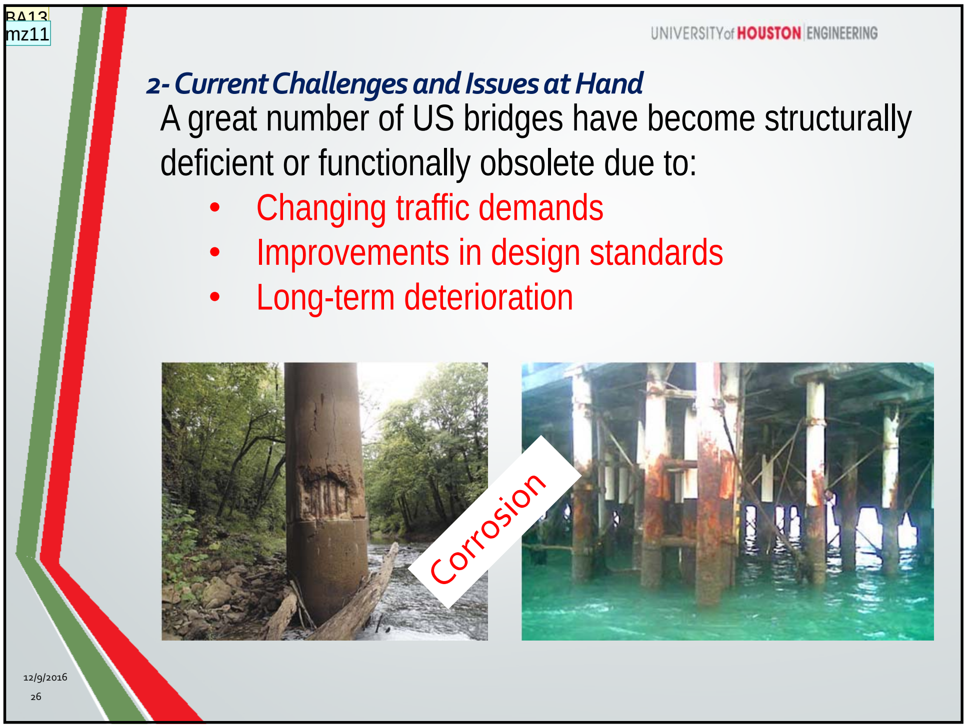


RA12
mz10

2- Current Challenges and Issues at Hand

A great number of US bridges have become structurally deficient or functionally obsolete due to:

- Changing traffic demands
- Improvements in design standards



RA13
mz11

2- Current Challenges and Issues at Hand

A great number of US bridges have become structurally deficient or functionally obsolete due to:

- Changing traffic demands
- Improvements in design standards
- Long-term deterioration

2- Current Challenges and Issues at Hand

A great number of US bridges have become structurally deficient or functionally obsolete due to:

- Changing traffic demands
- Improvements in design standards
- Long-term deterioration

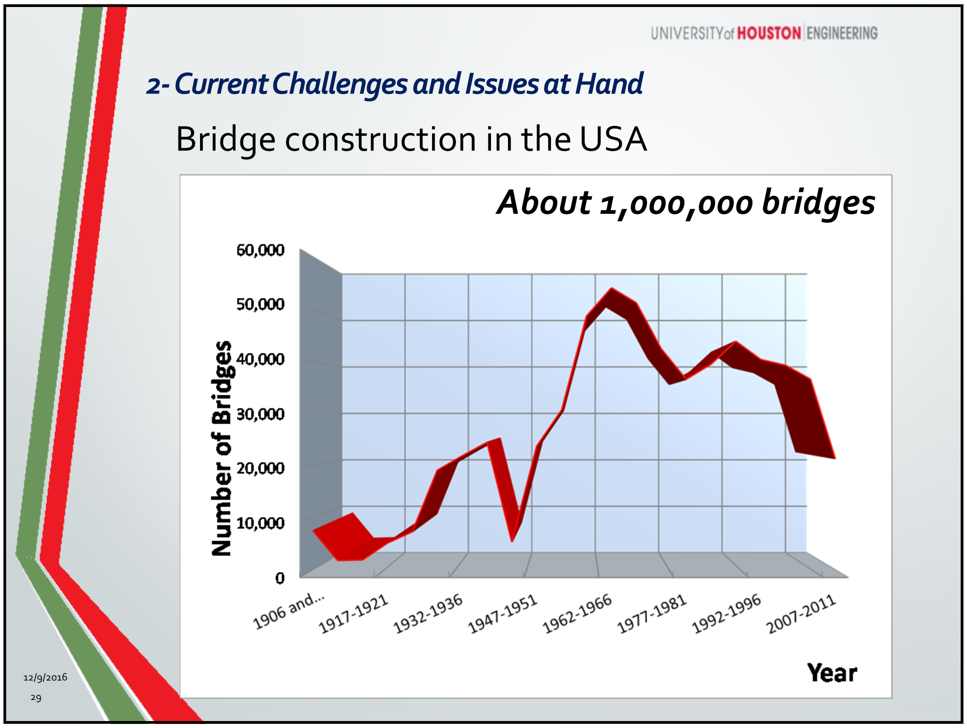
Bridge at US-385 and the Canadian River

RA14
mz12

2- Current Challenges and Issues at Hand

A great number of US bridges have become structurally deficient or functionally obsolete due to:

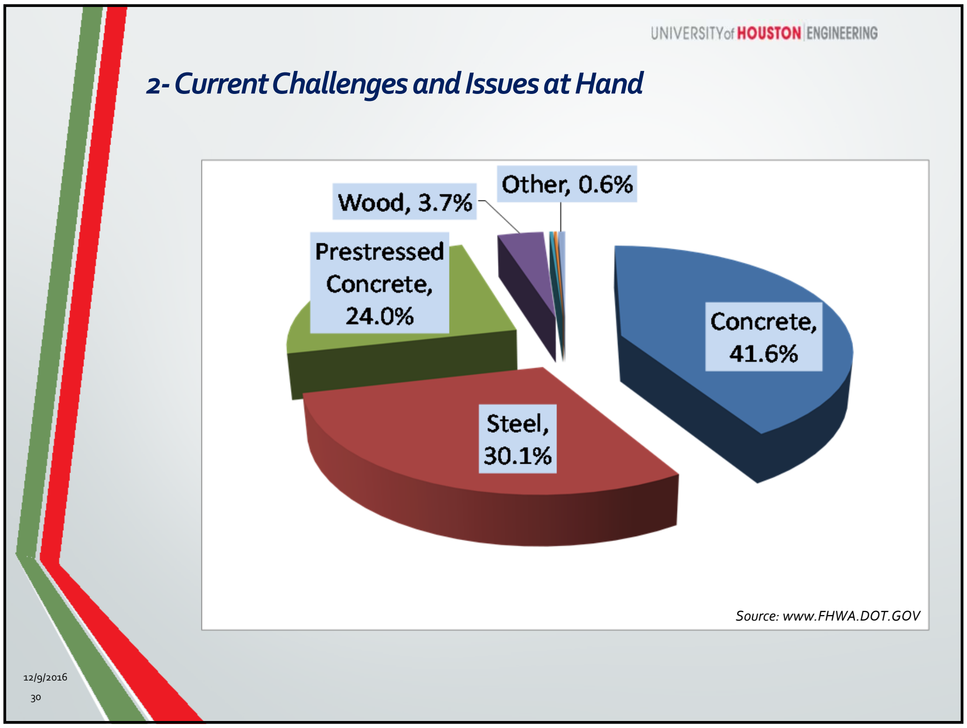
- Changing traffic demands
- Improvements in design standards
- Long-term deterioration
- Man-made structural damage



2- Current Challenges and Issues at Hand

Bridge construction in the USA

About 1,000,000 bridges



2- Current Challenges and Issues at Hand

Source: www.FHWA.DOT.GOV

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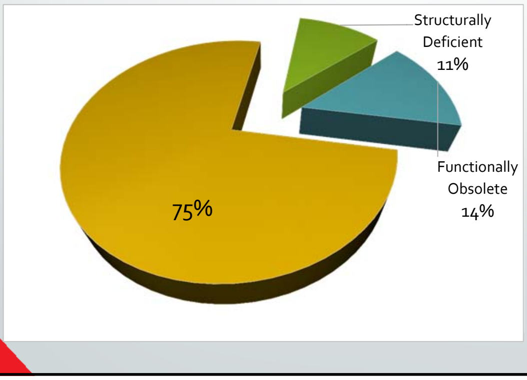
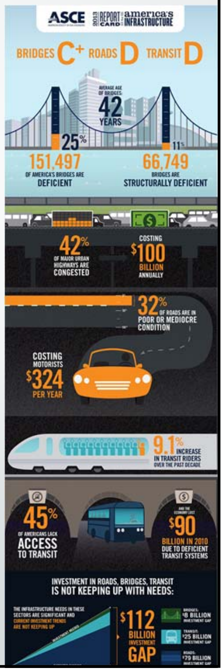
2- Current Challenges and Issues at Hand

ASCE 2013 Report Card for Bridges:

C+

Need to invest $20.5 billion annually till 2028





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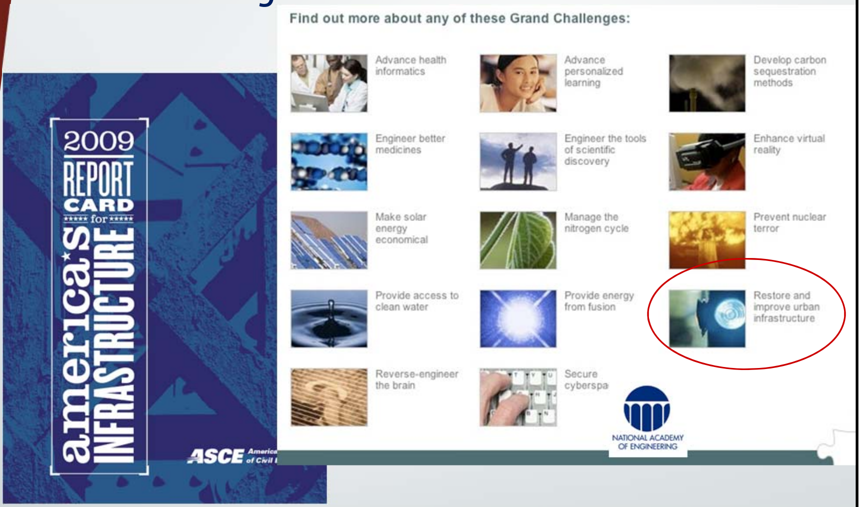
2- Current Challenges and Issues at Hand

Problem should be addressed and solutions should be proposed in the light of former experience and foresight :

- Traditional vs. new materials
- Economical solutions
- Immediate actions

ADVANCE COMPOSITE MATERIALS

2- Current Challenges and Issues at Hand


2009 REPORT CARD for america's INFRASTRUCTURE

ASCE

Find out more about any of these Grand Challenges:

- Advance health informatics
- Advance personalized learning
- Develop carbon sequestration methods
- Engineer better medicines
- Engineer the tools of scientific discovery
- Enhance virtual reality
- Make solar energy economical
- Manage the nitrogen cycle
- Prevent nuclear terror
- Provide access to clean water
- Provide energy from fusion
- Restore and improve urban infrastructure
- Reverse-engineer the brain
- Secure cyberspa

NATIONAL ACADEMY OF ENGINEERING

Nationally recognized need

BA22
mz14

3- Fiber-Reinforced Polymers (FRP)

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FRPs are advanced composite materials consisting of high strength fibers such as aramid, carbon or glass embedded in a polymer resin.

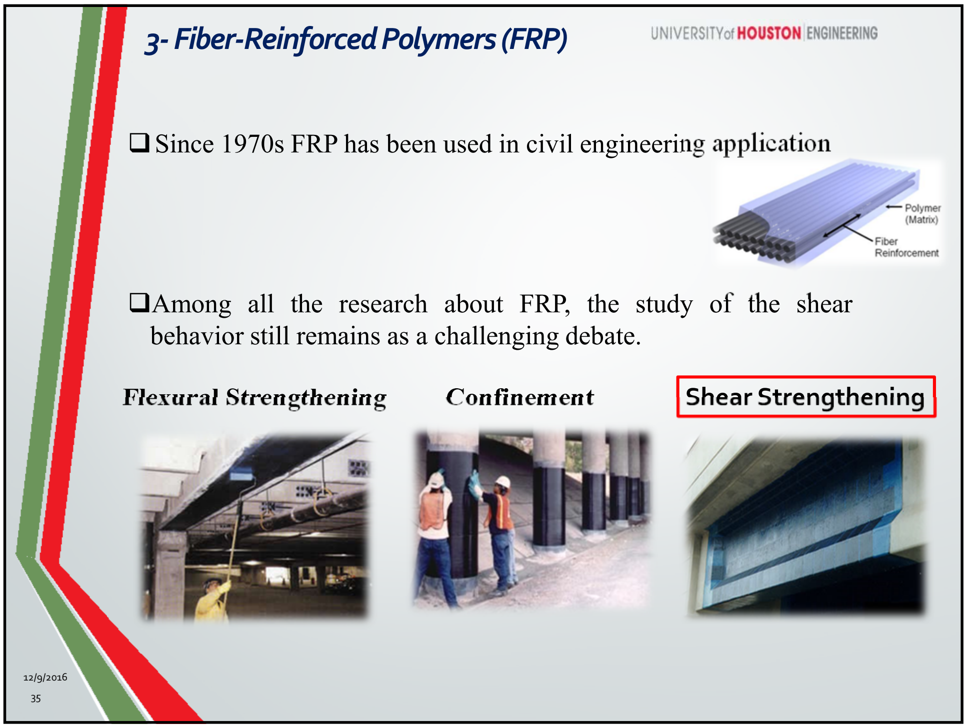
Commercially available forms

Reinforcing Bar and Prestressing Tendons

Pre-cured laminate shells

Grids

Fiber sheets

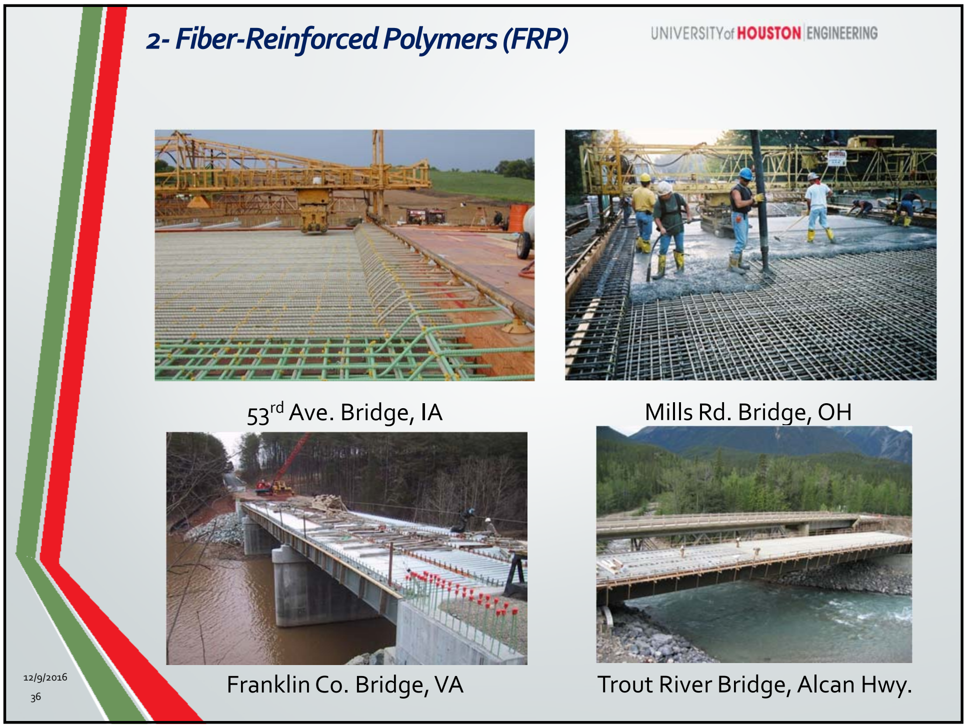


3- Fiber-Reinforced Polymers (FRP)

❑ Since 1970s FRP has been used in civil engineering application

❑ Among all the research about FRP, the study of the shear behavior still remains as a challenging debate.

