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Internal FRP Reinforced Concrete Structures

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

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Martin Kurth is a research assistant at the Institute of Structural Concrete of RWTH Aachen University, Germany since 2007. He obtained his Diploma Degree in the field of structural engineering at RWTH Aachen University in 2007.

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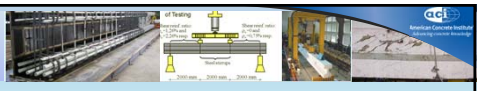

SHEAR CAPACITY OF CONCRETE BEAMS WITH FRP REINFORCEMENT

Martin Kurth
Josef Hegger

Institute of Structural Concrete
RWTH Aachen University

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Motivation

Often observed shear failure modes of FRP-RC members

Diagonal tension failure

Shear compression failure

Aims of the research project (AiF)

- Truss angle
- Strength reduction factor for concrete cracked in shear
- Maximum strain allowed in the shear reinforcement
- New / modified design appraoch

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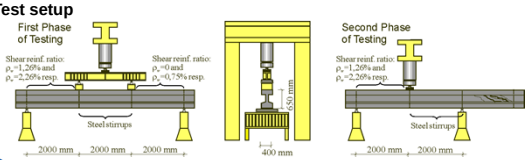
Experimental program

Geometry of tested beams and mechanical properties

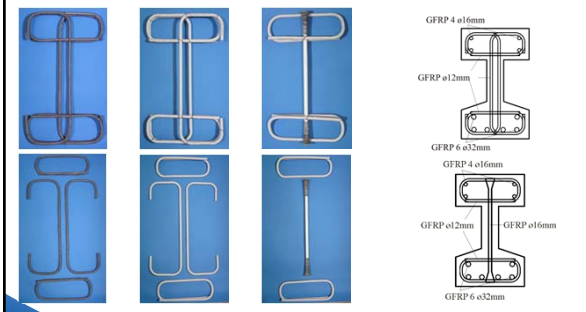
Span to depth a/d	Concrete strength f_{ck}	Shear reinforcement ρ_w	Flexural reinforcement E_{fl}	Shear reinforcement E_{fw}
~ 3,5	C30/37 C60/75	0 ~ 0.8% ~ 1.3% ~ 2.3%	59000 N/mm² up to 62600 N/mm²	56200 N/mm² up to 63700 N/mm²

Test setup



Used GFRP shear reinforcement

FiReP stirrups | Schöck stirrups | Schöck headed bars | Beam cross-sections



Test setup

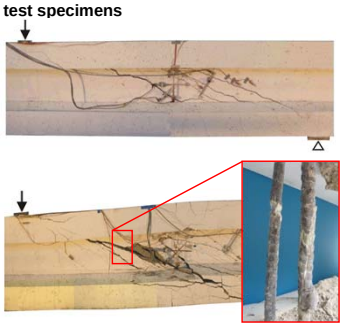
4-point-bending | **3-point-bending**

Test results

Failure of test specimens

$\rho_w = 0$ — **Diagonal tension failure**

$\rho_w = 0.8\%$ — **Rupture of the GFRP stirrups**



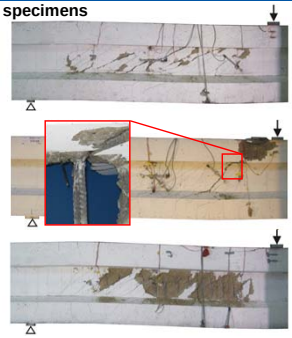
Test results

Failure of test specimens

$\rho_w = 1.3\%$ (C30/37) — **Crushing of the concrete struts**

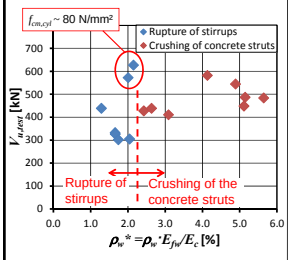
$\rho_w = 1.3\%$ (C60/75) — **Rupture of the GFRP stirrups**

