Approaches for Teaching Shear Analysis and Design of Reinforced Concrete

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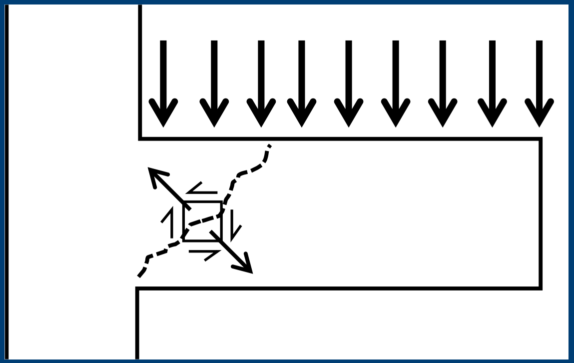
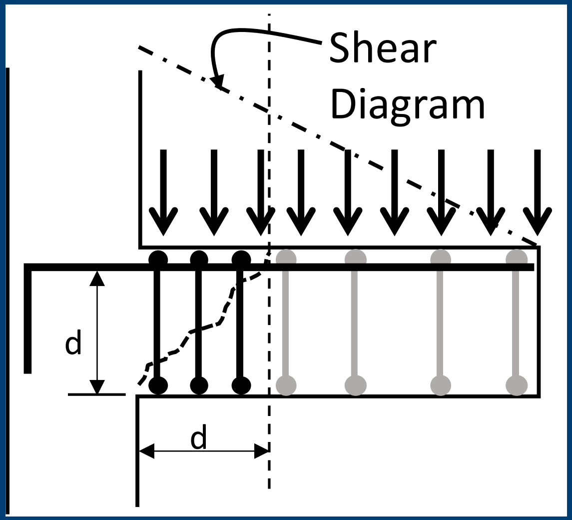
Introduction

- Not just content, but how is it delivered?
  - Address different learning styles
  - Instructors often have little pedagogical training
  - Instructors tend to emulate their experiences
- This presentation is focused on an introductory Concrete Design course

Technical Content

- Shear behavior based on combined flexural, axial, and shear stresses
- Rapid and brittle failure
  - $\varphi = 0.75$ (ACI 318-19 21.2.1)
  - Diagonal tension failure
  - Cracks at 45° for non-prestressed
- Overall philosopy
  - Estimate cracking
  - Cross cracks with stirrups



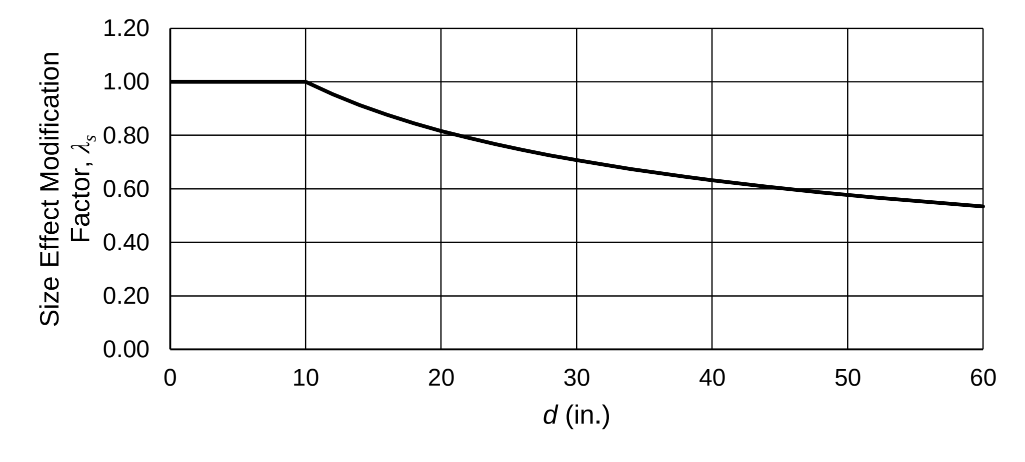


Technical Content

- Shear Design
  - $\varphi V_n \geq V_u$
  - $V_n = V_c + V_s$ (ACI 22.5.1.1)
- Ultimate Shear Force (V_u)
  - Based on the shear diagram, changes along length
  - Based on force at *d* from the support for typical supports

