



American Concrete Institute®  
Advancing concrete knowledge


## FRP Strengthening of Reinforced Concrete Columns

ACI Spring 2011 Convention  
April 3 - 7, Tampa, FL

ACI WEB SESSIONS

## ACI Web Sessions

The audio for this web session will begin momentarily and will play in its entirety along with the slides.

However, if you wish to skip to the next speaker, use the scroll bar at left to locate the speaker's first slide (indicated by the  icon in the bottom right corner of slides 10, 39, and 65). Click on the thumbnail for the slide to begin the audio for that portion of the presentation.


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## ACI Web Sessions

ACI is bringing you this Web Session in keeping with its motto of "Advancing Concrete Knowledge." The ideas expressed, however, are those of the speakers and do not necessarily reflect the views of ACI or its committees.

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## ACI Conventions

ACI conventions provide a forum for networking, learning the latest in concrete technology and practices, renewing old friendships, and making new ones. At each of ACI's two annual conventions, technical and educational committees meet to develop the standards, reports, and other documents necessary to keep abreast of the ever-changing world of concrete technology.

With over 1,300 delegates attending each convention, there is ample opportunity to meet and talk individually with some of the most prominent persons in the field of concrete technology. For more information about ACI conventions, visit [www.aciconvention.org](http://www.aciconvention.org).



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## Fall 2011 Seminars

These seminars, cosponsored by ACI and the Portland Cement Association (PCA), will cover all the major changes in the new edition of the **318-11 Building Code**.

DATE	LOCATION	DATE	LOCATION
September 13	Chicago, IL	November 3	Charlotte, NC
September 27	Philadelphia, PA	November 8	Boston, MA
September 29	Houston, TX	November 10	Detroit, MI
October 4	Seattle, WA	November 15	Des Moines, IA
October 6	Los Angeles, CA	November 17	Portland, OR
October 11	New York, NY	November 29	Denver, CO
October 13	Minneapolis, MN	December 1	Phoenix, AZ
October 20	Cincinnati, OH	December 6	Atlanta, GA
October 25	New Brunswick, NJ	December 8	Washington, DC
October 27	St. Louis, MO	December 13	Dallas, TX
November 1	Orlando, FL	December 15	San Francisco, CA

For more information, visit [ACI seminars](#).

## ACI Web Sessions

This ACI Web Session includes 3 speakers presenting at the ACI spring convention held in Tampa, FL April 3 – 7, 2011. Additional presentations will be made available in future ACI Web Sessions.

Please enjoy the presentations.




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*Advancing concrete knowledge*

## FRP Strengthening of Reinforced Concrete Columns

ACI Spring 2011 Convention  
April 3 - 7, Tampa, FL

**William J. Gold**, ACI Member, is the Engineering Services Manager for BASF Corporation - Building Systems in Cleveland, OH. He has over 12 years of experience in the use of advanced composite materials in the construction industry. He holds a Bachelor's degree in Architectural Engineering from the University of Kansas. He is the current Secretary of ACI Committee 440 and was a member of the Task Group that prepared ACI 440.7R-10.