Flexural Strengthening **Confinement** **Shear Strengthening**



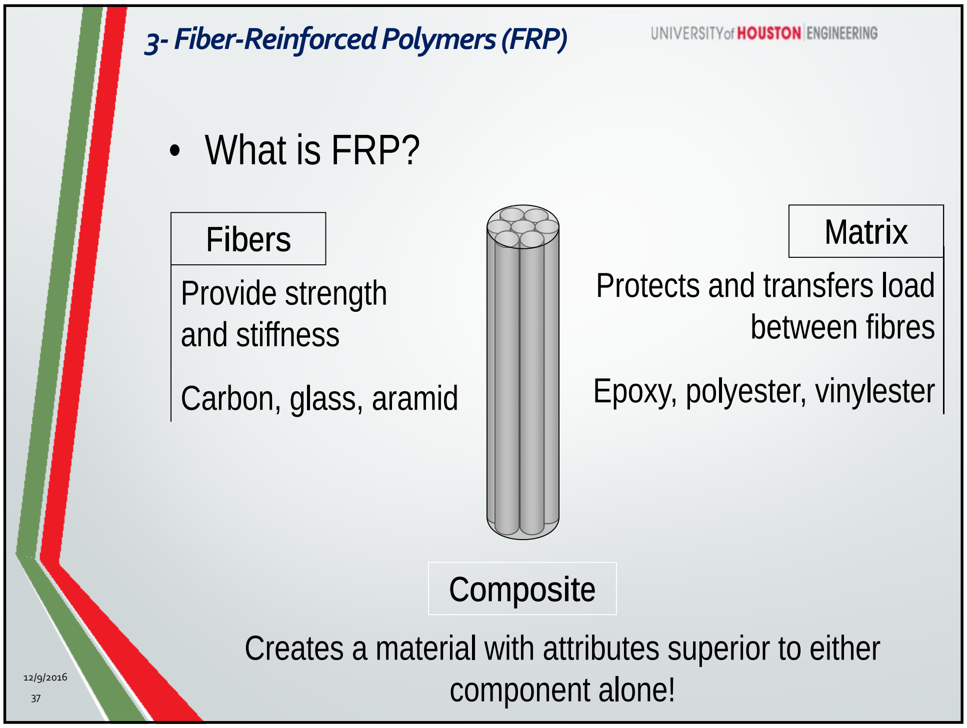
2- Fiber-Reinforced Polymers (FRP)

53rd Ave. Bridge, IA

Mills Rd. Bridge, OH

Franklin Co. Bridge, VA

Trout River Bridge, Alcan Hwy.



3- Fiber-Reinforced Polymers (FRP)

- What is FRP?

Fibers

Provide strength and stiffness

Carbon, glass, aramid

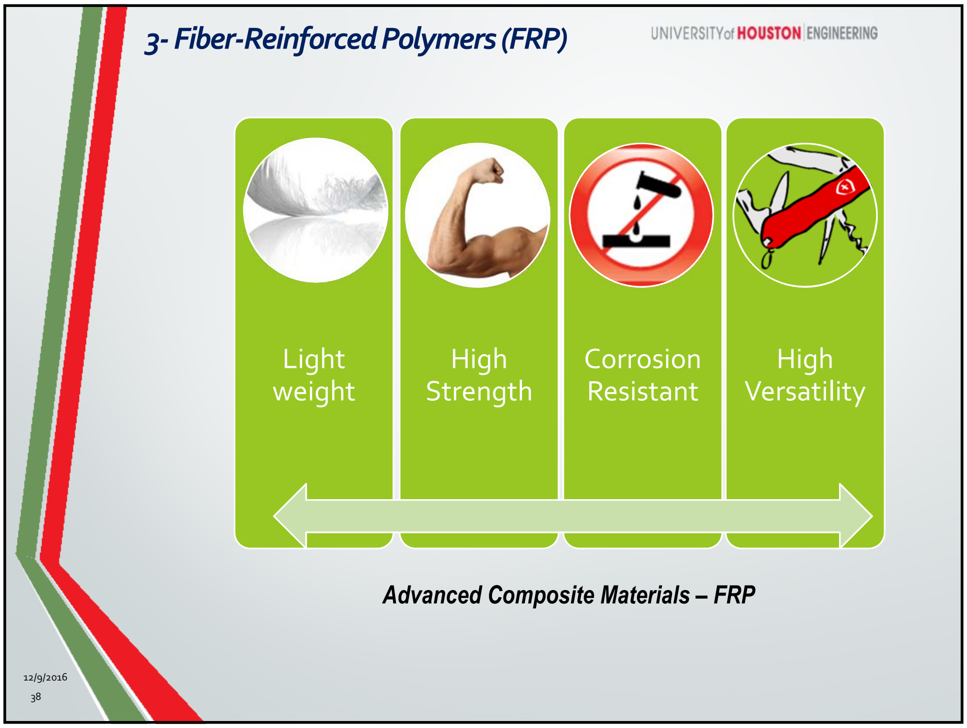
Matrix

Protects and transfers load between fibres

Epoxy, polyester, vinylester

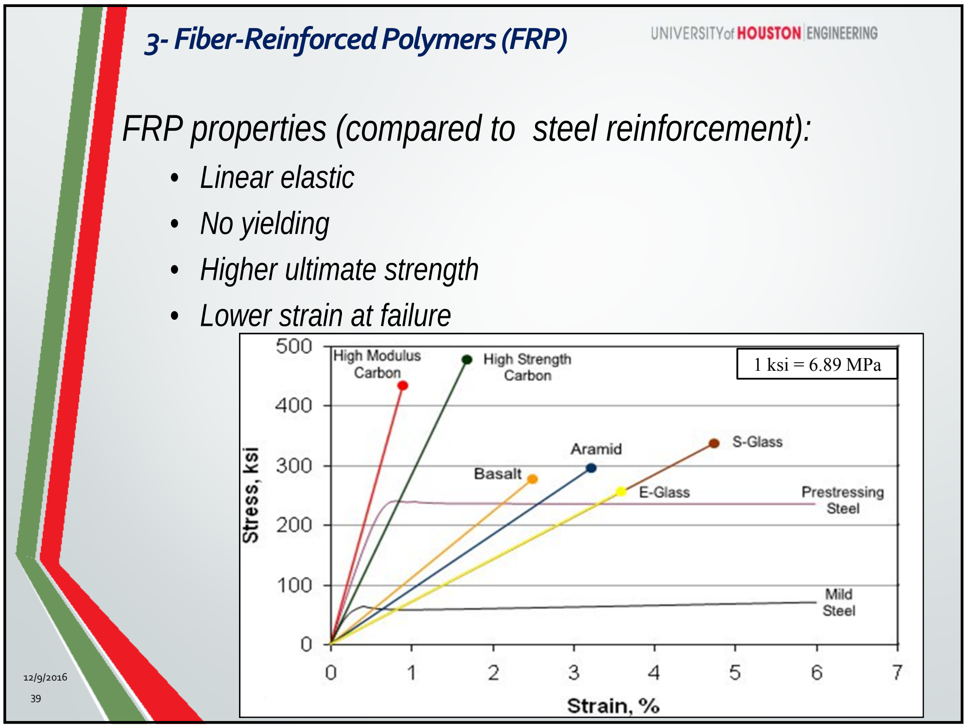
Composite

Creates a material with attributes superior to either component alone!



3- Fiber-Reinforced Polymers (FRP)

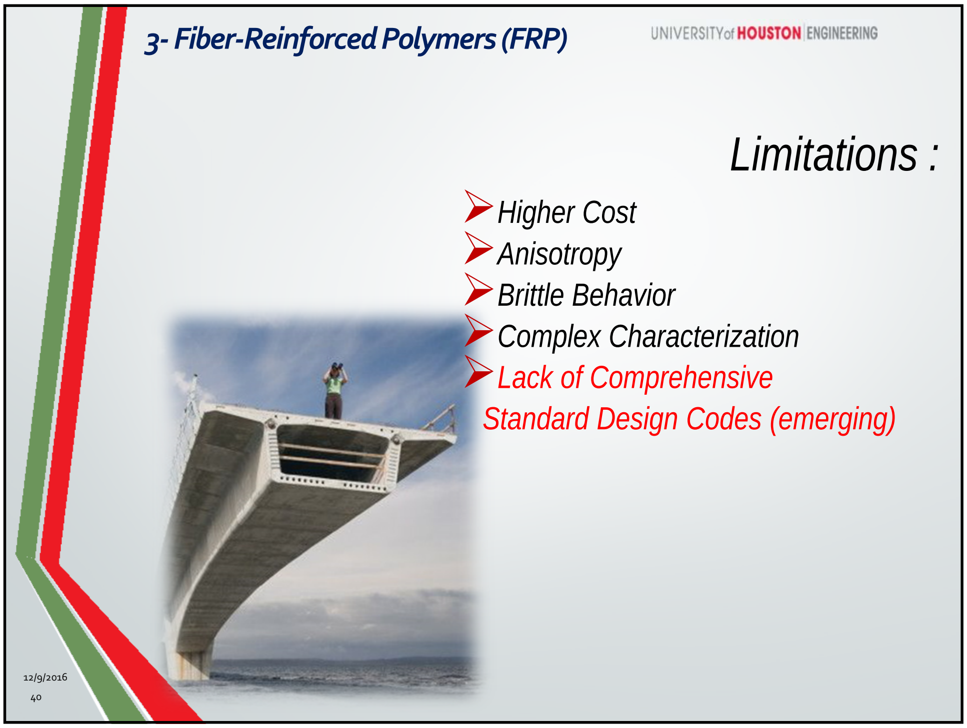
Advanced Composite Materials – FRP



3- Fiber-Reinforced Polymers (FRP)

FRP properties (compared to steel reinforcement):

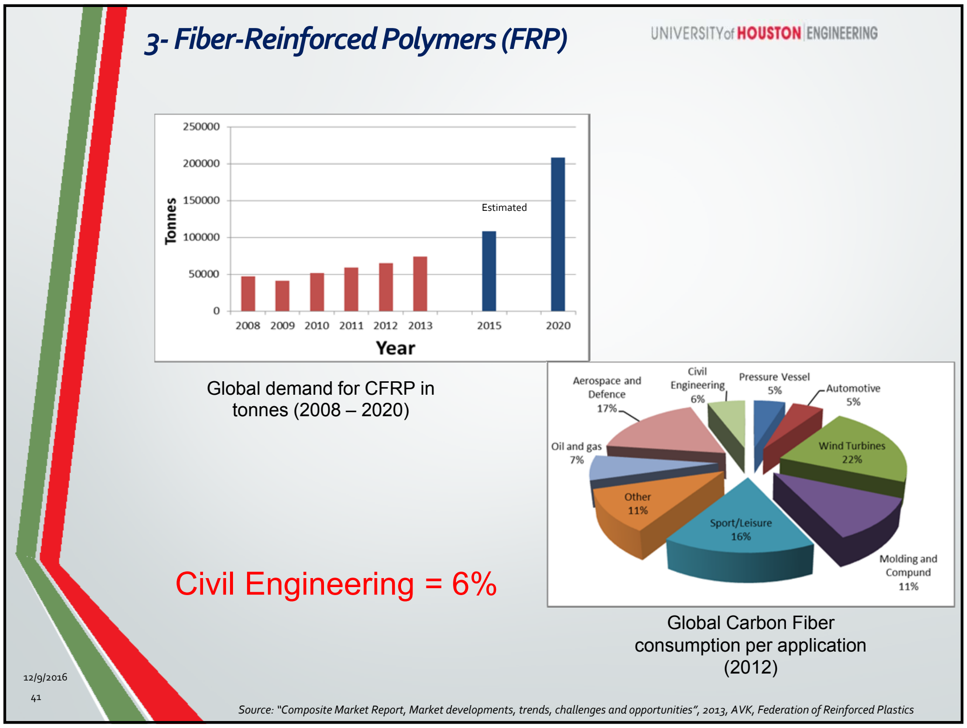
- *Linear elastic*
- *No yielding*
- *Higher ultimate strength*
- *Lower strain at failure*



3- Fiber-Reinforced Polymers (FRP)

Limitations :

- *Higher Cost*
- *Anisotropy*
- *Brittle Behavior*
- *Complex Characterization*
- *Lack of Comprehensive Standard Design Codes (emerging)*



3- Fiber-Reinforced Polymers (FRP)

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Global demand for CFRP in tonnes (2008 – 2020)

Global Carbon Fiber consumption per application (2012)

Civil Engineering = 6%

Source: "Composite Market Report, Market developments, trends, challenges and opportunities", 2013, AVK, Federation of Reinforced Plastics

3- Fiber-Reinforced Polymers (FRP)

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General use of FRP in Transportation

Aircrafts

A380
Fiber Metal Laminate

Race Cars

McLaren – Formula 1
CFRP Thermoset
Car Body Structure

Trucks

SMC Thermoset Parts
for Driver Cabin

Cars

GMT-Thermoplastic

Helicopters

Rotor Blade
Erosion Protection

Sport Cars

CFRP Thermoset Car
Body Structure

Buses

SMC Thermoset
Panels

Concept Cars

Injection Moulded
Thermoplastic Car Body

Automotive/Railway and Aerospace

3- Fiber-Reinforced Polymers (FRP)

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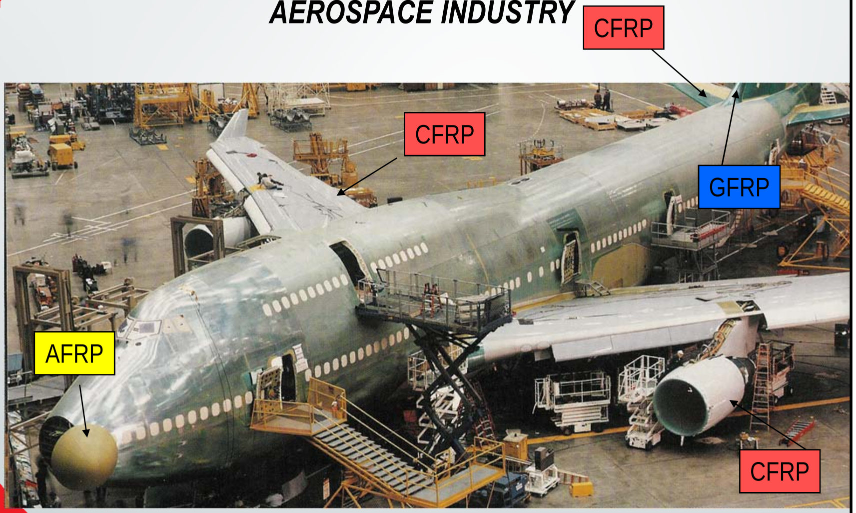
AEROSPACE INDUSTRY



Airbus 380

3- Fiber-Reinforced Polymers (FRP)