Technical Content

- Concrete Contribution
  - Changes in 318-19
  - Size effect factor
  - Multiple equations (ACI 22.5.5.1)



For $A_v \geq A_{v,min}$ either of

$$V_c = \left[2\lambda\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d$$

$$V_c = \left[8\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d$$

For $A_v < A_{v,min}$

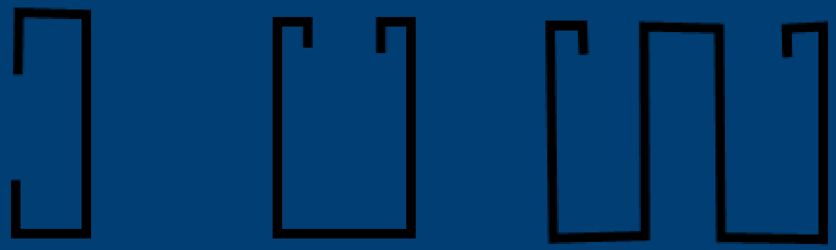
$$V_c = \left[8\lambda_s\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right] b_w d$$

Technical Content

- d = effective depth at section considered for shear
- b_w = width of rectangular beam or T-beam web
- f'_c = specified 28-day compressive strength in psi
- λ = modification factor to account for properties of lightweight concrete
- $\lambda_s = \sqrt{\frac{2}{1+\frac{d}{10}}} \leq 1$
- $\rho_w = \frac{A_s}{b_w d}$

Technical Content

- Steel Contribution
  - Stirrups typically installed vertically
  - $V_s = \frac{A_v f_{yt} d}{s}$ (ACI 22.5.10.5)



- Determining required stirrups
  - $V_u \leq \varphi[V_c + V_s] = \varphi 2\lambda\sqrt{f_c'} b_w d + \varphi \frac{A_v f_{yt} d}{s}$
  - $s(x) \leq \frac{\varphi A_v f_{yt} d}{V_u(x) - \varphi V_c}$
  - Often stepwise approach
  - Must consider minimum steel and maximum spacing

Active Learning Strategies

- Based on experience at four different universities

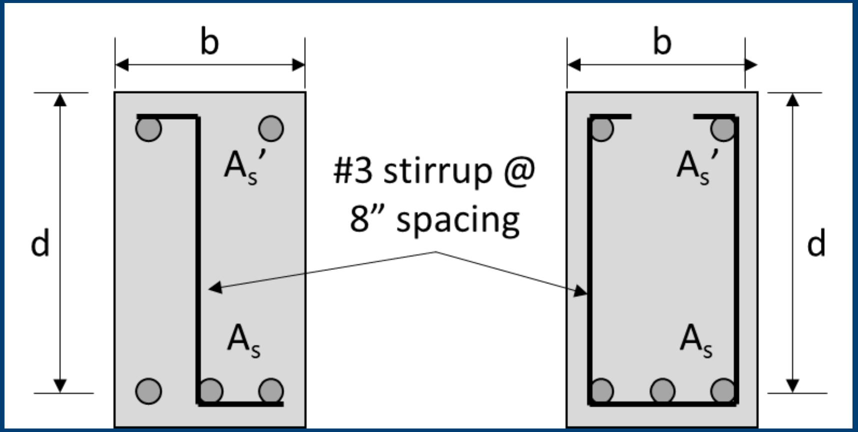
Shear Topic	RHIT	OU	UMD	Cornell
Shear Stresses in an Uncracked Elastic Beam	MC, NA	MC, NA	LC, NA	MC, A
Crack Initiation and Propagation (i.e. Mohr's circle, crack patterns)	MC, A	HC, A	MC, A	MC, A
Concrete Contribution to Shear Strength, V_c	HC, A	HC, A	HC, A	HC, A
Steel Contribution to Shear Strength, V_s	HC, A	HC, A	HC, A	HC, A
Shear Analysis of Reinforced Concrete Beams	HC, A	HC, A	HC, A	HC, A
Shear Design of Reinforced Concrete Beams	HC, A	HC, A	HC, A	HC, A
Variable Spacing of Stirrups	HC, A	HC, A	MC, NA	HC, A
Min. Web Reinforcement and Max. Stirrup Spacing	MC, A	MC, A	MC, A	HC, A
Shear in Members with Axial Load	LC, NA	LC, NA	LC, NA	MC, A
Pattern Loading	LC, NA	MC, A	MC, NA	HC, A
Continuous Members	LC, NA	MC, A	NC, NA	HC, A
Two-Way Shear	NC, NA	NC, NA	NC, NA	HC, A
Other Shear Design Methods (Compression Field Theories, Shear Friction)	NC, NA	NC, NA	NC, NA	NC, NA
HC – High Coverage, MC – Moderate Coverage, LC – Light Coverage, NC – Not Covered, A – Assessed, NA – Not Assessed.				