## FRP Confinement of Concrete Columns




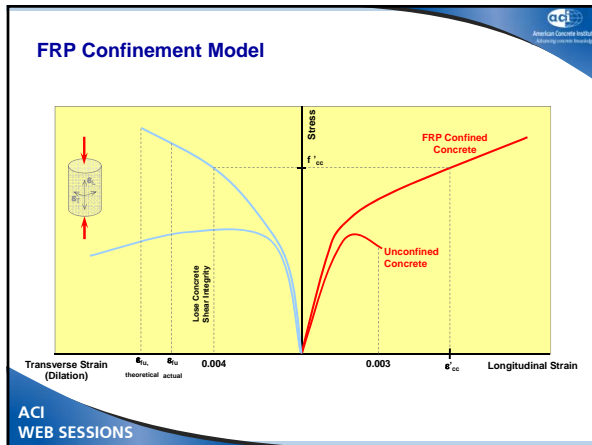
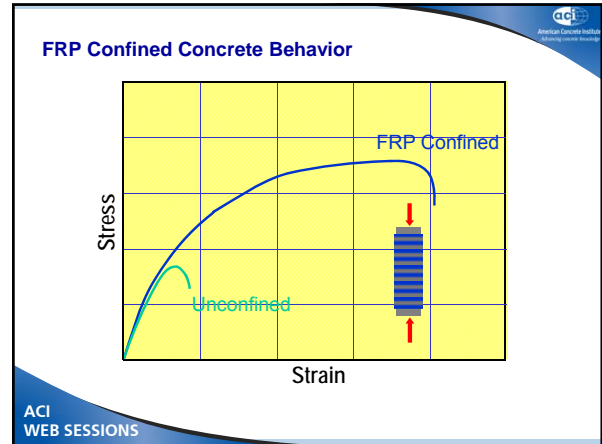
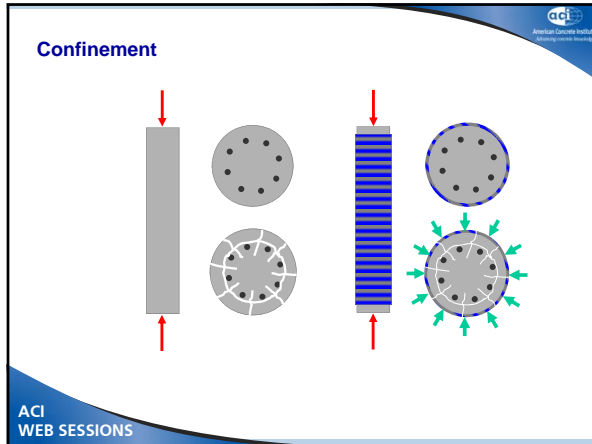
William J. Gold, P.E.  
Engineering Services Manager  
BASF Corporation

## FRP Confinement of Concrete Columns

**Topics**

- ACI 440.2R-08 Guidelines for Column Confinement
  - Background on guidelines
  - Details of guidelines for circular and square columns
  - Limitations and recommendations
- Case Study





### FRP Confined Concrete

**Strain Limitation**

For pure axial loading:

ACI 440.2R-08 Eq. (12-5)  $\epsilon_{fe} = \kappa_\epsilon \epsilon_{fu}$

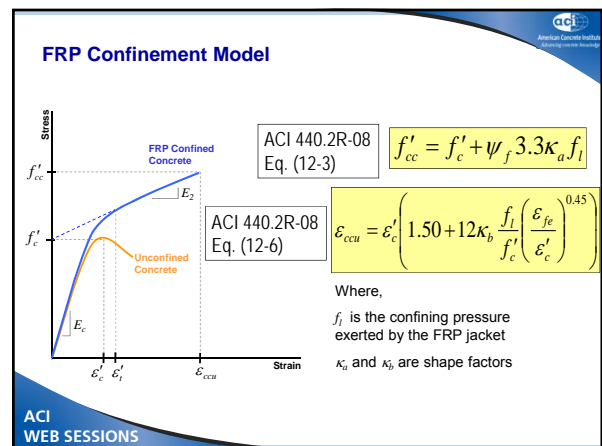
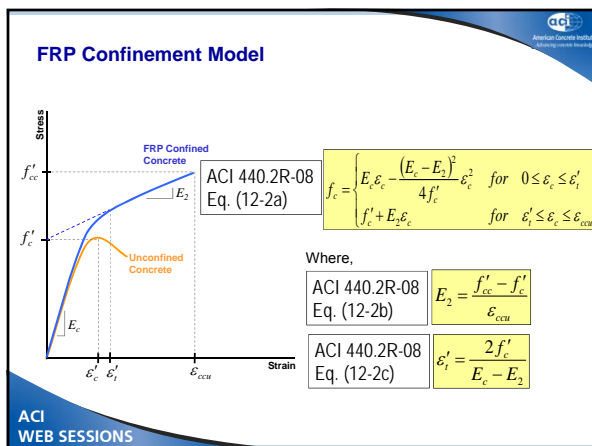
$\kappa_\epsilon = 0.55$  *Recommended value (accounts for variation in FRP strain vs concrete transverse strain)*

For combined axial + bending:

ACI 440.2R-08 Eq. (12-12)  $\epsilon_{fe} = 0.004 \leq \kappa_\epsilon \epsilon_{fu}$

*Limit to maintain shear integrity of concrete*

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### Circular Sections

FRP Jacket

Confining pressure:  
 ACI 440.2R-08 Eq. (12-4)  $f_l = \frac{2E_f n t_f \epsilon_{fc}}{D}$