$\rho_w = 2.3\%$ — **Crushing of the concrete struts**

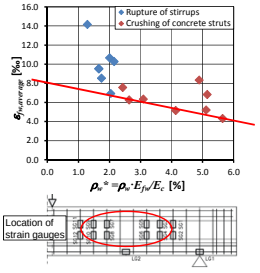


Test results

Maximum imposed shear force

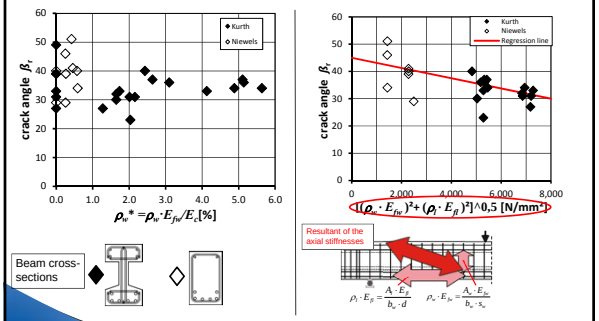


Average stirrup strains at failure



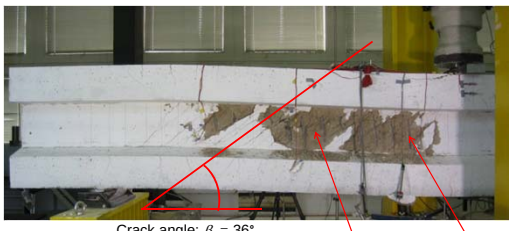
Test results

Inclination angles of shear cracks



Test results

Maximum shear force (Crushing of the compression struts)



Test results

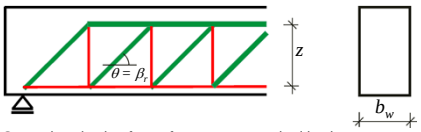
Maximum shear force (according to Eurocode 2)

Design equation:

$$V_{Rd,max} = \frac{b_w \cdot z \cdot \upsilon_1 \cdot f_{cd}}{\cot\theta + \tan\theta}$$

Equation for verifying calculations:

$$V_{R,max} = \frac{b_w \cdot z \cdot \upsilon_1 \cdot f_{cm,cyl}}{\cot\theta + \tan\theta}$$

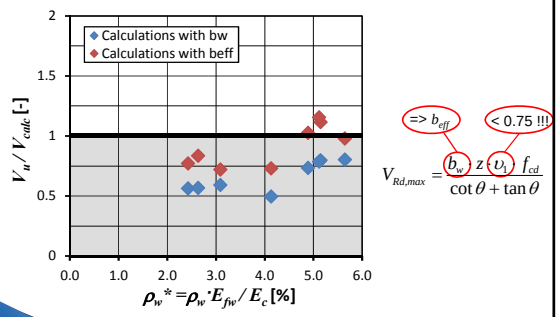


υ_1: Strength reduction factor for concrete cracked in shear

NA (Germany): υ_1 = 0.75 [≤ C50/60]
0.75 · (1.1 – f_{ck}/500) [> C55/67]

Test results

Maximum shear force; Verifying calculations



Shear tests without transverse reinforcement

Comparison of predicted and experimental results

Design equations:

Modified EC2 (Sheffield)

$$V_{Rd,cf} = \left[\frac{0.18}{\gamma_c} \cdot k \cdot \left(100 \cdot \rho_{fl} \cdot \frac{E_f}{E_s} \cdot \phi_s \cdot f_{ck}\right)^{1/3} + k_1 \cdot \sigma_{cp}\right] \cdot b_w \cdot d$$

$$\rho_{fl} = \frac{A_{fl}}{b_w d} \le 0.02$$

$$\phi_s = \frac{\varepsilon_{fld,ef}}{\varepsilon_y}$$

ACI 440.1R06

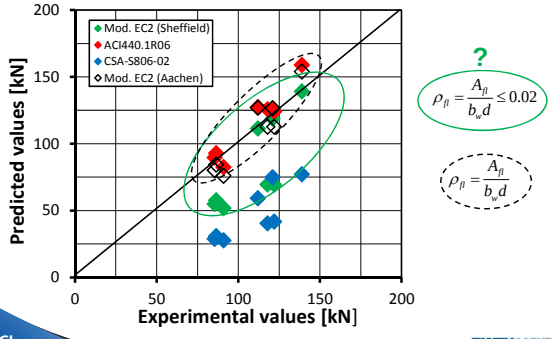
$$V_c = \frac{2}{5}\sqrt{f_c'} \cdot b_w \cdot c$$