Active Learning Strategies

- Support instruction and content delivery
- Selected to match objectives and available time
- Engagement, reflection, and retention
- Promote a variety of learning styles
- Promote higher order thinking

Think-Pair-Share (engagement, retention, reflection)

- Preparation time: 5-10 minutes
- Activity time: < 5 minutes
- Examples
  - Area of shear reinforcement for different stirrup configurations
  - Strength reduction factor value
- Recommendations
  - Make time for each portion
  - Vary student groups



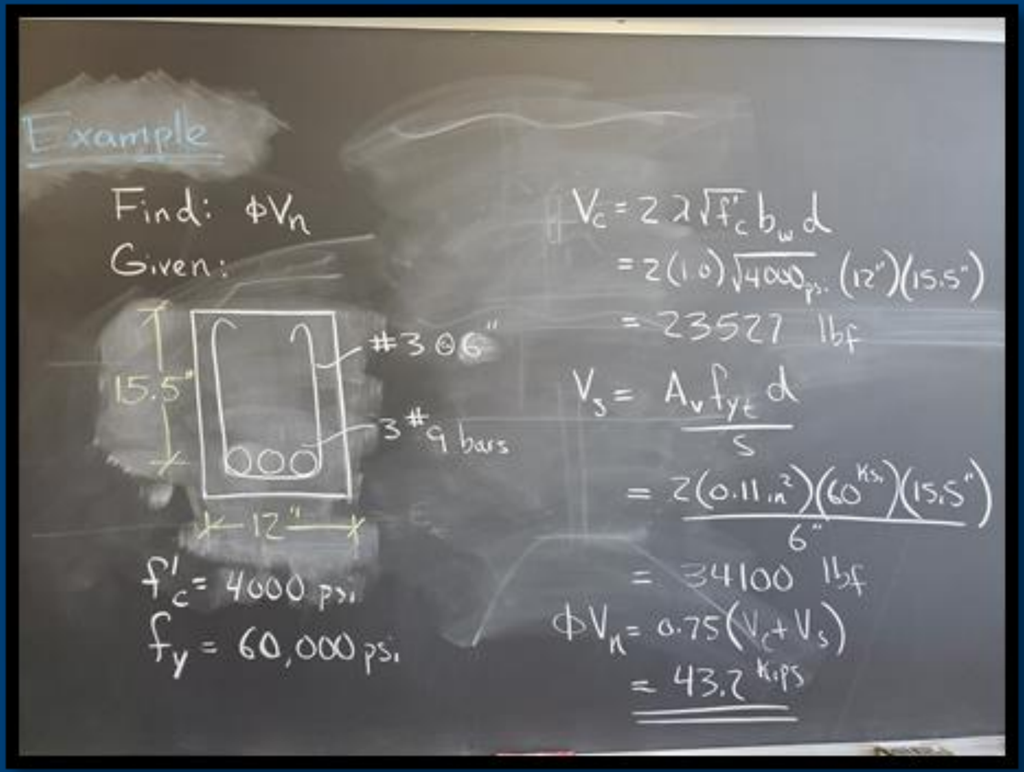
Muddiest Point (engagement, retention, reflection)