Shape factors:  
 $\kappa_a = \kappa_b = 1.0$

Concrete

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### Rectangular Sections

Equivalent circular column

Confining pressure:  
 ACI 440.2R-08 Eq. (12-4)  $f_l = \frac{2E_f n t_f \epsilon_{fc}}{D}$

$D = \sqrt{b^2 + h^2}$

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### Rectangular Sections

Effective confinement area,  $A_e$

Shape factors:  
 ACI 440.2R-08 Eq. (12-9)  $\kappa_a = \frac{A_e (b/h)^2}{A_c}$   
 ACI 440.2R-08 Eq. (12-10)  $\kappa_b = \frac{A_e (h/b)^{0.5}}{A_c}$

Confining stress concentrated at corners

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### Rectangular Sections

Effective Confined Area

ACI 440.2R-08 Eq. (12-11) similar  $A_e = A_c - \left[ \frac{b}{3h} (h - 2r)^2 + \frac{h}{3b} (b - 2r)^2 \right]$

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### Effect of FRP Confinement Ratio

Light FRP confinement will exhibit "descending branch" and should be avoided.

$\frac{f_l}{f'_c} > 0.08$

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### Other Limits

**Limit maximum size and proportions of rectangular columns**

- No side dimension (b or h) greater than 36-in
- Aspect ratio (h/b) no more than 2.0

**High strength concrete**

- Use of FRP to improve strength of existing concrete with  $f'_c > 10,000$ -psi is not recommended

**Service stress limits**

- Concrete service stresses  $< 0.65 f'_c$
- Steel service stresses  $< 0.60 f_y$

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### Using the Confinement Model

Compressive Strength:  
with existing steel spiral reinforcing:

ACI 440.2R-08  
Eq. (12-1a)  $\phi P_n = 0.85\phi [0.85 f_{cs} (A_g - A_{st}) + f_y A_{st}]$

with existing steel-tie reinforcing:

ACI 440.2R-08  
Eq. (12-1b)  $\phi P_n = 0.80\phi [0.85 f_{cs} (A_g - A_{st}) + f_y A_{st}]$

Use the confined concrete compressive strength in ACI 318 equations

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### Using the Confinement Model

Increases Ductility

Increases Strength

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### Axial-Moment Interaction

FRP Confined Concrete

Unconfined Concrete

Balance Line

Strengthening effect only significant for compression controlled members

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### Rebuilding the Pentagon Washington, DC USA

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### Challenges

#### Damage to Wedge 1 / E-Ring

- Substantial structural and fire damage existed particularly in the outer ring of "Wedge 1"
- All repairs had to be complete less than one year in order to allow the building to be completely re-opened and operational by 09/11/2002.

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### Challenges

#### Removal of Damaged Section

- Damaged areas were completely removed
- The removed sections were to be re-built with expansion joints connecting old to new construction

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### Challenges

**Removal of Damaged Section**

- Damaged portions of structure were completely demolished in order to rebuild



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### Challenges

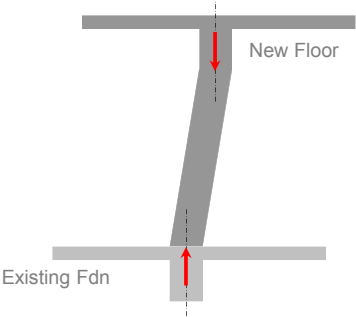
**Re-pouring of E-ring**

- A second challenge arose during the reconstruction of E-ring
- Existing column lines were not matching up with existing foundations



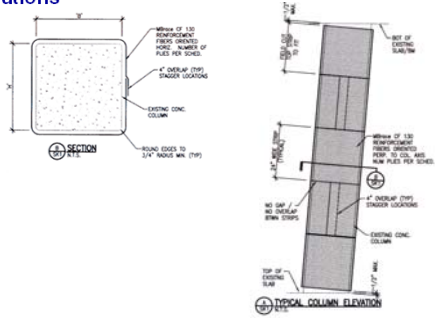
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### Challenges