CSA-S806-02

$$V_c = \frac{130}{1000 + d} \cdot \lambda \cdot \phi_c \cdot \sqrt{f_c'} \cdot b_w \cdot d \ge 0.08 \cdot \lambda \cdot \phi_c \cdot \sqrt{f_c'} \cdot b_w \cdot d$$

Shear tests without transverse reinforcement

Comparison of predicted and experimental shear resistance



Shear tests with transverse reinforcement

Comparison of predicted and experimental shear resistance

Design equations:

Modified EC2 (Sheffield)

$$V_{Rd,f} = V_{Rd,sf} + V_{Rd,cf}$$

$$V_{Rd,sf} = \frac{A_{fw}}{s} \cdot z \cdot \varepsilon_{fd,ef} \cdot E_{fw}$$

Design value: $\varepsilon_{fd} = 0.0045$
For comparison: $\varepsilon_f = \varepsilon_{f,test}$

$$V_{Rd,\max} = \alpha_{cw} b_w z \nu_1 f_{cd} / 2$$

ACI 440.1R-06

$$V = V_c + V_f$$

$$V_f = \frac{A_{fv} \cdot f_{fv} \cdot d}{s} \le 0.664 \cdot \sqrt{f_c'} \cdot b_w \cdot d$$

For comparison: $f_{fv} = \varepsilon_{f,m,test} \cdot E_{fv}$

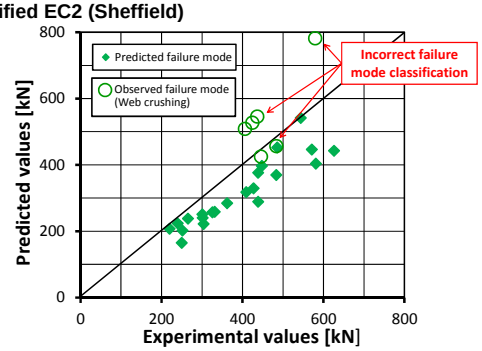
CSA-S806-02

$$V_r = V_c + V_{sF}$$

$$V_{sF} = \frac{0.4 \cdot \phi_F \cdot A_v \cdot f_{Fu} \cdot d}{s} \le 0.6 \cdot \lambda \cdot \phi_c \cdot \sqrt{f_c'} \cdot b_w \cdot d$$

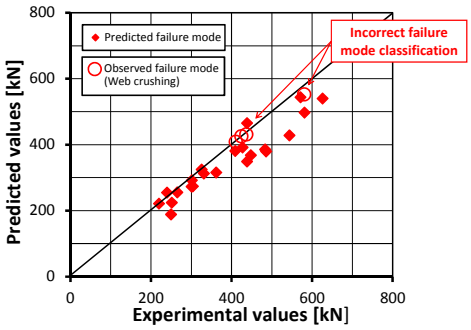
Shear tests with transverse reinforcement

Modified EC2 (Sheffield)



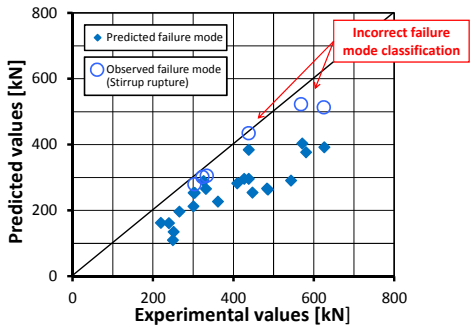
Shear tests with transverse reinforcement

ACI 440.1R-06



Shear tests with transverse reinforcement

CSA-S806-02



Summary and conclusions

- 20 shear tests on concrete I-beams reinforced with FRP
- ρ_w = 0: diagonal tension failure
- ρ_w = 0.75% and 1.26% (C60/75): rupture of the GFRP stirrups
- ρ_w = 1.26%(C30/37) and 2.26%: crushing of the web
- Shear crack angle depends on the resultant of the related axial stiffnesses
- Maximum shear capacity of FRP-reinforced beams is lower compared to steel RCS
- Predicted shear resistance according to ACI 440.1R-06 with low scatter in results
- Incorrect failure mode classification

Future work

- Design equations
- Shear resistance for beams without transverse reinforcement => empirical approach
- Shear resistance for beams with transverse reinforcement => additive approach
- Limitation of the stress level in the FRP shear reinforcement

Slamah Krem is a PhD candidate at the University of Waterloo, Canada. He is a former lecturer at Alfateh University. His main fields of interest are experimental and analytical investigation of reinforced concrete structure, high performance concrete, and concrete durability. This paper is a part of his ongoing comprehensive research program on bond and flexural behvaiour of SCC beams reinforced or prestressed with CFRP bars.