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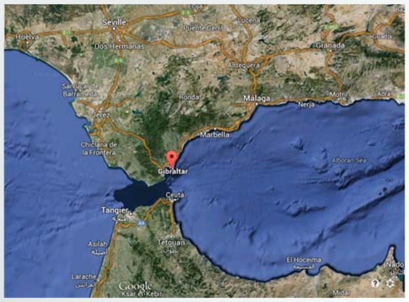
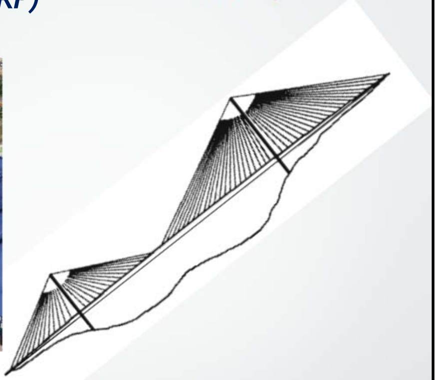
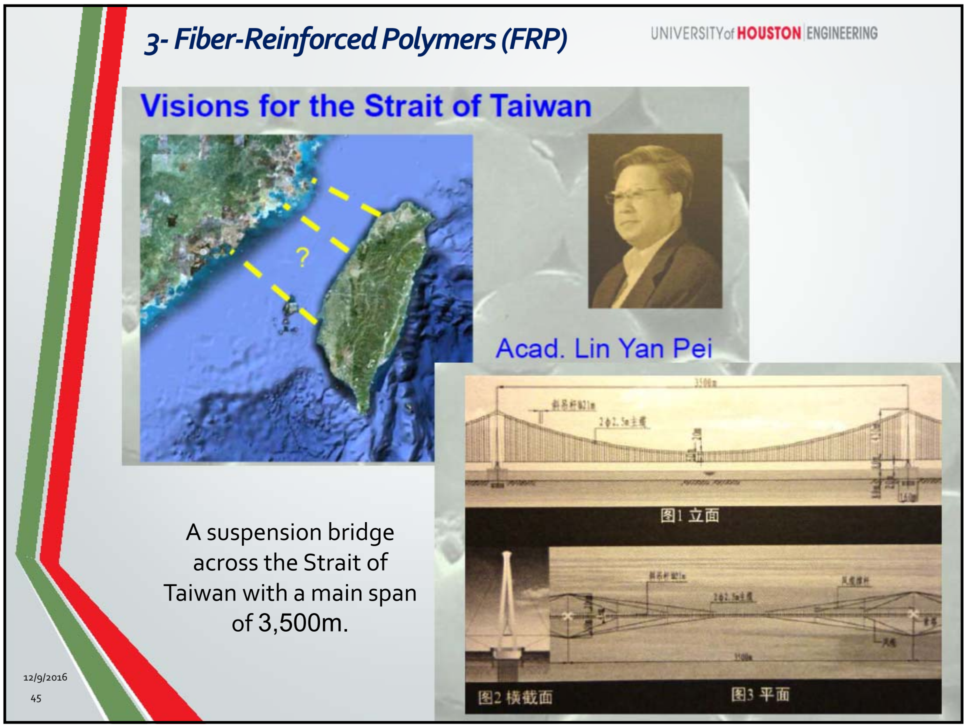




Proposal for a carbon fiber-reinforced composite bridge across the Straight of Gibraltar at its narrowest site according to Meier (1987) as a cable net structure.

Spans: 3,100 – 8,400 m.
The heights of the towers are approximately 850 and 1,250 m. above sea level



3- Fiber-Reinforced Polymers (FRP)

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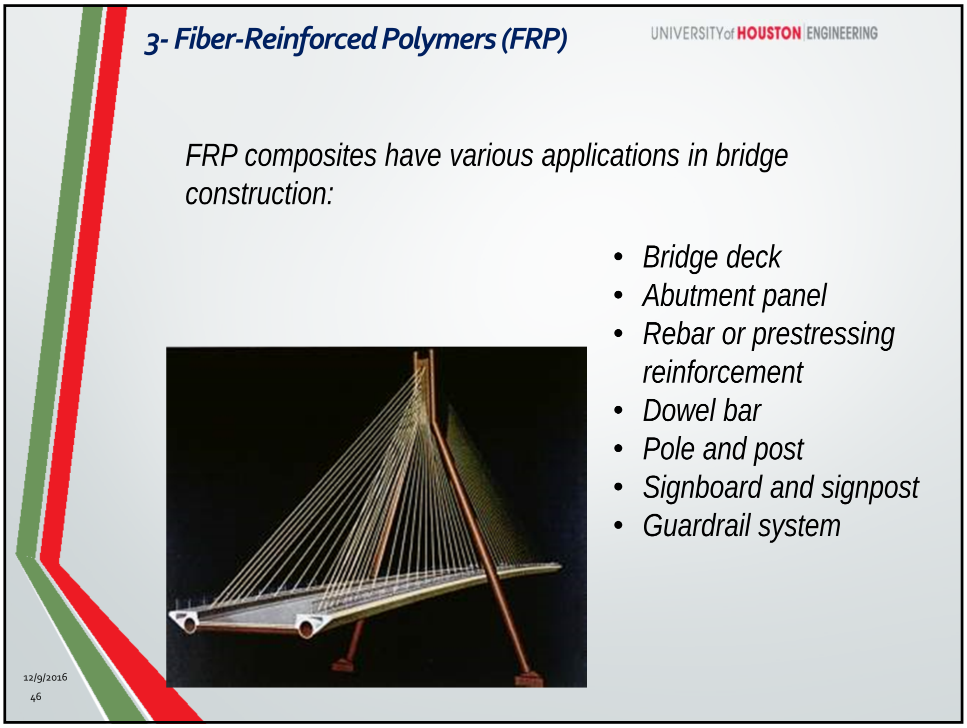
Visions for the Strait of Taiwan

Acad. Lin Yan Pei

A suspension bridge across the Strait of Taiwan with a main span of 3,500m.



3- Fiber-Reinforced Polymers (FRP)

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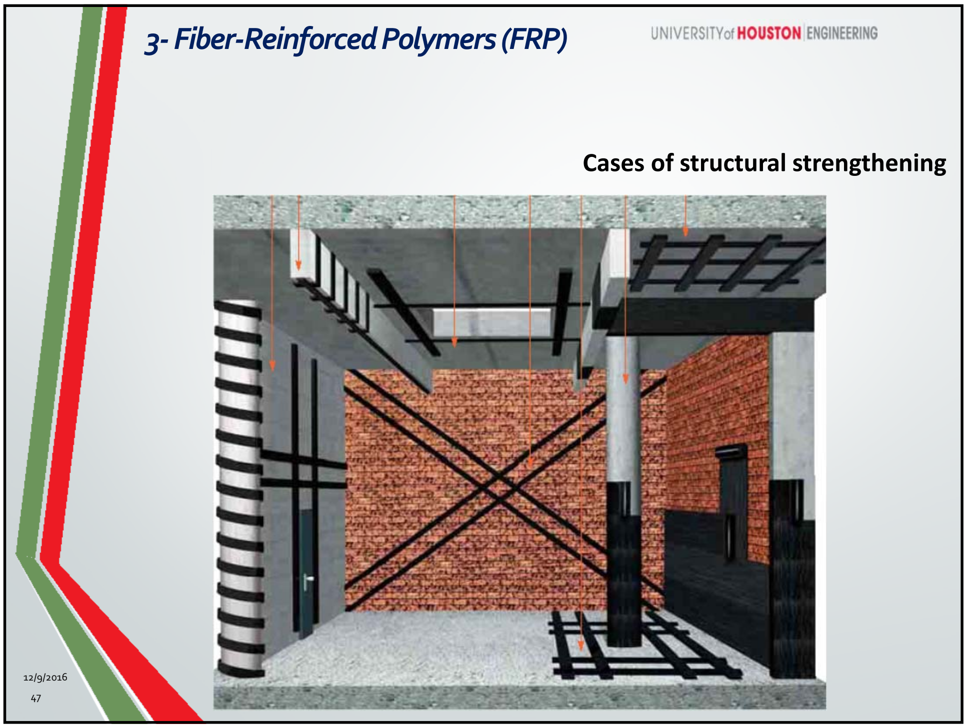
FRP composites have various applications in bridge construction:

- *Bridge deck*
- *Abutment panel*
- *Rebar or prestressing reinforcement*
- *Dowel bar*
- *Pole and post*
- *Signboard and signpost*
- *Guardrail system*



3- Fiber-Reinforced Polymers (FRP)

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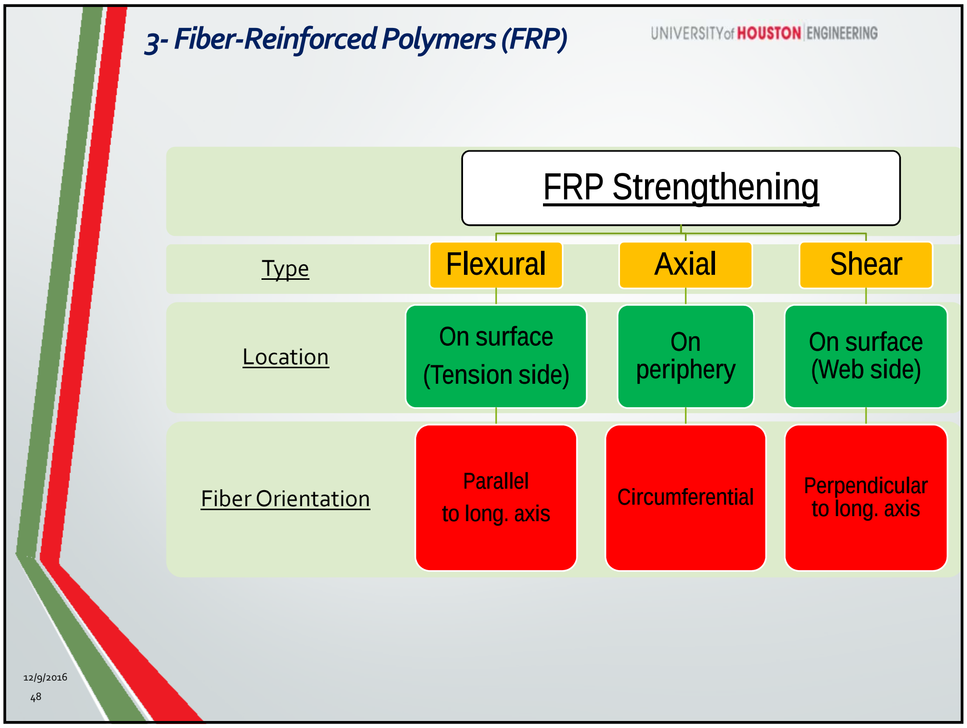
Cases of structural strengthening



3- Fiber-Reinforced Polymers (FRP)

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FRP Strengthening

Type	Flexural	Axial	Shear
Location	On surface (Tension side)	On periphery	On surface (Web side)
Fiber Orientation	Parallel to long. axis	Circumferential	Perpendicular to long. axis

3- Fiber-Reinforced Polymers (FRP)

ISIS Canada Design Manual

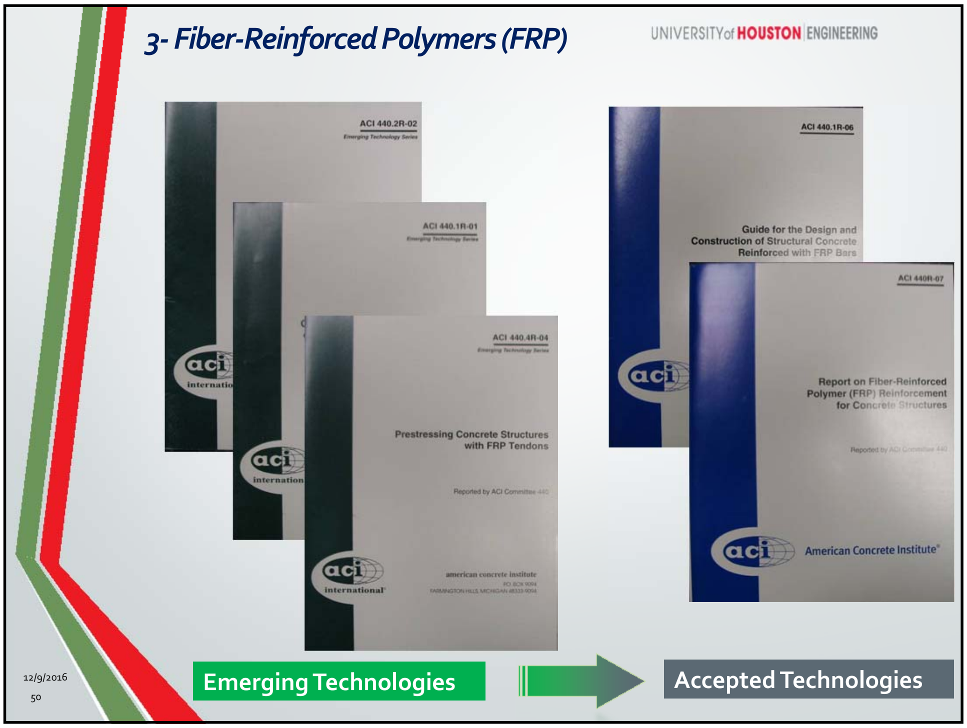
CSA S806-12

ACI 440.2R-08

European fib TG9.3 (2001)

Available Design

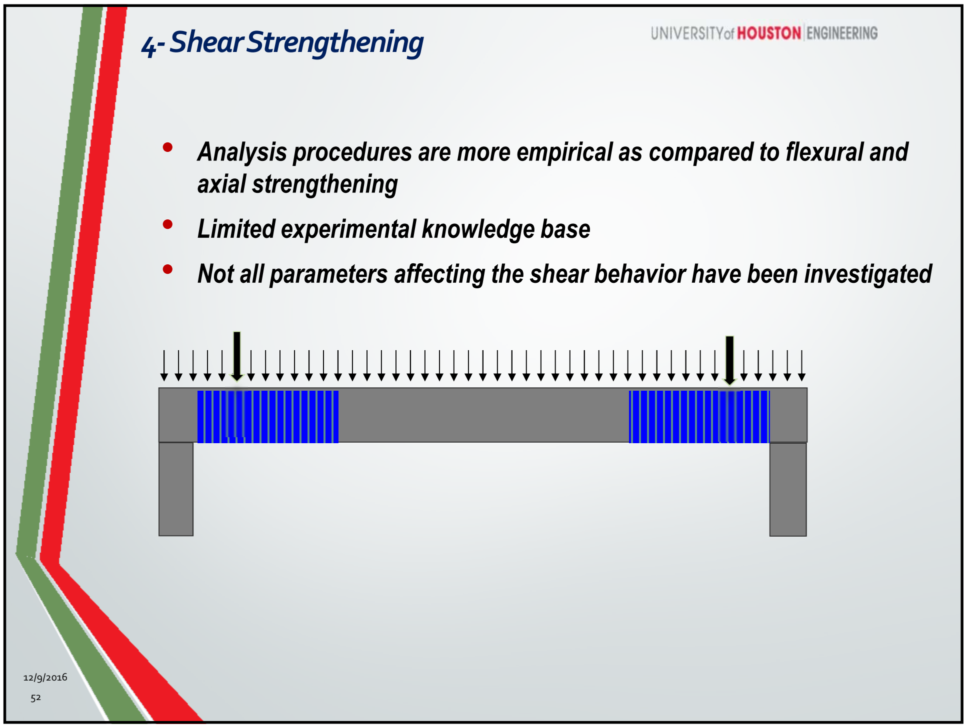
Guidelines Worldwide



3- Fiber-Reinforced Polymers (FRP)