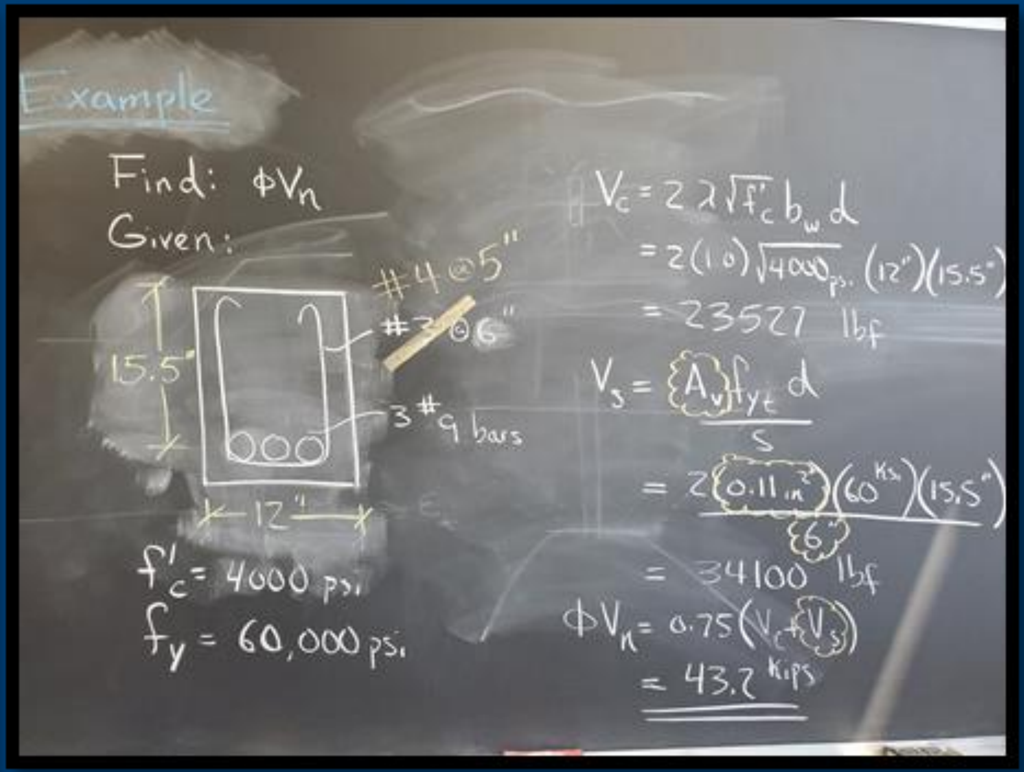
- Preparation time: < 5 minutes
- Activity time: < 5 minutes
- Help instructor know if students are struggling
- Examples
  - “Please write down a question that you have about today’s topic.”
  - “Please write down the concept from today that was the most unclear.”
- Recommendations
  - Collect student responses and address at next class
  - Use for difficult topics like variable spacing and maximum V_u

Variations (engagement, retention, reflection)

- Preparation time: < 5 minutes
- Activity time: < 5 minutes
- Examples
  - "How would this problem change if the following given information were altered?"
  - "How would changing from a uniform loading to single point load affect the maximum V_u?
- Recommendations
  - Helps students think critically about problem approach
  - Good for addressing common mistakes

Variations (engagement, retention, reflection)