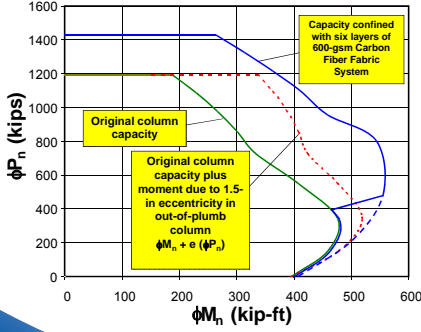
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### Solutions



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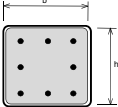
### Solutions



Capacity confined with six layers of 600-gsm Carbon Fiber Fabric System

Original column capacity

Original column capacity plus moment due to 1.5-in eccentricity in out-of-plumb column  $\phi M_n + e (\phi P_n)$




$h = 18\text{-in}$   
 $b = 18\text{-in}$   
 $\rho_b = 0.034$   
 $f_c = 5000\text{-psi}$   
 $f_y = 60,000\text{-psi}$

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### Solutions

**Confinement completed on one column**



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**Conclusion**

**Reconstruction Nearly Complete**

- Project was completed on-time
- The Pentagon was fully re-opened by 09/11/2002




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**FRP Confinement of Concrete Columns**

**Conclusion**

- ACI 440.2R-08 Guidelines for Column Confinement
  - Basic confinement model
  - Circular and Rectangular Sections
  - Size Limitations
- Practical guidelines
  - Development of P-M Diagrams
- ACI 440 Moving Forward
  - Specific seismic guidelines
  - Specific blast guidelines (Joint effort with ACI Committee 370)



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**Antonio De Luca**, ACI Member, is a Post-Doctoral Associate at the Department of Civil, Architectural, and Environmental Engineering at the University of Miami, Coral Gables, FL. He received his BS and MSc from the University of Naples—Federico II, Naples, Italy, and his PhD from the University of Miami. His research interests include the use of advanced composite material systems as internal and external reinforcement in concrete structures.

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**Volumetric Response of FRP-Confined Full-Scale RC Columns**

Antonio De Luca (University of Miami)  
 Fabio Nardone (University of Naples-“Federico II”)  
 Fabio Matta (University of South Carolina)  
 Gian Piero Lignola (University of Naples-“Federico II”)  
 Andrea Prota (University of Naples-“Federico II”)  
 Antonio Nanni (University of Miami)

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**Research significance**

The real novelty of this experimental program is the size of the column specimens.

Full-scale experiments are generally limited by high cost and availability of high-capacity testing equipment.

Full-scale experiments are therefore critical not only to validate a new technology, but also to produce compelling evidence to justify rational design methodologies.



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**Research significance**

Databases by Hassan & Chaallal (2007) and Rocca et al. (2008) assemble relevant experimental data on RC prismatic columns externally confined with FRP wraps and tested under axial compressive load from 1994 to 2007.

- only 16 of the 113 column specimens (14%) have short section sides larger than 12 in.;
- only 1 column specimen is higher than 8 ft;
- the ratio between specimen height and short section side is always smaller than 5;
- 9 columns (8%) are confined with glass FRP (GFRP).

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### Objectives

- ▶ To investigate the effectiveness of the FRP confinement in relation to different cross-sectional geometries and sizes;
- ▶ To investigate the contribution of GFRP and glass-basalt hybrid FRP (HFRP) laminates to concrete confinement;
- ▶ To assess the equivalence of confined column performance when different glass fibers of comparable quality are used.

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### Experimental program

Specimens were intended to represent real size building columns designed according to a dated ACI 318 code (i.e., prior to 1970) for gravity loads only

S-1 type  
24 in. by 24 in.  
2 #4 cross-ties  
8 #8 rebar  
#4 tie

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### Experimental program

Specimens were intended to represent real size building columns designed according to a dated ACI 318 code (i.e., prior to 1970) for gravity loads only

R-1 type  
20 in. by 29 in.  
2 #4 cross-ties  
8 #8 rebar  
#4 tie

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### Experimental program

Specimens were intended to represent real size building columns designed according to a dated ACI 318 code (i.e., prior to 1970) for gravity loads only

R-0.5 type  
14 in. by 20 in.  
4 #8 rebar  
#4 tie

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### Experimental program

Uni-directional continuous fiber sheets were installed.