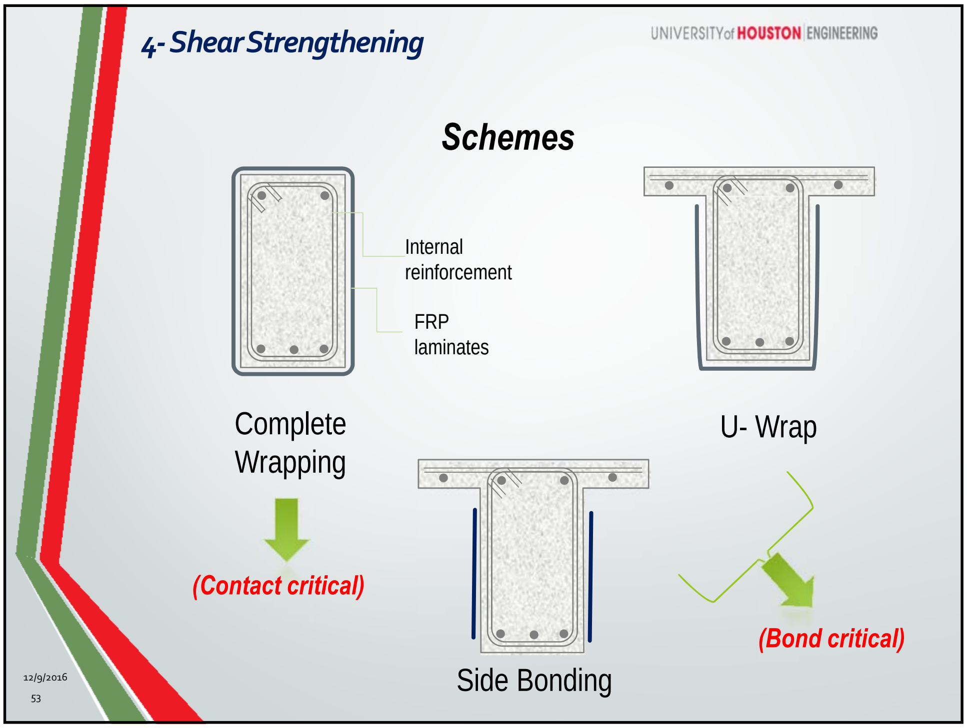
Emerging Technologies → Accepted Technologies

4- Shear Strengthening



4- Shear Strengthening

- Analysis procedures are more empirical as compared to flexural and axial strengthening
- Limited experimental knowledge base
- Not all parameters affecting the shear behavior have been investigated



4- Shear Strengthening

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Schemes

Internal reinforcement

FRP laminates

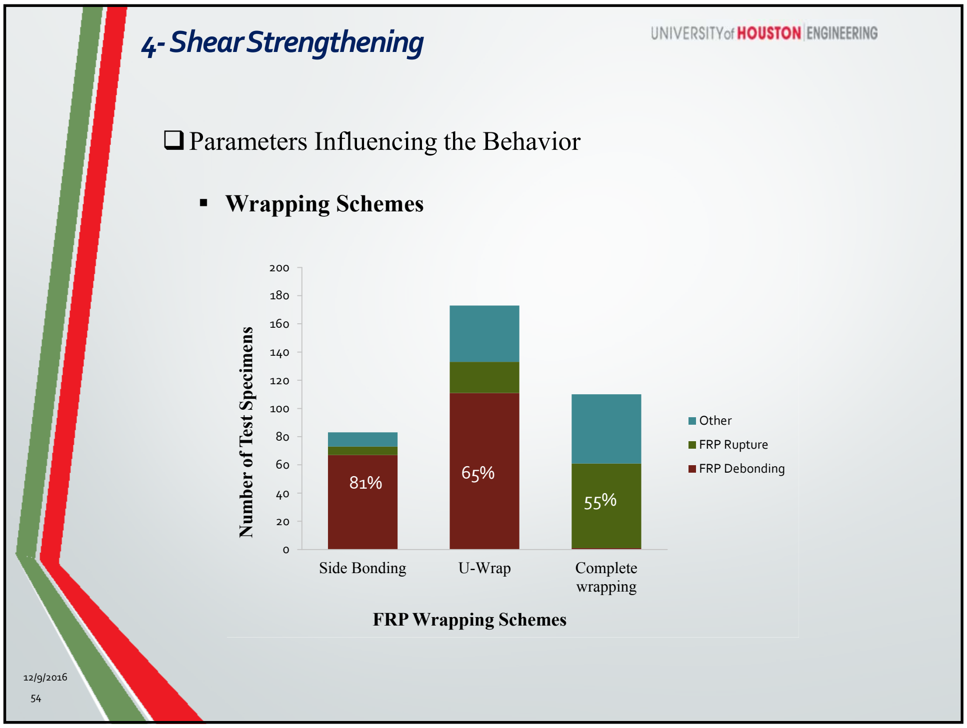
Complete Wrapping

(Contact critical)

U- Wrap

Side Bonding

(Bond critical)



4- Shear Strengthening

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❑ Parameters Influencing the Behavior

- **Wrapping Schemes**

4- Shear Strengthening

❑Main Approaches

Truss Model Approach

Triantafillou (1998)
Khalifa et al. (1998, 1999)
Triantafillou et al. (2000)
Chaallal et al. (2002)
Pellegrino et al. (2002)
Hsu et al. (2003); Zhang and Hsu (2005)

Mechanics-Based Model

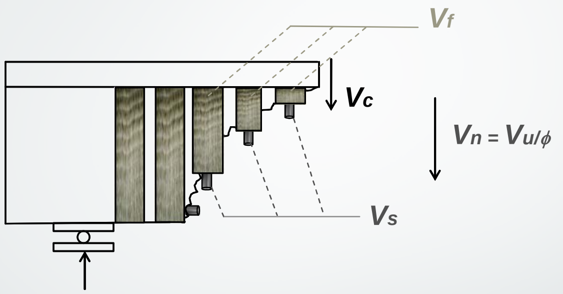
Cao et al. (2005)
Caroline and Talsten (2005)
Monti and Liotta (2005)

Non-Uniform Strain Distribution

Khalifa et al. (1999)
Chen and Teng (2003)

4- Shear Strengthening

❑ Shear Mechanism Based on Truss Model



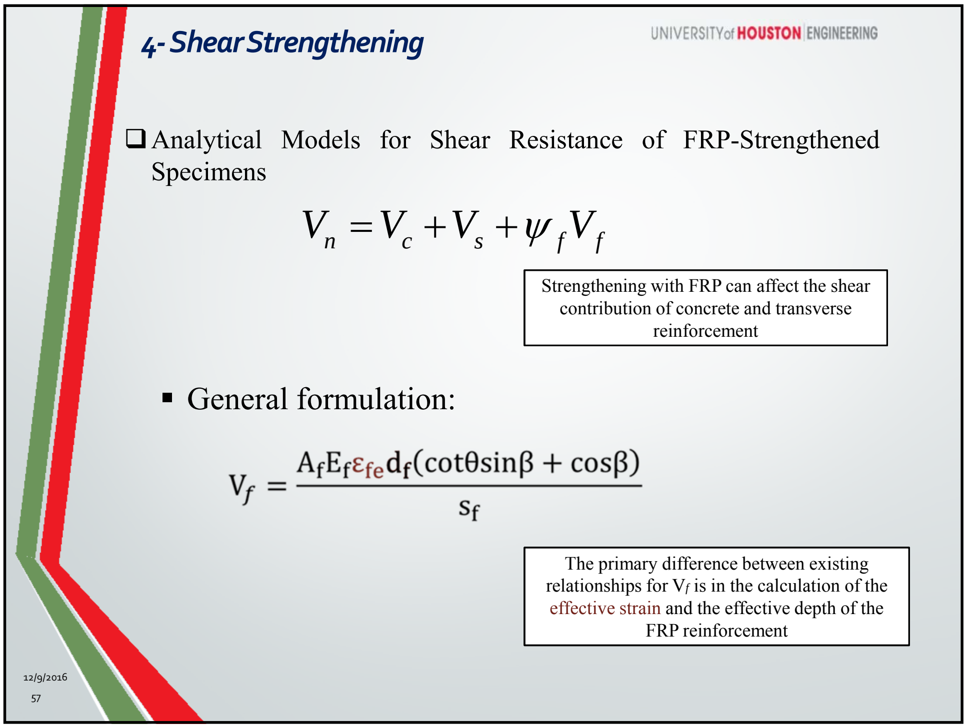
General Form of Design Equations :

$$V_n = \boxed{V_c + V_s} + \boxed{\psi_f V_f}$$

Adopted from RC design

Considered similar as steel

The shear contribution of each component is derived separately. However, a high level of interaction exists between them.



4- Shear Strengthening

❑ Analytical Models for Shear Resistance of FRP-Strengthened Specimens

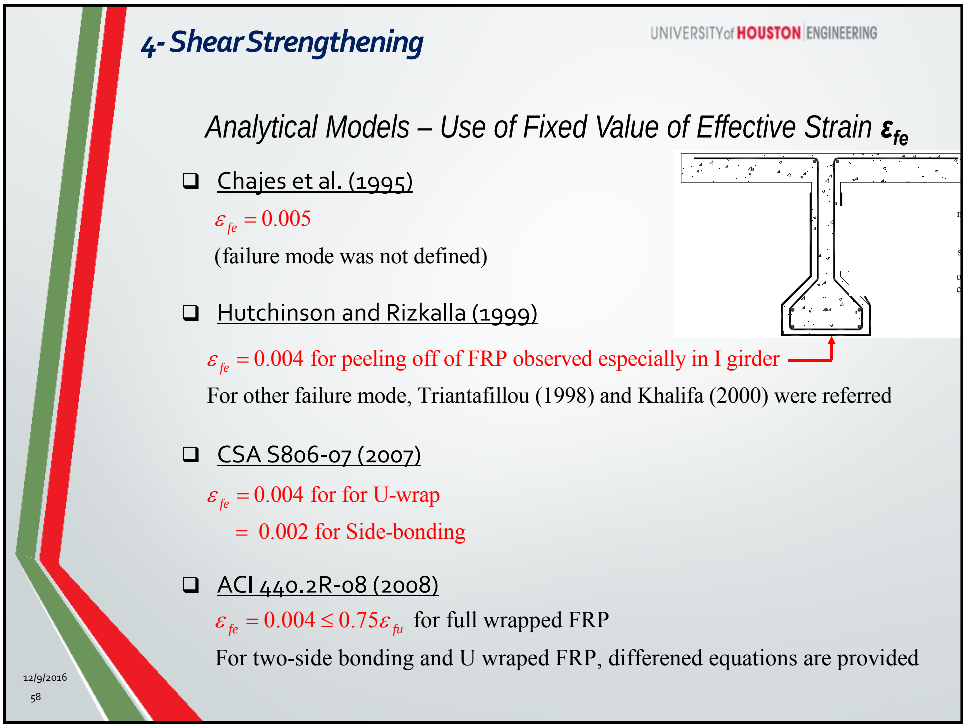
$$V_n = V_c + V_s + \psi_f V_f$$

Strengthening with FRP can affect the shear contribution of concrete and transverse reinforcement

- General formulation:

$$V_f = \frac{A_f E_f \varepsilon_{fe} d_f(\cot\theta \sin\beta + \cos\beta)}{s_f}$$

The primary difference between existing relationships for V_f is in the calculation of the effective strain and the effective depth of the FRP reinforcement



4- Shear Strengthening

Analytical Models – Use of Fixed Value of Effective Strain ε_{fe}

❑ Chajes et al. (1995)

$\varepsilon_{fe} = 0.005$

(failure mode was not defined)

❑ Hutchinson and Rizkalla (1999)

$\varepsilon_{fe} = 0.004$ for peeling off of FRP observed especially in I girder

For other failure mode, Triantafillou (1998) and Khalifa (2000) were referred

❑ CSA S806-07 (2007)

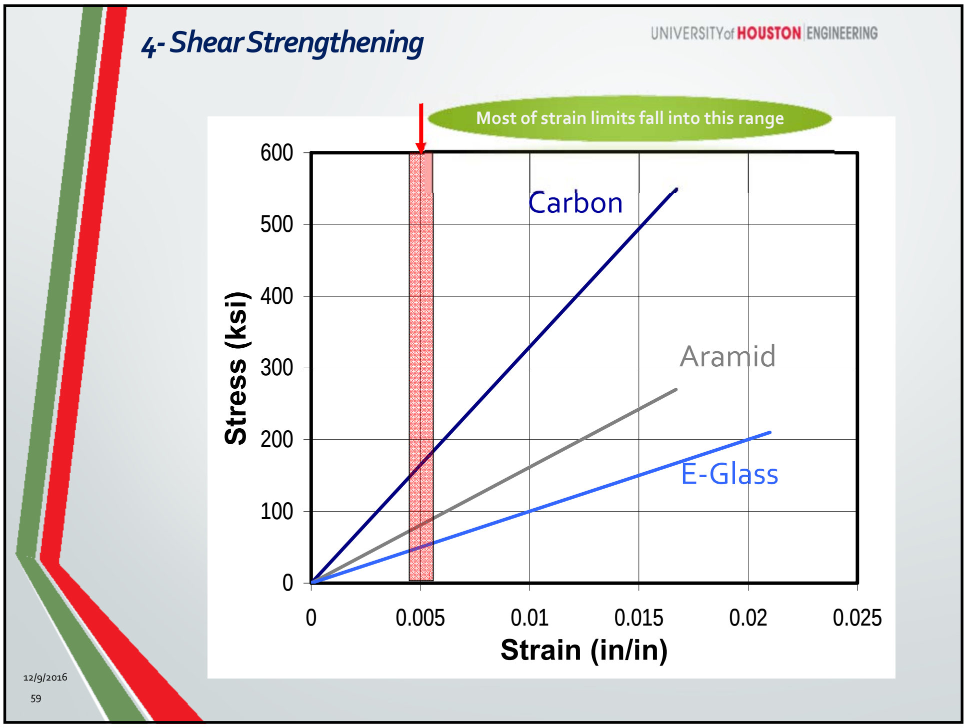
$\varepsilon_{fe} = 0.004$ for for U-wrap

$= 0.002$ for Side-bonding

❑ ACI 440.2R-08 (2008)

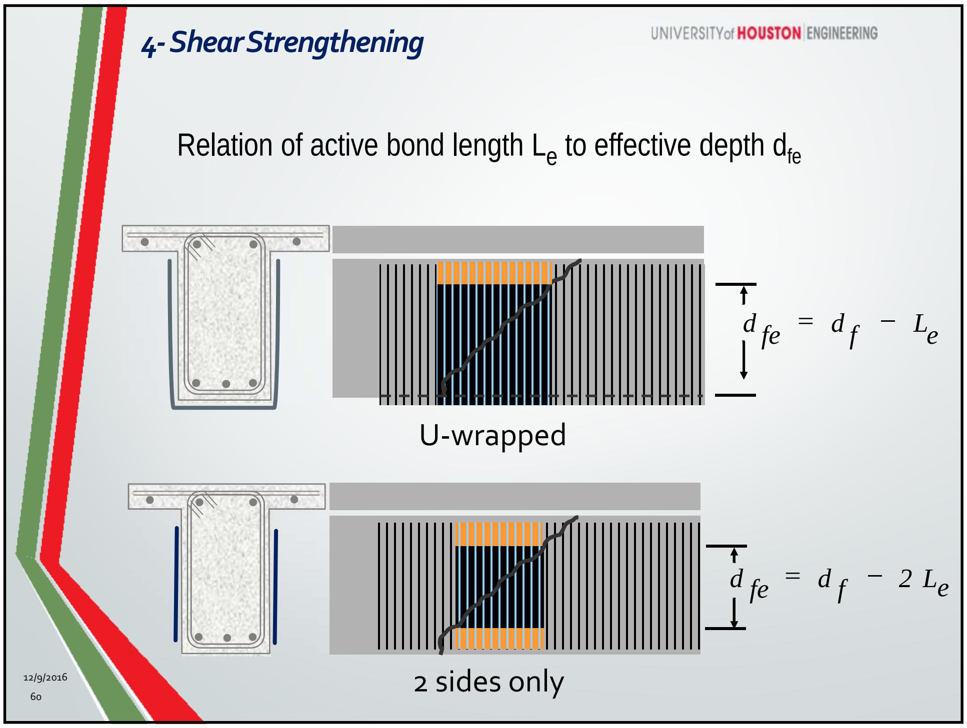
$\varepsilon_{fe} = 0.004 \leq 0.75\varepsilon_{fu}$ for full wrapped FRP