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Development Length of CFRP Bars Embedded in Concrete

S. Krem, PhD Candidate
K. Soudki, Professor
University of Waterloo, Ontario

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OUTLINES

1. Introduction
2. Research Needs
3. Experimental Program
4. Results
5. Conclusions

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1. Introduction

Corrosion of steel reinforcement in reinforced concrete is the main deterioration process that affects structure service life and structure safety.

- Cost in USA is about $8.3 billion annually
- In Canada to repair all deficient bridge $10 billion

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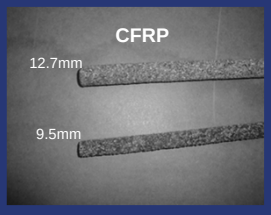
1. Introduction

Fiber Reinforced Polymers (FRP)

FRP bars are composite materials consisting of reinforcing fibres embedded in a polymer resin matrix.



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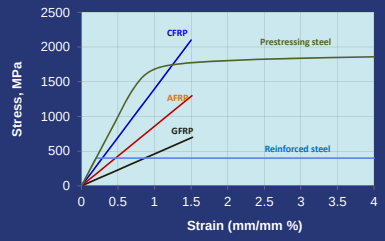
1. Introduction

Fiber Reinforced Polymers (FRP)

- ✓High longitudinal tensile strength
- ✓Corrosion resistant – will not corrode
- ✓Light weight



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2. Research Needs

1. ACI 440.1R-06 Eqn. (11-6), the development length Eqn. for the FRP bars, is mainly based on GFRP bars and it may be not valid for CFRP bars.

✚

2. The development length of the CFRP bars is, typically, above than $100d_b$, which is beyond the database range used to formulate this equation.

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3. Experimental Program

Test Matrix

Group	Dimension		Reinforcement				
	Cross section (b×h) mm	Length, (l) mm	Type	Diameter, mm	Actual ratio	Balanced ratio	Shear
I	150×150	1700	CFRP	6.3	0.0016	0.0052	8M-75
II	150×200	2200		9.5	0.0028	0.0045	8M-75
III	150×300	3000		12.7	0.0033	0.0036	8M-100
IV	150×200	2200	GFRP	12.7	0.0054	0.0074	8M-75

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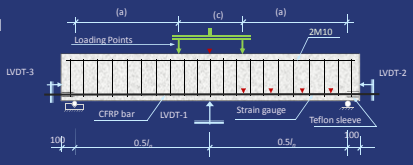
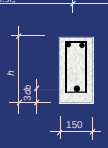
3. Experimental Program

Typical beam configuration

Longitudinal Section



Cross Section



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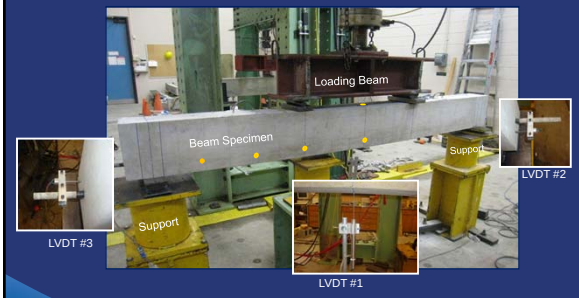
3. Experimental Program

Instrumentation and test setup



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4. Results

Pullout mode of failure

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4. Results

Bar rupture mode of failure

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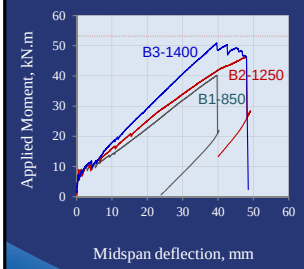
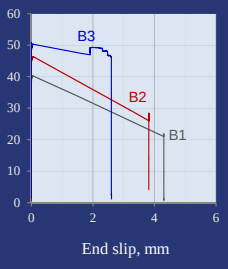
4. Results