Glass A	Glass B	Hybrid
t = 0.019"	t = 0.050"	t = 0.011"

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### Experimental program

S-1 type – 4 specimens

- ▶ S-1-control
- ▶ S-1-5GA
- ▶ S-1-2GB
- ▶ S-1-8H

Section A-A and B-B  
#4 steel ties @ 2 in. on center  
#4 steel ties @ 16 in. on center  
#4 steel ties @ 2 in. on center

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### Experimental program

R-1 type – 3 specimens

- ▶ R-1-control
- ▶ R-1-5GA
- ▶ R-1-8H

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### Experimental program

R-0.5 type – 5 specimens

- ▶ R-0.5-control
- ▶ R-0.5-5GA
- ▶ R-0.5-2GB
- ▶ R-0.5-5GB
- ▶ R-0.5-8H

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### Test setup

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### Experimental results

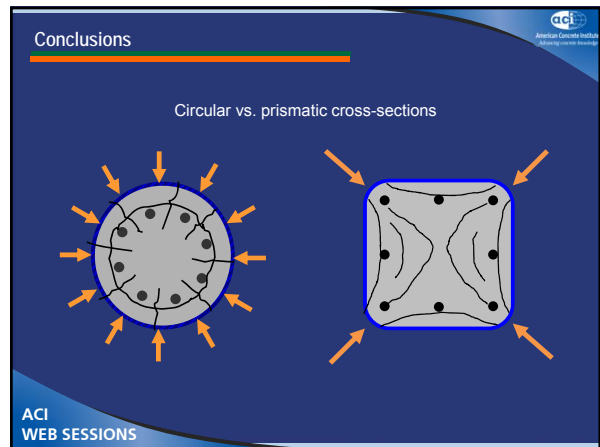
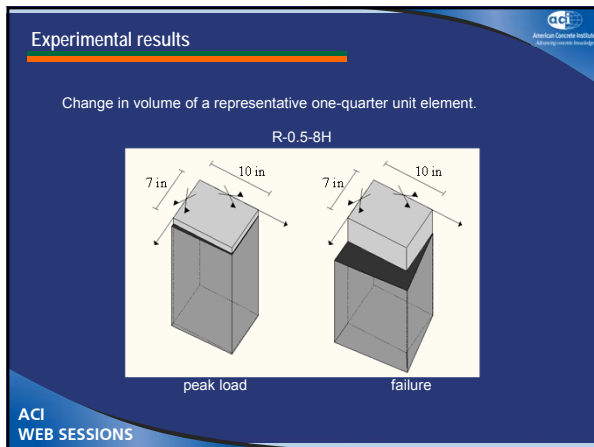
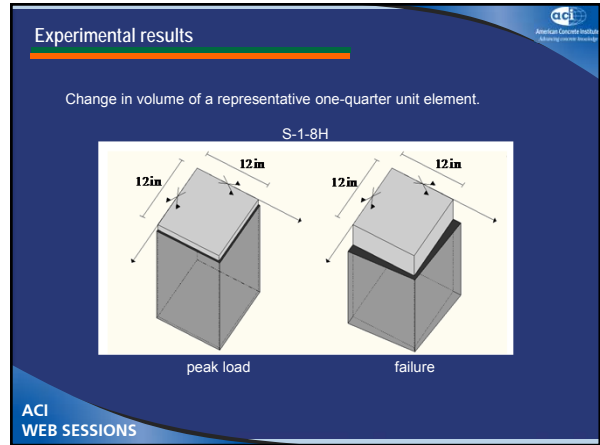
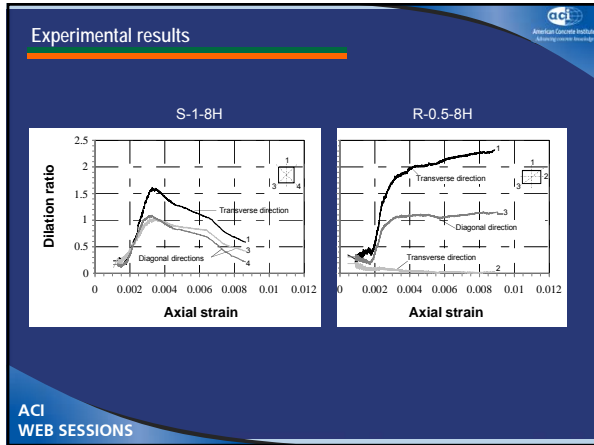
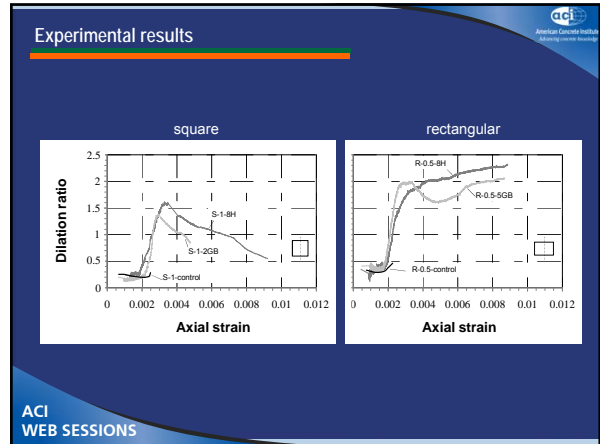
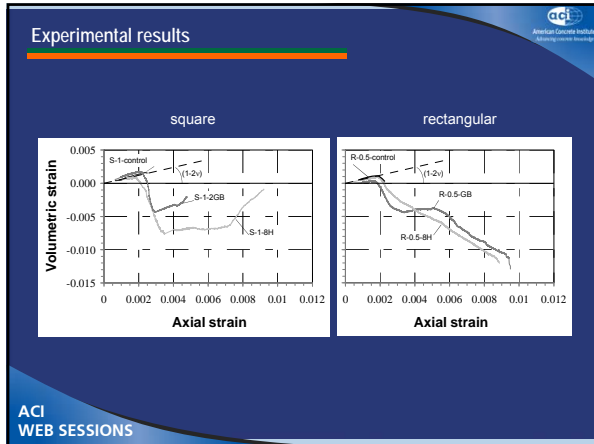
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### Experimental results