For two-side bonding and U wraped FRP, differened equations are provided



4- Shear Strengthening

Most of strain limits fall into this range



4- Shear Strengthening

Relation of active bond length L_e to effective depth d_{fe}

$d_{fe} = d_f - L_e$

U-wrapped

$d_{fe} = d_f - 2L_e$

2 sides only

4- Shear Strengthening

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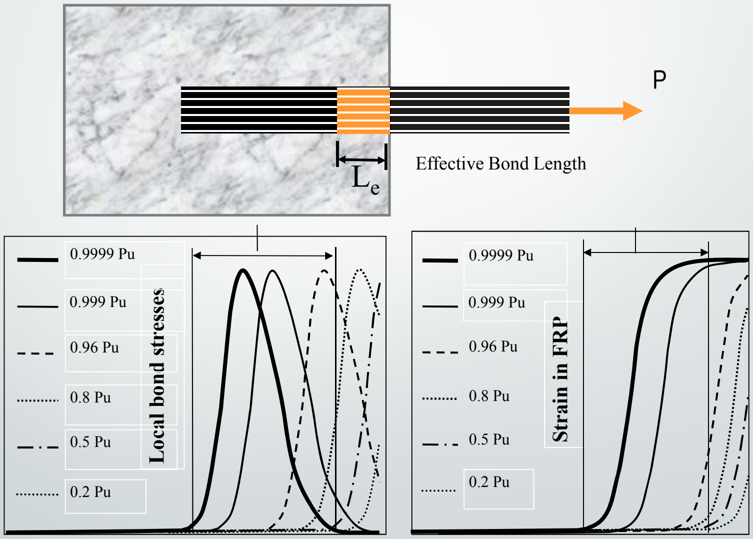
Determination of active bond length L_e:



4- Shear Strengthening

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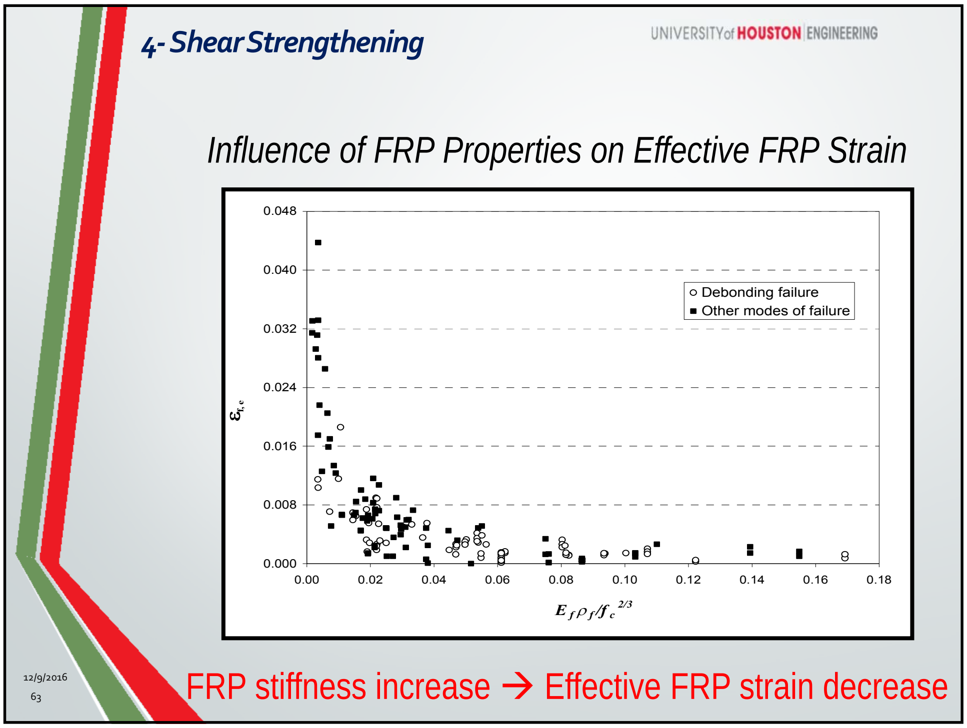
Effective bond length as specified by various Codes:

Code	Year	Expression
ACI 440.2R-08 (USA)	2008	$L_e = \frac{23300}{(nE_f\,t_f)^{0.58}}$
ISIS, CSA S806-02 (Canada)	2002	$L_e = \frac{25350}{(E_f\,t_f)^{0.58}}$
FIB B14- Appendix A1 (Europe)	2001	$L_e = \sqrt{\frac{E_f t_f}{c_2 f_{ctm}}} \quad c_2 = 2$
FIB B14- Appendix A2 (Europe)	2001	$L_e = c_2\sqrt{\frac{E_f t_f}{f_{ck} f_{ctm}}} \quad c_2 = 1.44$
CS TR55 (UK)	2004	$L_e = 0.7\sqrt{\frac{E_f t_f}{f_{ctm}}}$
CNR-DT 200/04 (Italy)	2005	$L_e = \sqrt{\frac{E_f t_f}{2f_{ctm}}}$
Eurocode 8-3 (Europe)	2004	$L_e = \sqrt{\frac{E_f t_f}{4f_{ctm}}}$
CIDAR (Australia)	2006	$L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_c'}}}$

Mostly based on stiffness of FRP



4- Shear Strengthening

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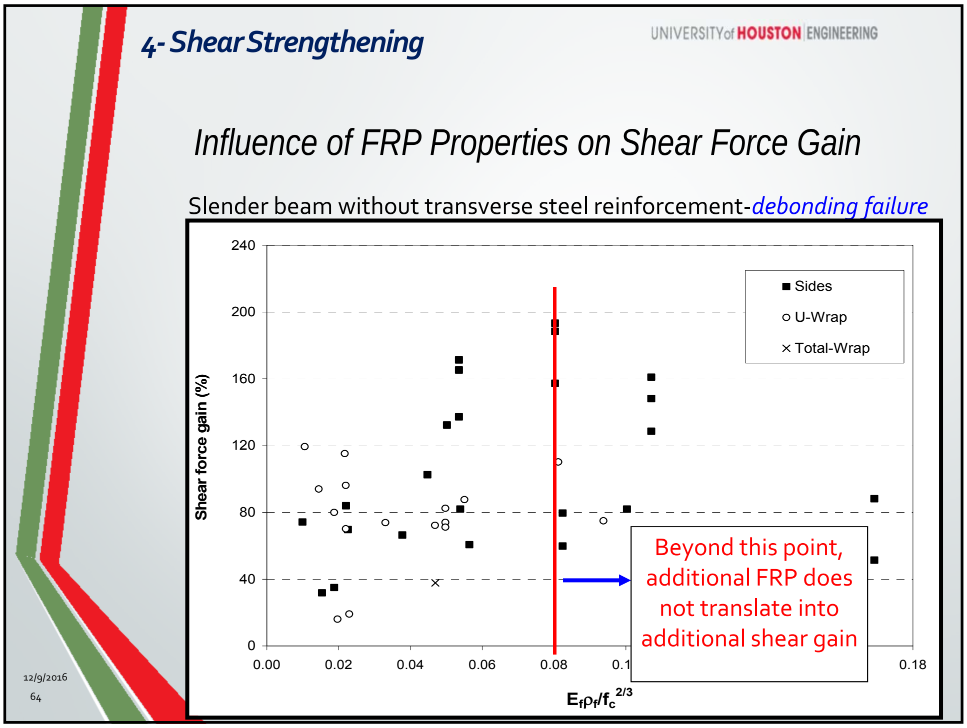
Influence of FRP Properties on Effective FRP Strain

FRP stiffness increase → Effective FRP strain decrease



4- Shear Strengthening

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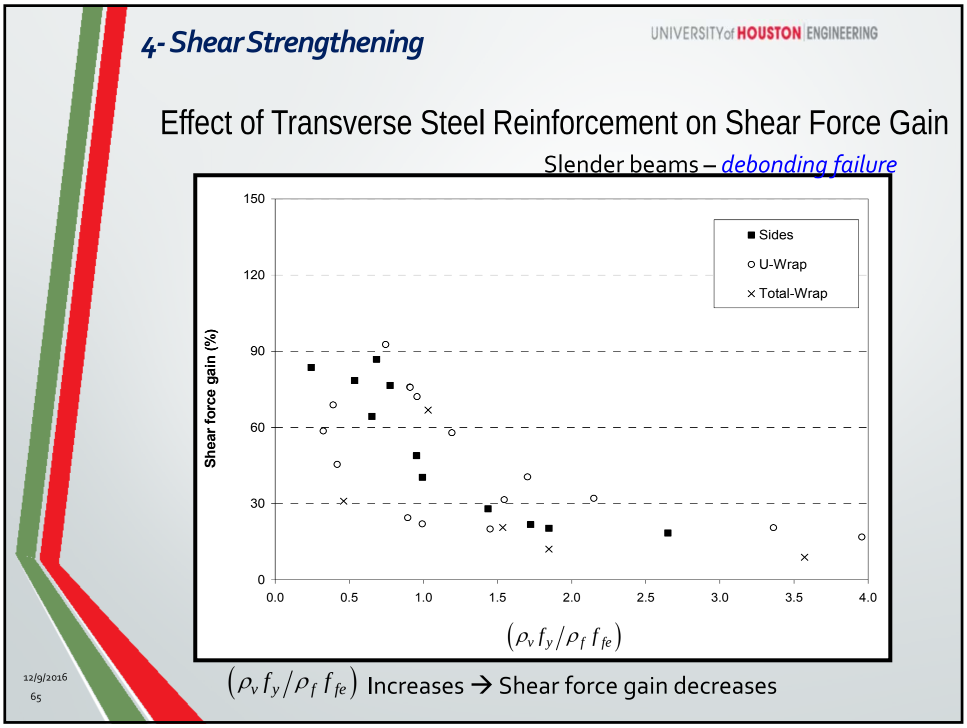
Influence of FRP Properties on Shear Force Gain

Slender beam without transverse steel reinforcement-*debonding failure*

Beyond this point, additional FRP does not translate into additional shear gain



4- Shear Strengthening

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Effect of Transverse Steel Reinforcement on Shear Force Gain

Slender beams – *debonding failure*

$(\rho_v f_y/\rho_f f_{fe})$ Increases → Shear force gain decreases

12/9/2016
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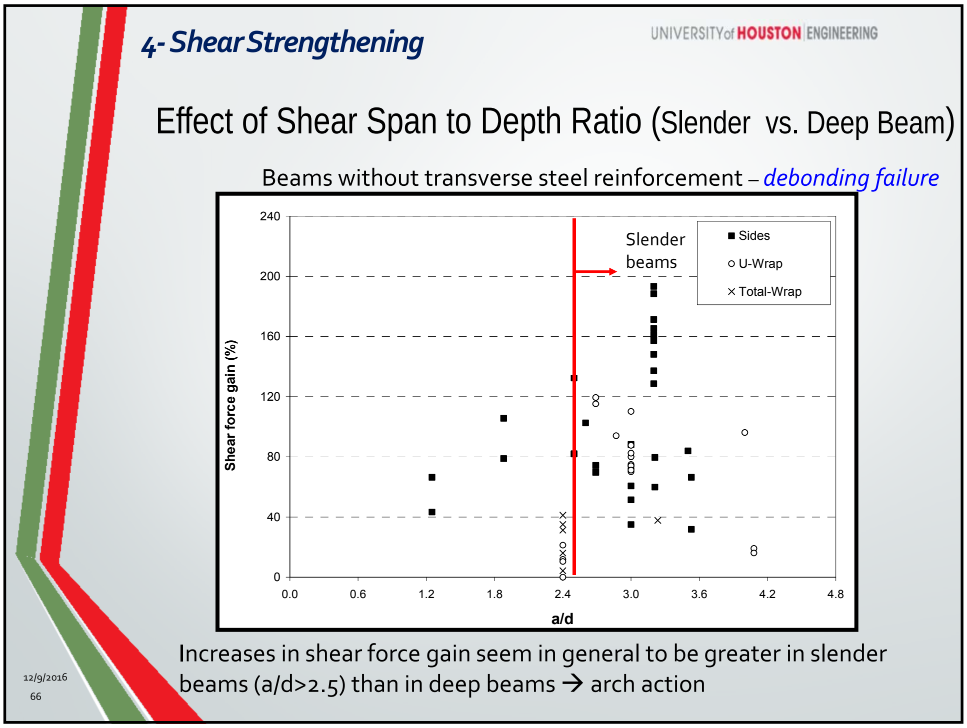

4- Shear Strengthening

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Effect of Shear Span to Depth Ratio (Slender vs. Deep Beam)

Beams without transverse steel reinforcement – *debonding failure*

Increases in shear force gain seem in general to be greater in slender beams (a/d>2.5) than in deep beams → arch action

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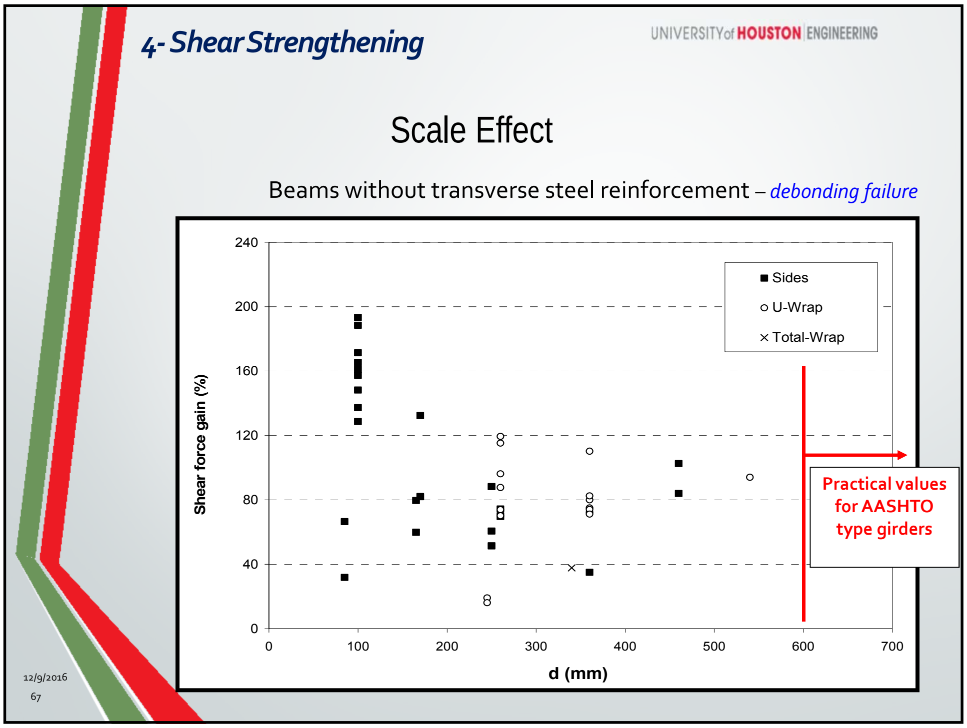
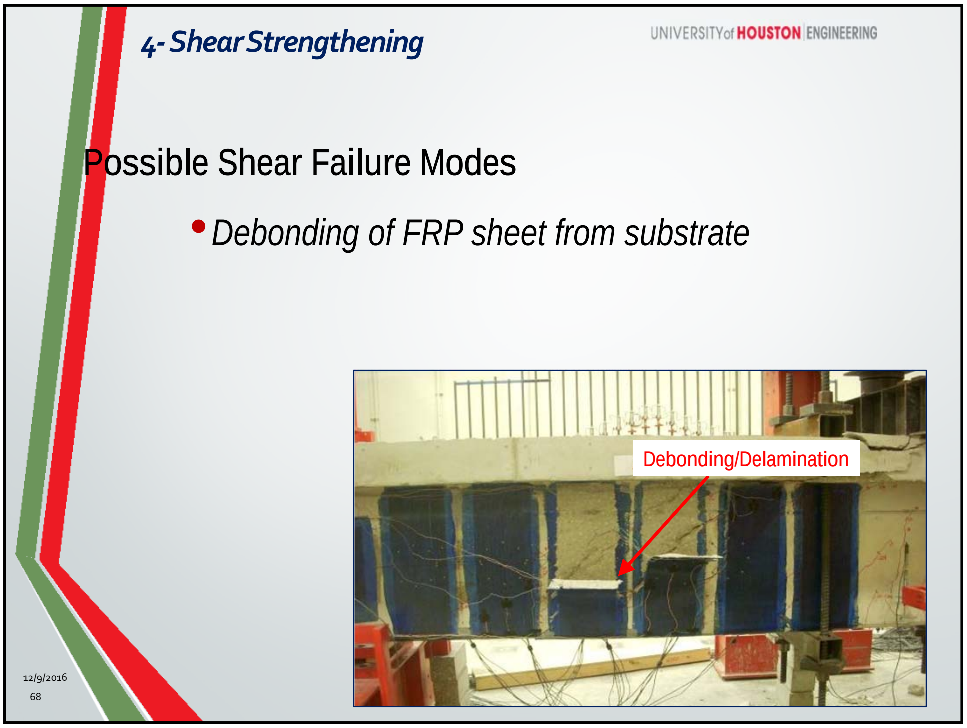