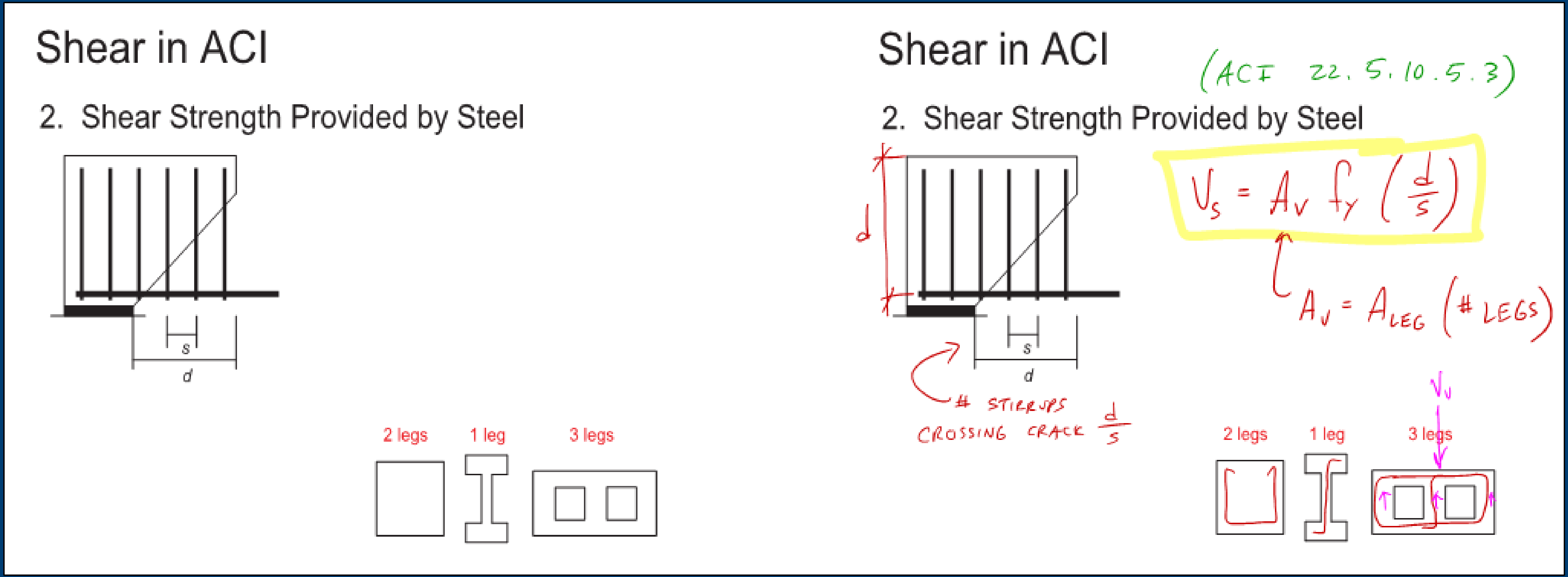




Skeleton Notes (variety of learning styles)

- Preparation time: > 60 minutes per lesson the first time
- Activity time: 15 – 50 minutes
- Description
  - Notes without key concepts or problem solutions distributed before class
  - Faculty member fills in during class
  - Helps students be organized and listen more
- Recommendations
  - Focus on providing items not critical for students to physically write
  - Critical content should be left blank

Skeleton Notes (variety of learning styles)

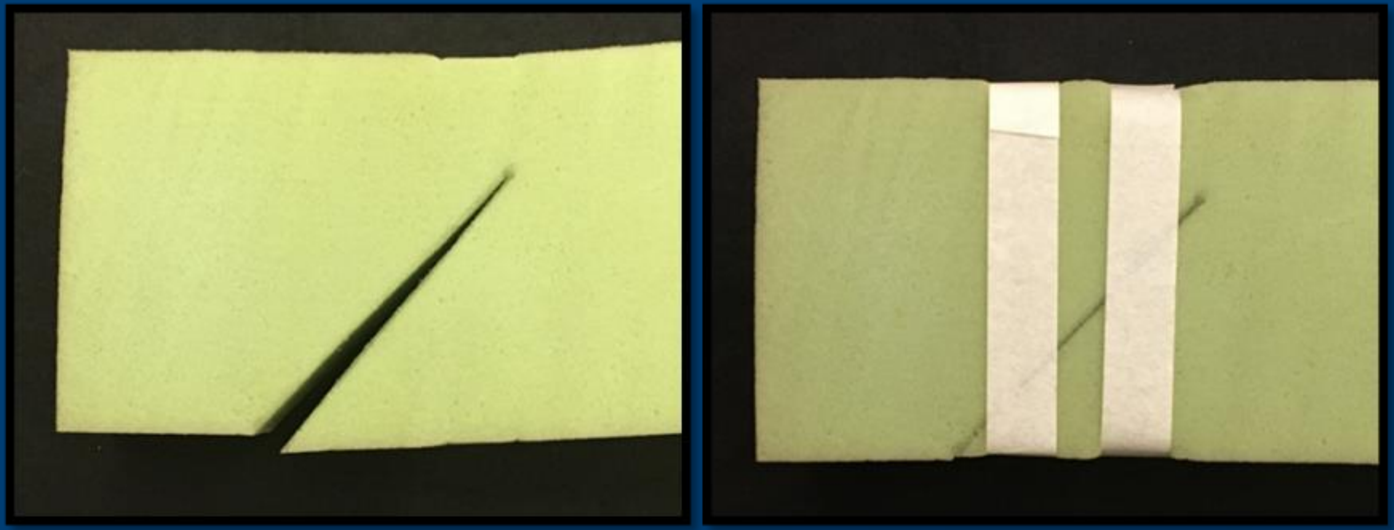


Physical Artifacts/Demonstrations (variety of learning styles)