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### Experimental results

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Conclusions

1. The shape of the cross-section influences the effectiveness of the confinement. In prismatic columns, the FRP confinement effectiveness is more significant in terms of enhancement of concrete axial deformation rather than increment in axial strength.
2. Effectiveness is higher for square shapes than for rectangular ones, and decreases as the side aspect ratio of a rectangular cross-section increases.

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Conclusions

3. The transverse expansion of the concrete core in the plane of the cross-section, defined by means of the dilation ratio, changes with the direction along which it is evaluated.
4. The presence of the FRP jacket allows a "growth" in volume of the concrete core by offsetting buckling of the longitudinal bars and by delaying unstable crack propagation.
5. Difference in the FRP material manufacturers does not affect performance when confining materials are of comparable quality. The contribution to column confinement of the hybrid glass-basalt FRP laminates was similar to that of the GFRP laminates.

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Acknowledgements



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**Sami H. Rizkalla, F.ACI**, is a Distinguished Professor of civil and construction engineering in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University, where he also serves as the Director of the Constructed Facilities Laboratory and NSF I/UCRC in Repair of Structures and Bridges.

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**Behavior of Concrete Piles Confined with CFRP Grid**

Ding, Seliem, Rizkalla,  
G. Wu, and Z. Wu

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## OUTLINE

1. Background
2. Experimental Program
3. Material Properties
4. Test Results
5. Analysis of Results
6. Field Application

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## Background

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## Experimental Program

Specimen	Details of Confinement	Longitudinal Reinforcement
CN	No Confinement	None
S@6	W3.5 Square <b>Steel Spirals @ 6 in.</b> (152mm)	4 NO. 3 (G60)
S@3	W3.5 Square <b>Steel Spirals @ 3 in.</b> (76mm)	4 NO. 3 (G60)
1C-8	<b>1 Layer of C-GRID</b> with 8 in. (203mm) overlap	None
1C-16	<b>1 Layer of C-GRID</b> with 16 in. (406mm) overlap	None
2C-C-8	<b>2 Continuous Layers of C-GRID</b> with 8 in. (203mm) overlap	None
2C-S-8	<b>2 Separate Layers of C-GRID</b> with 8 in. (203mm) overlap	None

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## Experimental Program

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## Experimental Program


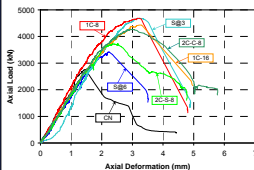
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## Material Properties