Scale Effect

Beams without transverse steel reinforcement – *debonding failure*

Practical values for AASHTO type girders



Possible Shear Failure Modes

- *Debonding of FRP sheet from substrate*

Debonding/Delamination

4- Shear Strengthening

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Possible Shear Failure Modes

- *Debonding of FRP sheet from substrate*
- *Loss of aggregate interlock (i.e., loss of V_c)*

** Photo taken from the work of George C. Manos and Kostas V. Katakalos 2013 " The Use of Fiber Reinforced Plastic for The Repair and Strengthening of Existing Reinforced Concrete Structural Elements Damaged by Earthquakes"*

4- Shear Strengthening

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Possible Shear Failure Modes

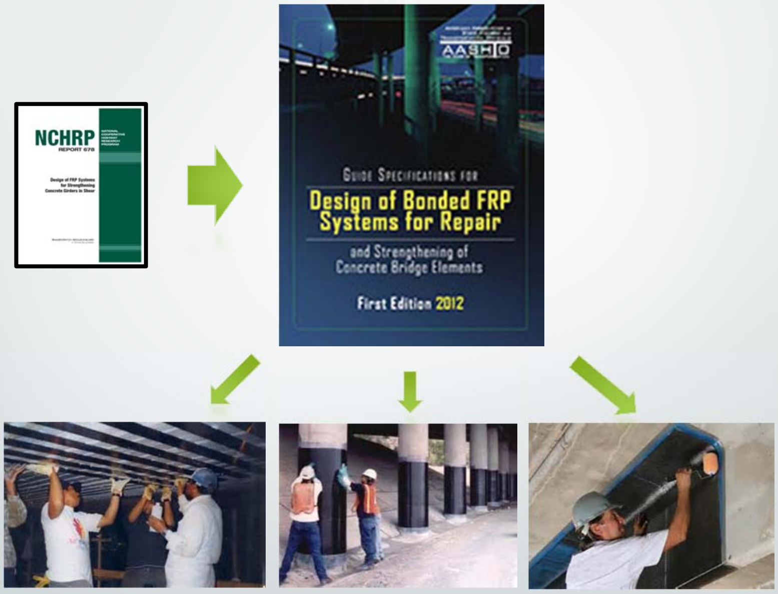
- *Debonding of FRP sheet from substrate*
- *Loss of aggregate interlock (i.e., loss of V_c)*
- *Loss of web width/area*

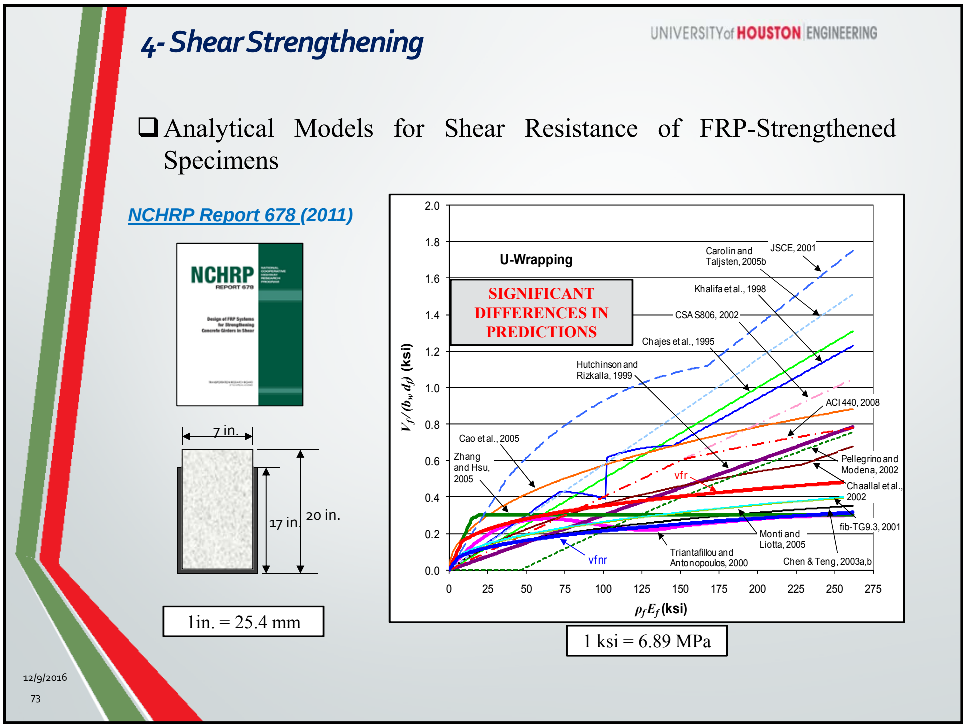
4- Shear Strengthening

Possible Shear Failure Modes

- *Debonding of FRP sheet from substrate*
- *Loss of aggregate interlock (i.e., loss of V_c)*
- *Loss of web width/area*
- *FRP rupture due to stress concentration*

4- Shear Strengthening





4- Shear Strengthening

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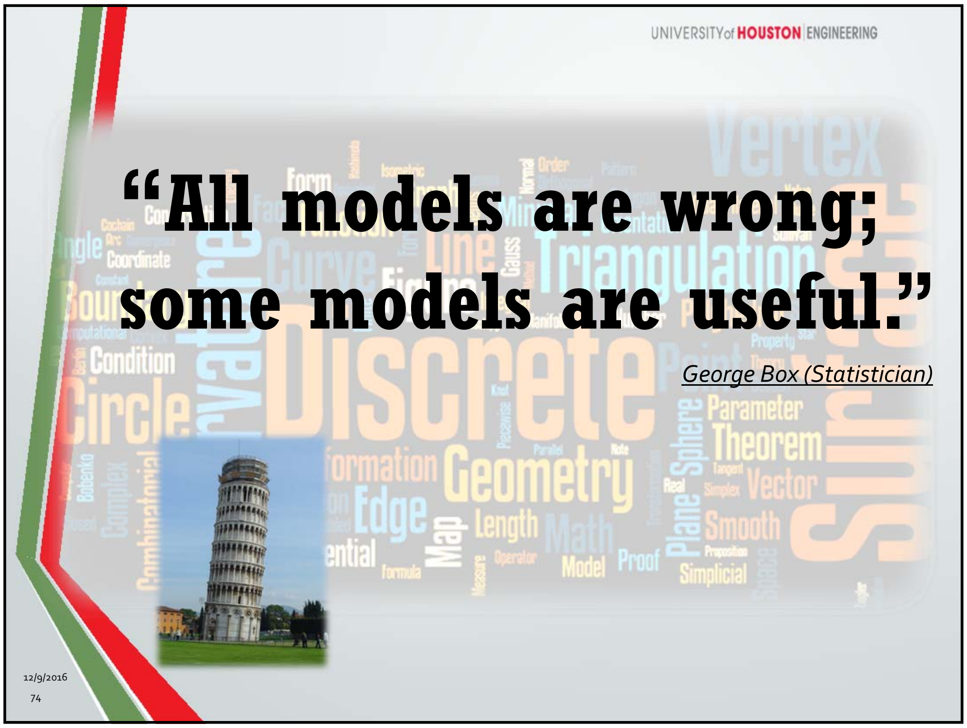
- ❑ Analytical Models for Shear Resistance of FRP-Strengthened Specimens

NCHRP Report 678 (2011)

1in. = 25.4 mm

1 ksi = 6.89 MPa



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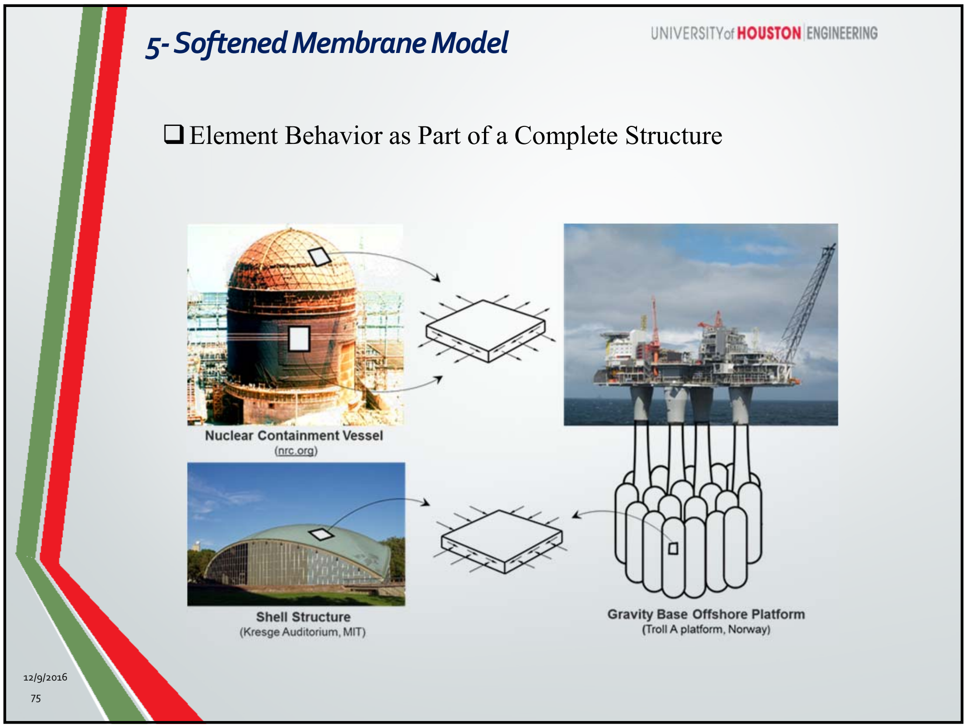
"All models are wrong; some models are useful."

George Box (Statistician)



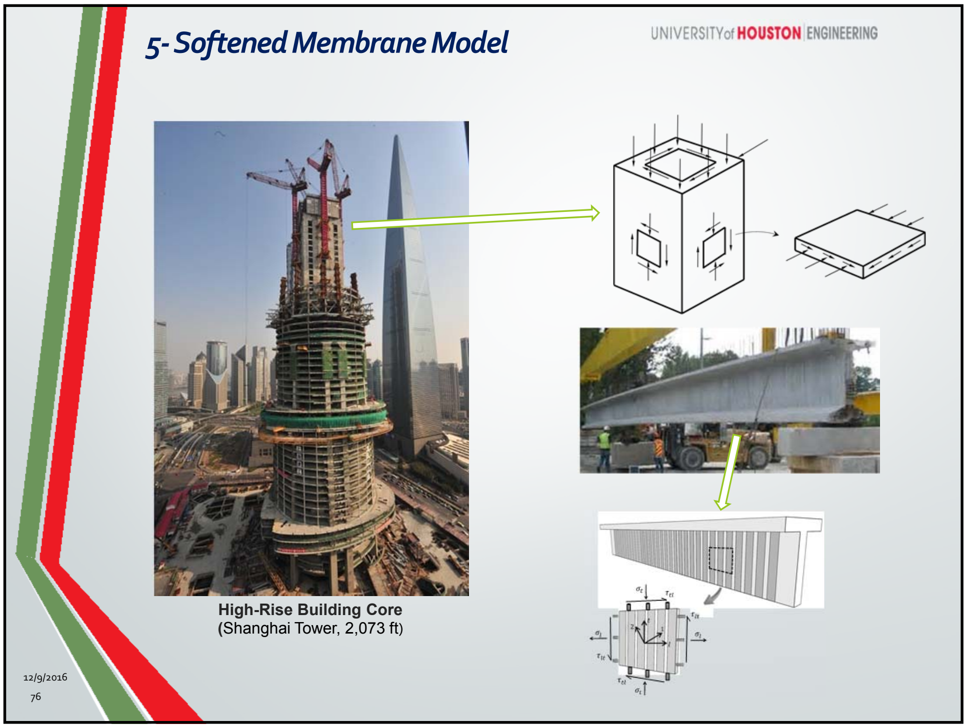
5- Softened Membrane Model

- ❑ Element Behavior as Part of a Complete Structure

Nuclear Containment Vessel
(nrc.org)

Shell Structure
(Kresge Auditorium, MIT)

Gravity Base Offshore Platform
(Troll A platform, Norway)



5- Softened Membrane Model

High-Rise Building Core
(Shanghai Tower, 2,073 ft)

5- Softened Membrane Model

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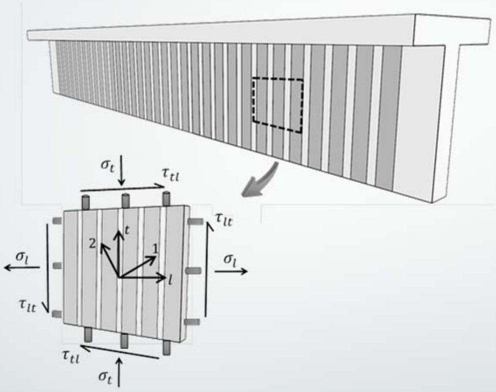
☐ Element Study based on Truss Model



An efficient method to assess the overall shear response of a strengthened member is to study the behavior of an element constituting the structure.