Flexure test results of beams Group III (12.7 CFRP bars)





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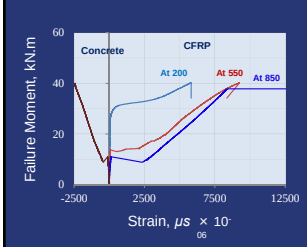
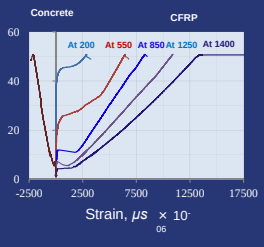
4. Results

Strain reading along the embedment length, Group III



Pull out failure mode (B1)



Bar rupture failure mode (B3)

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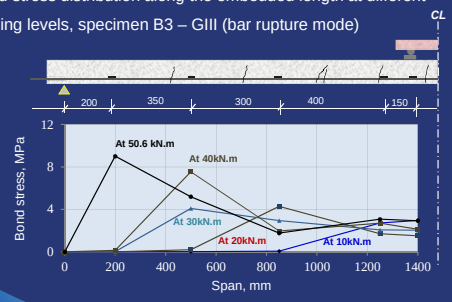
4. Results

Bond Stress Profile

Bond stress distribution along the embedded length at different loading levels, specimen B3 – GIII (bar rupture mode)



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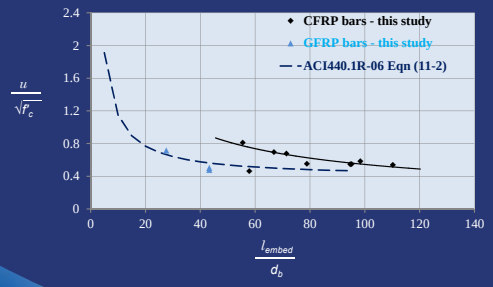
4. Results

Average bond stress of CFRP bars



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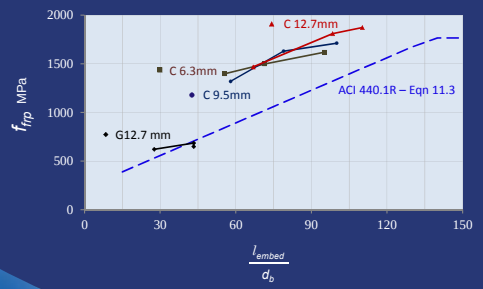
4. Results

Achievable bar stress at given embedment length



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4. Results

Based on results, a proposed Eqn. is formulated as below:

$$L_{dev\text{ - }pullout} = \frac{d_b f_{frp}}{a\sqrt{f'_c}}$$

Where: a is equal to 2.16 $MPa^{0.5}$, (26.0 $psi^{0.5}$) for CFRP bars, and 1.90 $MPa^{0.5}$, (22.6 $psi^{0.5}$) for GFRP bars.

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4. Results

Development length based on CAN/CSA, ACI440.1 and experimental results

Bar diameter	Guaranteed tensile strength, MPa	Development length, mm, based on		
		CAN/CSA-S6-06	ACI 440.1R-06	Proposed Eqn.
6.3 CFRP	1355.5	261	658	502
9.5 CFRP	1431.0	411	1058	800
12.7 CFRP	1765.0	674	1806	1318
12.7 GFRP	708.0	270	569	601

$$l_d = \frac{d_b\left(\frac{f_{frp}}{0.083\sqrt{f'_c}} - 340\right)\alpha}{13.6 + \frac{c}{d_b}}$$ ACI 440.1R-06

$$l_d = 0.45\frac{k_1 k_s}{d_{cs} + k_{tr}\frac{E_{frp}}{E_s}}\left(\frac{f_{frp}}{f_{cr}}\right)A_{frp}$$ CSA –S6-06

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5. Conclusions

1. The average bond stress of FRP bars in the cracked region of a beam was only about 50% of the average bond stress over the entire embedment length.

2. The bond strength of the CFRP bars is better than those of GFRP bars by about 15% at the tested ratio of l_{db}/d_b.

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5. Conclusions

3. ACI 440.1R-06 Eqn. (11.6) overestimate the development length of the CFRP by about 30%, while CAN/CSA-S6-06 is unconservative by about 50%.

4. More research is needed to include the effect of cover thickness and concrete compressive strength.

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