Average Max Load for Transverse Wires lb (N)	1170 (5230)
Average Ultimate Tensile Strain for Main Wires $\epsilon$	1.03 %


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### Testing of Pile Specimens

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### Test Results

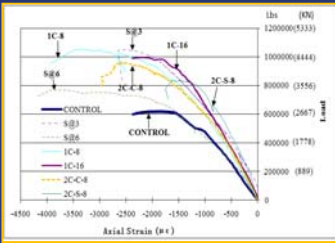


ID	Peak Load kips (kN)	Ratio
CN	619 (2753)	1.00
S@6	769 (3421)	1.24
S@3	1052 (4679)	1.70
1C-8	1052 (4679)	1.70
1C-16	997 (4435)	1.61
2C-C-8	960 (4270)	1.55
2C-S-8	838 (3727)	1.35

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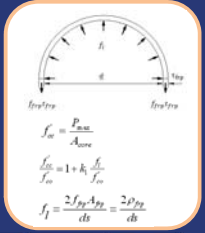
### Test Results

ID	Peak Load kips (kN)	Axial Strain at Peak Load, $\mu\epsilon$
CN	619 (2753)	1808
S@6	769 (3421)	3774
S@3	1052 (4679)	2578
1C-8	1052 (4679)	3332
1C-16	997 (4435)	2217
2C-C-8	960 (4270)	2604
2C-S-8	838 (3727)	1499



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### Analysis of Results

Source	Karfibart and Gass (1973)	Hosono et al. (1995)	Myrland et al. (1999)	Saafi et al. (2000)	Tremblay (2000)
Equation		$\frac{f_{cc}}{f_{c0}} = 1 + k_1 \frac{f_{FRP}}{f_{c0}}$			
$k_1$	$2.1(\frac{f_{FRP}}{f_{c0}})^{0.88}$	$6.0(\frac{f_{FRP}}{f_{c0}})^{0.5}$	1.88	$2.2(\frac{f_{FRP}}{f_{c0}})^{0.88}$	$3.5(\frac{f_{FRP}}{f_{c0}})^{0.88}$

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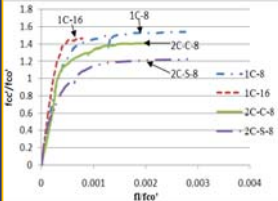
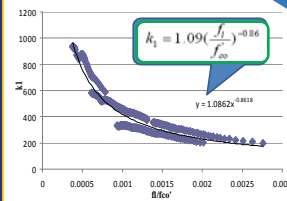
Specimen ID	Concrete and Concrete Strength $f_c$ (ksi/Mpa)	Experimental Strength $f_{cc}$ (ksi/Mpa)	Calculated Strength $f_{cc}$ (ksi/Mpa)	Ratio of $f_{cc}/f_c$	Source
1C-8	5.000	8.38 (59)	8.47 (60)	1.67	Reference [3]
1C-16	5.000	8.11 (56)	8.71 (62)	1.74	
2C-C-8	5.000	7.81 (54)	8.87 (63)	1.84	
1C-8	5.000	8.38 (59)	8.47 (60)	1.67	Reference [5]
1C-16	5.000	8.11 (56)	8.71 (62)	1.74	
2C-C-8	5.000	7.81 (54)	8.87 (63)	1.84	
2C-S-8	5.000	7.81 (54)	8.87 (63)	1.84	
1C-8	5.000	8.38 (59)	8.47 (60)	1.67	Reference [6]
1C-16	5.000	8.11 (56)	8.71 (62)	1.74	
2C-C-8	5.000	7.81 (54)	8.87 (63)	1.84	

**Lam and Teng (2002a)**  
 $k_1 = 2.0$

**Saafi, M.**  
 $k_1 = 1.54(\frac{f_{FRP}}{f_{c0}})^{0.88}$

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### Analysis of Results

ID	Experimental Strength $f_{cc}$ (ksi (Mpa))	Calculated strength $f_{cc}$ (ksi (Mpa))	Ratio of $f_{cc}/f_c$
1C-8	8.58 (59)	9.04 (62)	1.05
1C-16	8.11 (56)	9.04 (62)	1.11
2C-C-8	7.81 (54)	9.38 (65)	1.20

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### -Field Application



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### Casting with SSC



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### Prototype Pile



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### Testing by FDOT



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### Testing by FDOT



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# Questions

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