5- Softened Membrane Model

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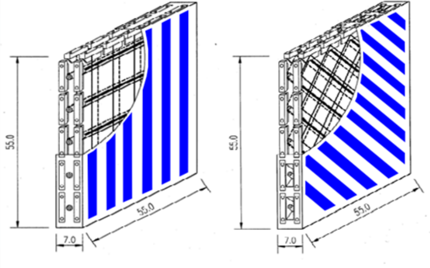
On-Going Panel Tester Project

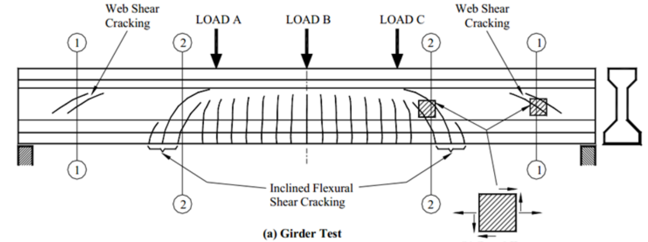
Universal Panel Tester



(a) 90 degree strips

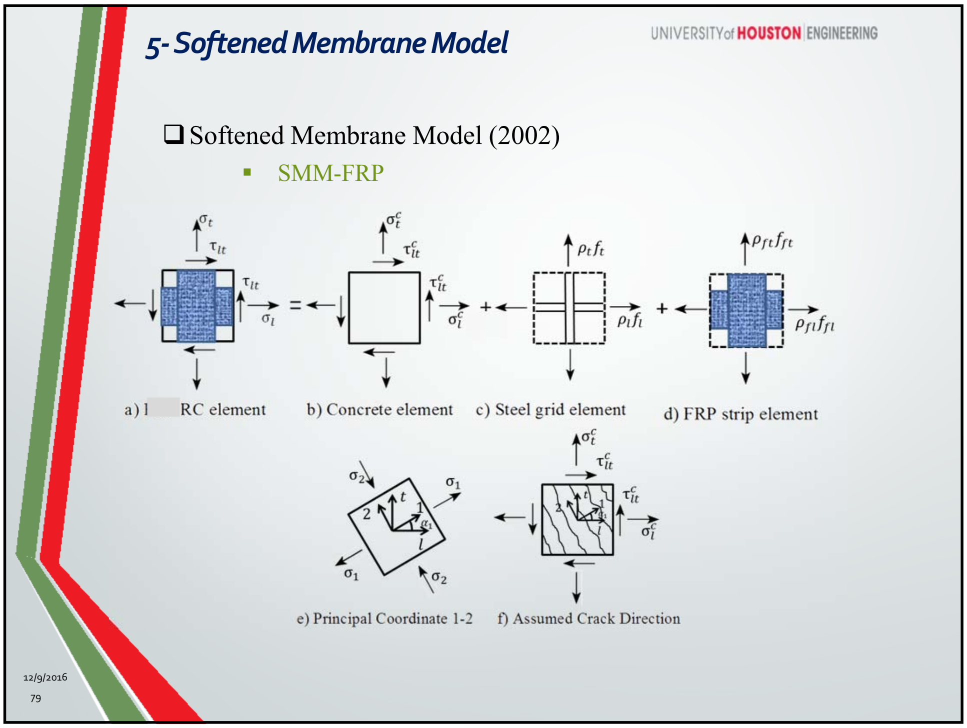
(b) 45 degree strips

FRP strengthened RC Panel



(a) Girder Test

(b) Panel Test

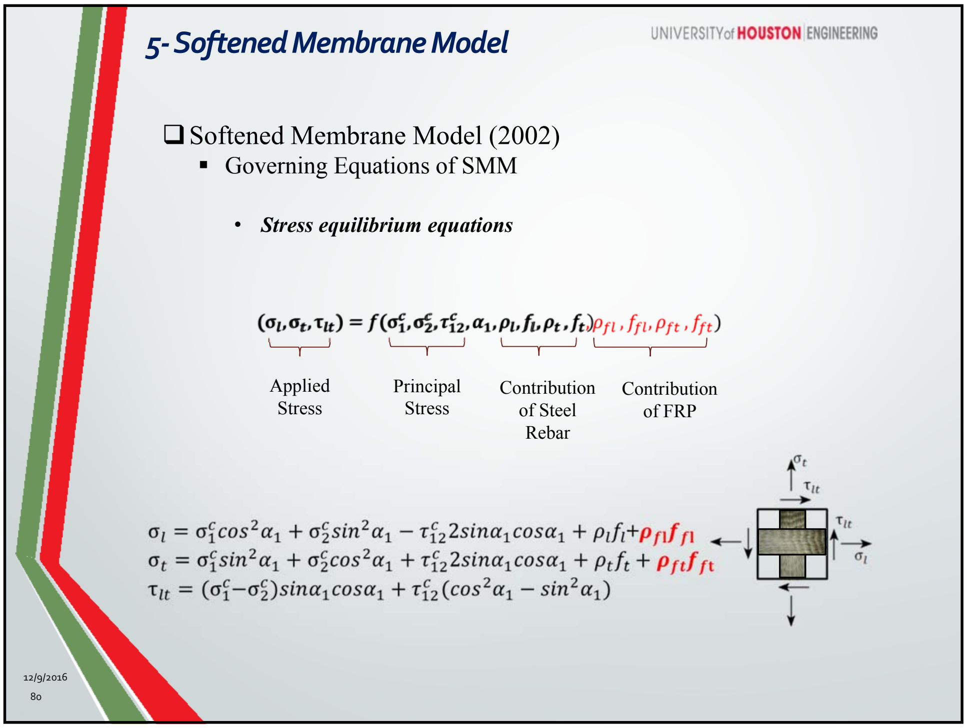


5- Softened Membrane Model

- ❑ Softened Membrane Model (2002)
  - SMM-FRP

a) I RC element b) Concrete element c) Steel grid element d) FRP strip element

e) Principal Coordinate 1-2 f) Assumed Crack Direction



5- Softened Membrane Model

- ❑ Softened Membrane Model (2002)
  - Governing Equations of SMM
    - ***Stress equilibrium equations***

$$\underbrace{(\sigma_l,\sigma_t,\tau_{lt})}_{\text{Applied Stress}} = f(\underbrace{\sigma_1^c,\sigma_2^c,\tau_{12}^c}_{\text{Principal Stress}},\alpha_1,\underbrace{\rho_l,f_l,\rho_t,f_t}_{\text{Contribution of Steel Rebar}})\underbrace{\rho_{fl},f_{fl},\rho_{ft},f_{ft}}_{\text{Contribution of FRP}})$$

$$\sigma_l = \sigma_1^c cos^2\alpha_1 + \sigma_2^c sin^2\alpha_1 - \tau_{12}^c 2sin\alpha_1 cos\alpha_1 + \rho_l f_l + \boldsymbol{\rho_{fl} f_{fl}}$$
$$\sigma_t = \sigma_1^c sin^2\alpha_1 + \sigma_2^c cos^2\alpha_1 + \tau_{12}^c 2sin\alpha_1 cos\alpha_1 + \rho_t f_t + \boldsymbol{\rho_{ft} f_{ft}}$$
$$\tau_{lt} = (\sigma_1^c - \sigma_2^c) sin\alpha_1 cos\alpha_1 + \tau_{12}^c (cos^2\alpha_1 - sin^2\alpha_1)$$

5- Softened Membrane Model

☐ Universal Panel Tester

Unique facility to test full scale panel elements under various combination of in-plane and out-of-plane stress conditions.

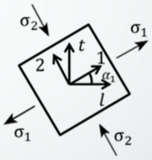
BA18

5- Softened Membrane Model

☐ Softened Membrane Model (2002)

- Governing Equations of SMM
  - ***Strain transformation equations***

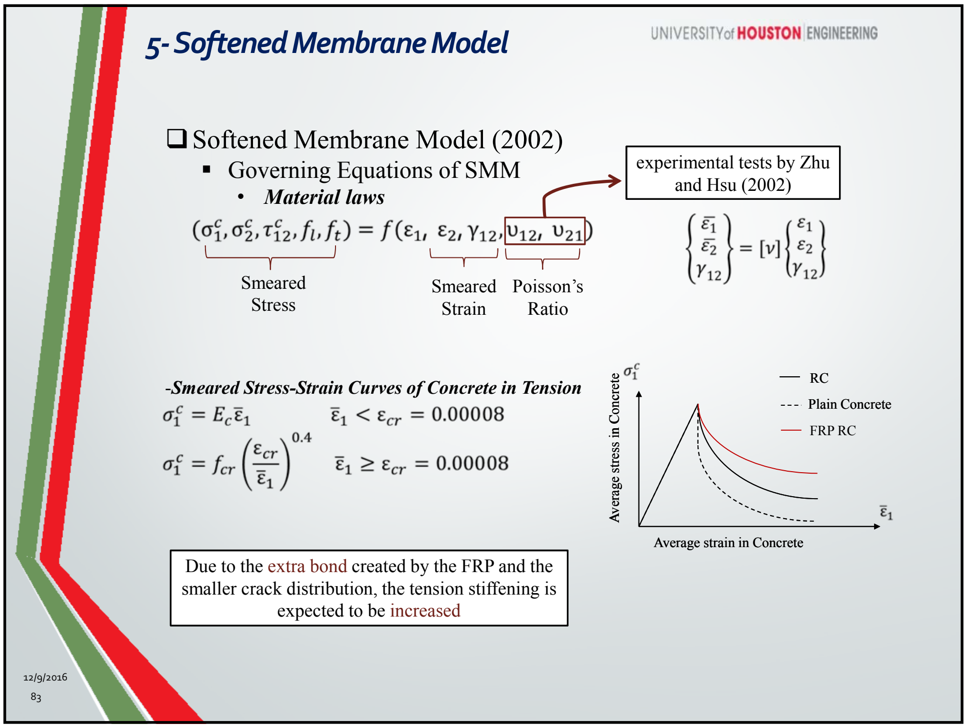
$$\underbrace{(\varepsilon_l, \varepsilon_t, \gamma_{lt})}_{\text{Smeared Strains}} = f\underbrace{(\varepsilon_1, \varepsilon_2, \gamma_{12})}_{\text{Principal Strain}}$$



$$\varepsilon_l = \varepsilon_1 cos^2\alpha_1 + \varepsilon_2 sin^2\alpha_1 - \frac{\gamma_{12}}{2} 2sin\alpha_1 cos\alpha_1$$

$$\varepsilon_t = \varepsilon_1 sin^2\alpha_1 + \varepsilon_2 cos^2\alpha_1 + \frac{\gamma_{12}}{2} 2sin\alpha_1 cos\alpha_1$$

$$\frac{\gamma_{lt}}{2} = (\varepsilon_1 - \varepsilon_2) sin\alpha_1 cos\alpha_1 + \frac{\gamma_{12}}{2}(cos^2\alpha_1 - sin^2\alpha_1)$$



5- Softened Membrane Model

❑ Softened Membrane Model (2002)

- Governing Equations of SMM
    - ***Material laws***

$$\underbrace{(\sigma_1^c,\sigma_2^c,\tau_{12}^c,f_l,f_t)}_{\text{Smeared Stress}} = f(\varepsilon_1,\ \underbrace{\varepsilon_2,\gamma_{12}}_{\text{Smeared Strain}},\underbrace{\boxed{\upsilon_{12},\ \upsilon_{21}}}_{\text{Poisson's Ratio}})$$

experimental tests by Zhu and Hsu (2002)

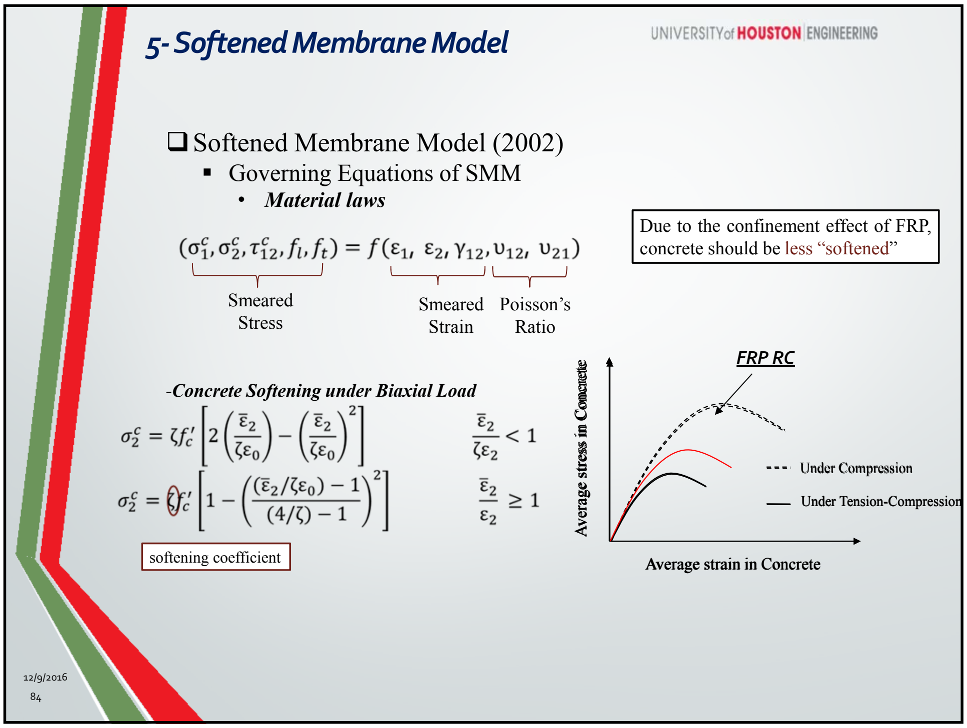
$$\begin{Bmatrix}\bar{\varepsilon}_1\\ \bar{\varepsilon}_2\\ \gamma_{12}\end{Bmatrix} = [\nu]\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

-Smeared Stress-Strain Curves of Concrete in Tension

$$\sigma_1^c = E_c\bar{\varepsilon}_1 \qquad \bar{\varepsilon}_1 < \varepsilon_{cr} = 0.00008$$

$$\sigma_1^c = f_{cr}\left(\frac{\varepsilon_{cr}}{\bar{\varepsilon}_1}\right)^{0.4} \qquad \bar{\varepsilon}_1 \geq \varepsilon_{cr} = 0.00008$$

Due to the extra bond created by the FRP and the smaller crack distribution, the tension stiffening is expected to be increased



5- Softened Membrane Model

❑ Softened Membrane Model (2002)

- Governing Equations of SMM
    - ***Material laws***

$$\underbrace{(\sigma_1^c,\sigma_2^c,\tau_{12}^c,f_l,f_t)}_{\text{Smeared Stress}} = f(\varepsilon_1,\ \underbrace{\varepsilon_2,\gamma_{12}}_{\text{Smeared Strain}},\underbrace{\upsilon_{12},\ \upsilon_{21}}_{\text{Poisson's Ratio}})$$

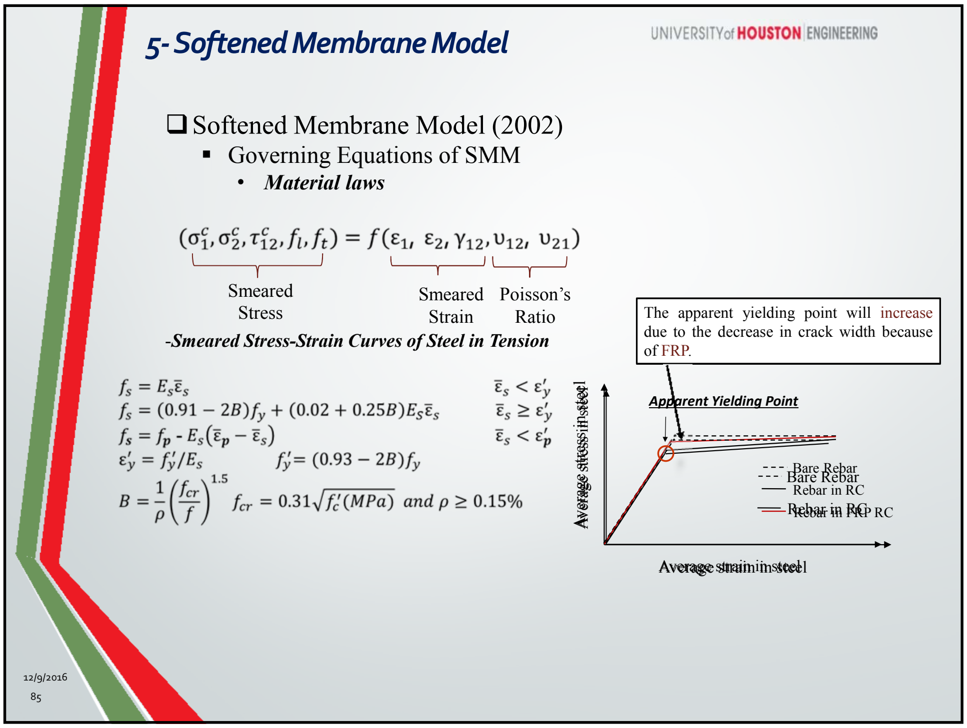
Due to the confinement effect of FRP, concrete should be less "softened"

-Concrete Softening under Biaxial Load

$$\sigma_2^c = \zeta f_c'\left[2\left(\frac{\bar{\varepsilon}_2}{\zeta\varepsilon_0}\right)-\left(\frac{\bar{\varepsilon}_2}{\zeta\varepsilon_0}\right)^2\right] \qquad \frac{\bar{\varepsilon}_2}{\zeta\varepsilon_2} < 1$$

$$\sigma_2^c = \zeta f_c'\left[1-\left(\frac{(\bar{\varepsilon}_2/\zeta\varepsilon_0)-1}{(4/\zeta)-1}\right)^2\right] \qquad \frac{\bar{\varepsilon}_2}{\varepsilon_2} \geq 1$$

softening coefficient



5- Softened Membrane Model

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❑ Softened Membrane Model (2002)

- Governing Equations of SMM
  - ***Material laws***

$$\underbrace{(\sigma_1^c, \sigma_2^c, \tau_{12}^c, f_l, f_t)}_{\text{Smeared Stress}} = f(\underbrace{\varepsilon_1,\ \varepsilon_2, \gamma_{12}}_{\text{Smeared Strain}}, \underbrace{\upsilon_{12},\ \upsilon_{21}}_{\text{Poisson's Ratio}})$$

-Smeared Stress-Strain Curves of Steel in Tension

$$f_s = E_s\bar{\varepsilon}_s \qquad \bar{\varepsilon}_s < \varepsilon_y'$$

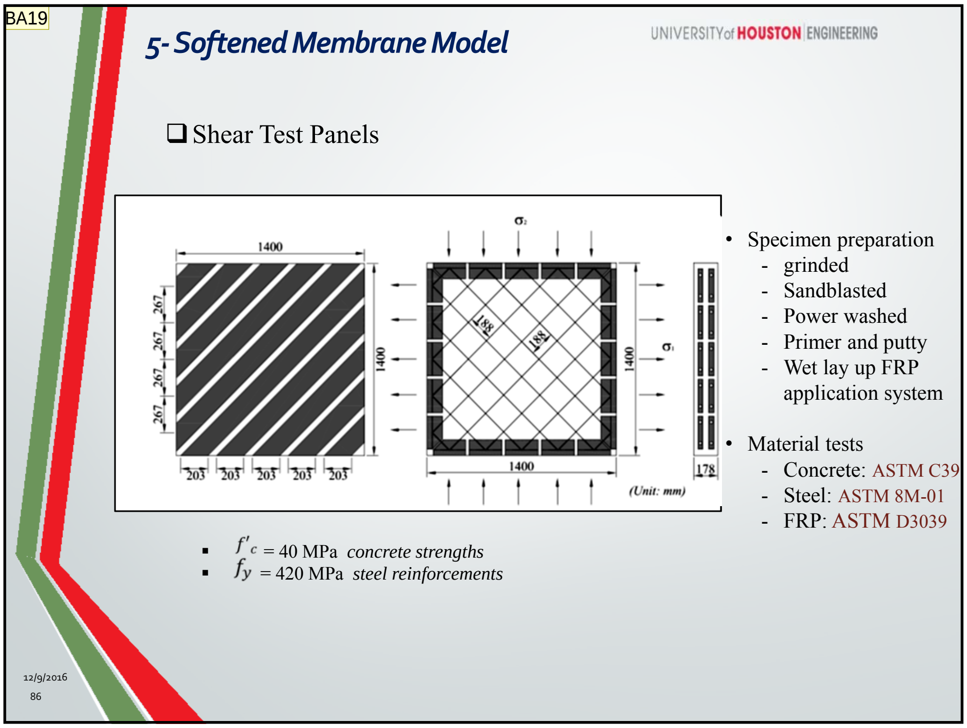
$$f_s = (0.91 - 2B)f_y + (0.02 + 0.25B)E_s\bar{\varepsilon}_s \qquad \bar{\varepsilon}_s \geq \varepsilon_y'$$

$$f_s = f_p - E_s(\bar{\varepsilon}_p - \bar{\varepsilon}_s) \qquad \bar{\varepsilon}_s < \varepsilon_p'$$

$$\varepsilon_y' = f_y'/E_s \qquad f_y' = (0.93 - 2B)f_y$$

$$B = \frac{1}{\rho}\left(\frac{f_{cr}}{f}\right)^{1.5} \quad f_{cr} = 0.31\sqrt{f_c'(MPa)} \ \ and \ \rho \geq 0.15\%$$

The apparent yielding point will increase due to the decrease in crack width because of FRP.



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5- Softened Membrane Model

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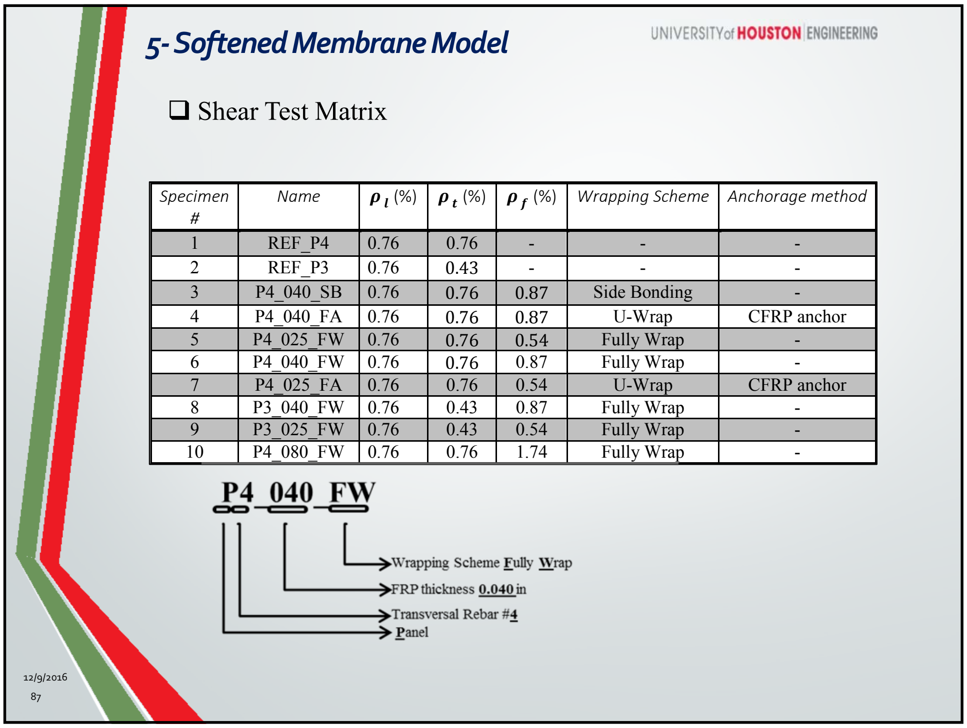
❑ Shear Test Panels

- Specimen preparation
  - grinded
  - Sandblasted
  - Power washed
  - Primer and putty
  - Wet lay up FRP application system
- Material tests
  - Concrete: ASTM C39
  - Steel: ASTM 8M-01
  - FRP: ASTM D3039

- f'_c = 40 MPa *concrete strengths*
- f_y = 420 MPa *steel reinforcements*



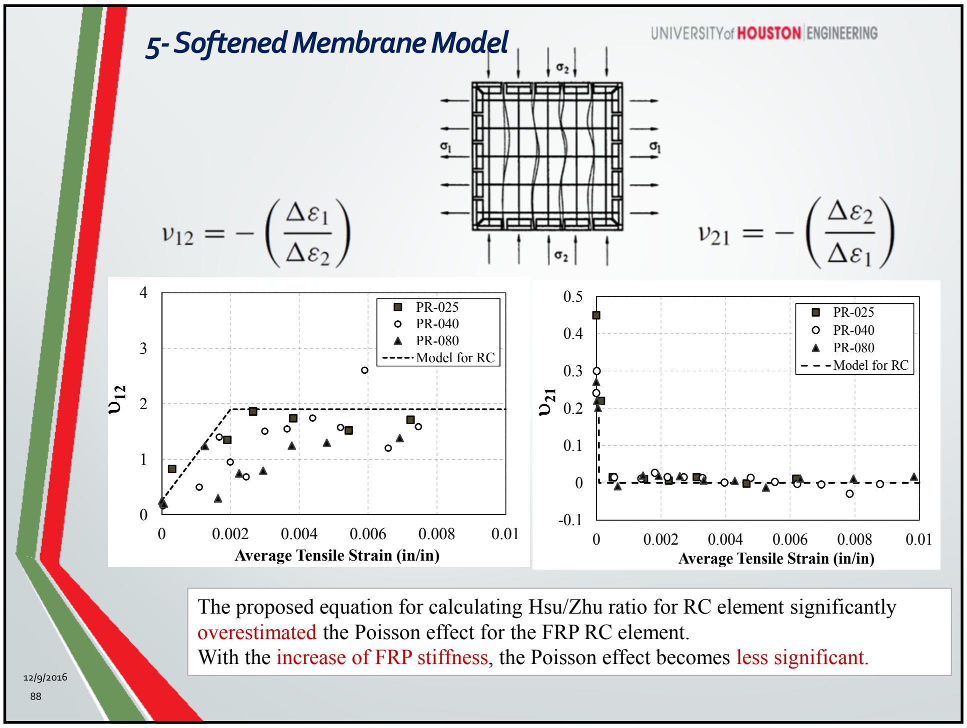
5- Softened Membrane Model

- ❑ Shear Test Matrix

Specimen #	Name	ρ_l (%)	ρ_t (%)	ρ_f (%)	Wrapping Scheme	Anchorage method
1	REF_P4	0.76	0.76	-	-	-
2	REF_P3	0.76	0.43	-	-	-
3	P4_040_SB	0.76	0.76	0.87	Side Bonding	-
4	P4_040_FA	0.76	0.76	0.87	U-Wrap	CFRP anchor
5	P4_025_FW	0.76	0.76	0.54	Fully Wrap	-
6	P4_040_FW	0.76	0.76	0.87	Fully Wrap	-
7	P4_025_FA	0.76	0.76	0.54	U-Wrap	CFRP anchor
8	P3_040_FW	0.76	0.43	0.87	Fully Wrap	-
9	P3_025_FW	0.76	0.43	0.54	Fully Wrap	-
10	P4_080_FW	0.76	0.76	1.74	Fully Wrap	-

P4_040_FW

- Wrapping Scheme Fully Wrap
- FRP thickness 0.040 in
- Transversal Rebar #4
- Panel



5- Softened Membrane Model

$$\nu_{12} = -\left(\frac{\Delta\varepsilon_1}{\Delta\varepsilon_2}\right)$$

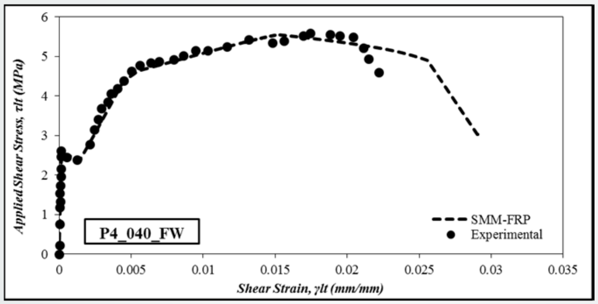
$$\nu_{21} = -\left(\frac{\Delta\varepsilon_2}{\Delta\varepsilon_1}\right)$$

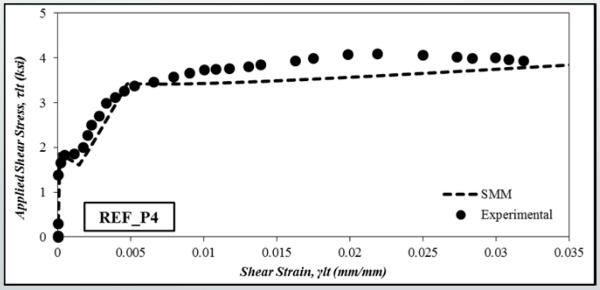
The proposed equation for calculating Hsu/Zhu ratio for RC element significantly overestimated the Poisson effect for the FRP RC element.
With the increase of FRP stiffness, the Poisson effect becomes less significant.

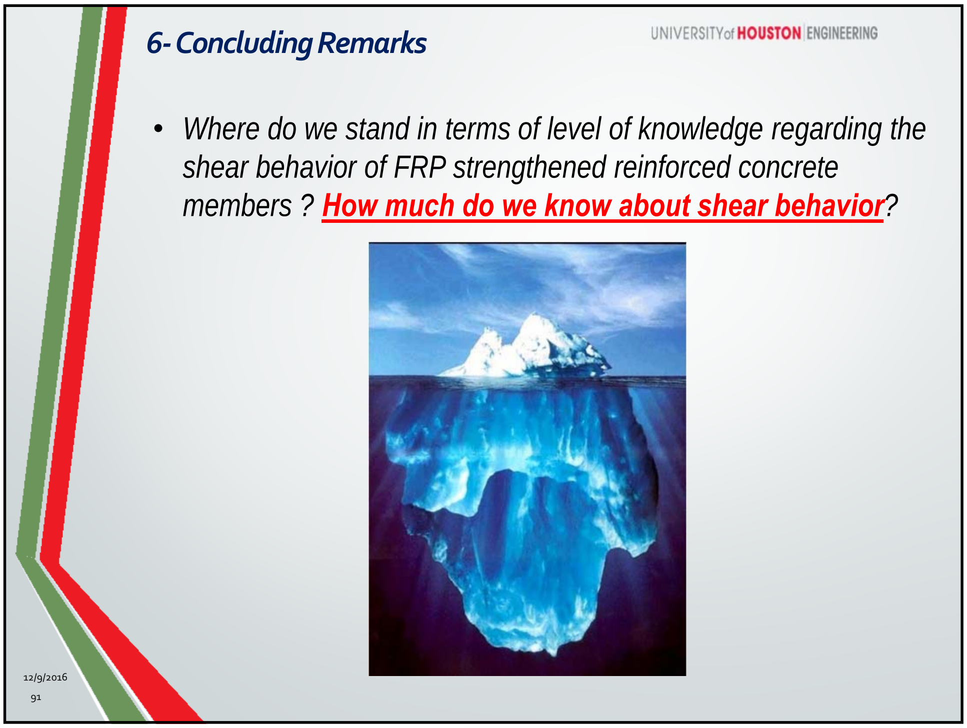
5- Softened Membrane Model

- ❑ To develop a model based on SMM for FRP strengthened RC members, new material Laws have to be used
  - *Smeared Stress-Strain Curves of Concrete in Tension*
  - *Concrete Softening under Biaxial Load*
  - *Smeared Stress-Strain Curves of Steel in Tension*
  - *Poisson Ratio under Biaxial Load*
- ❑ New material models consider:
  - Stiffness of FRP
  - Wrapping scheme
  - Spacing of External reinforcement
  - Steel reinforcement ratio
  - FRP reinforcement ratio
  - Bond

5- Softened Membrane Model







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6- Concluding Remarks

- *Where do we stand in terms of level of knowledge regarding the shear behavior of FRP strengthened reinforced concrete members ? **How much do we know about shear behavior**?*

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Preservation and Renewal of Civil Engineering Infrastructure Using FRP Composites

Thank you!

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