- Preparation time: 30 – 60 minutes
- Activity time: 15 – 30 minutes
- Description
  - Provides a tangible connection to the material
  - Multiple possibilities for shear behavior and design
- Recommendations
  - Great way to introduce new concepts and topics
  - Try to get students involved (may need multiple models)
  - Poll students to see what they wish they had seen

Physical Artifacts/Demonstrations (variety of learning styles)

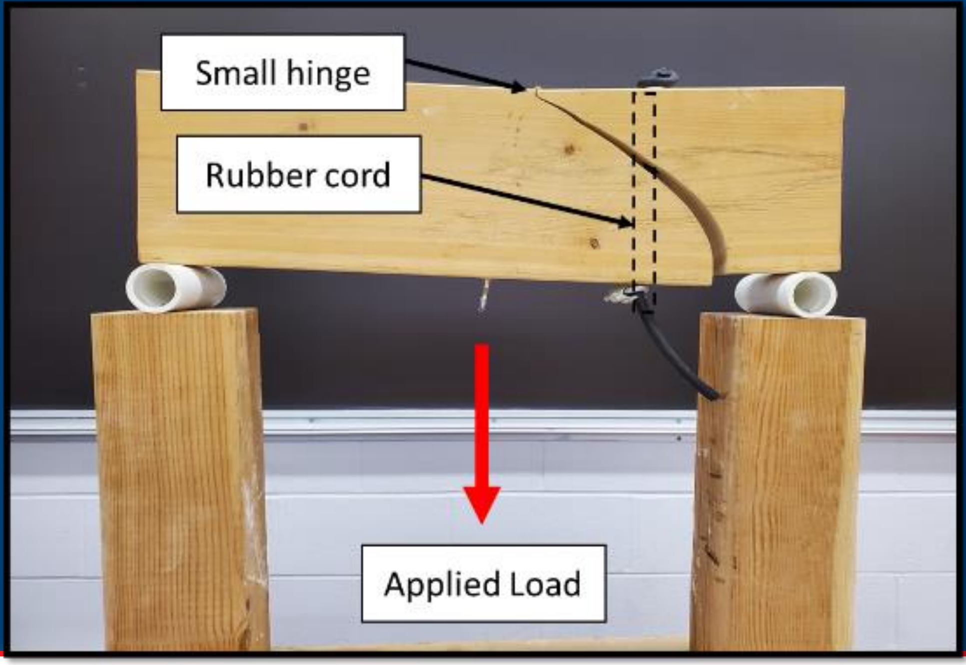
- Shear Reinforcement
  - Foam prism and masking tape
  - Can be qualitative or quantitative



(a) (b)

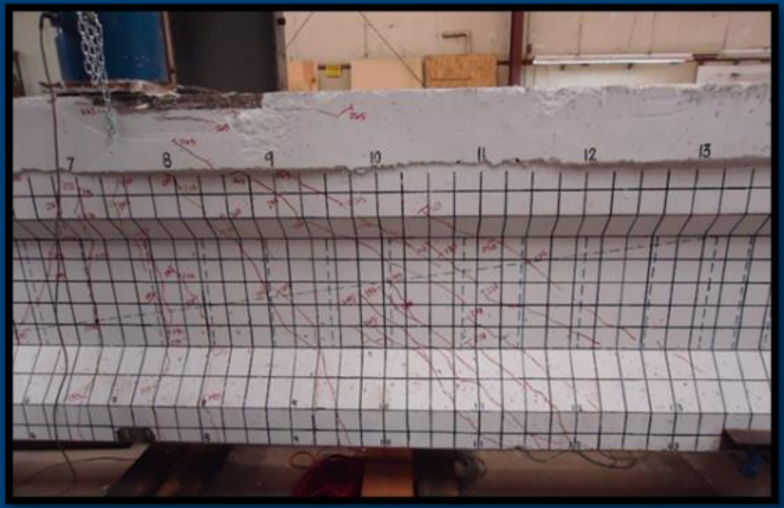
Physical Artifacts/Demonstrations (variety of learning styles)

- Shear Reinforcement, $V_{s,max}$
  - 2 x 6 with rubber hose
  - Visualization of excessive strain in the reinforcement



Physical Artifacts/Demonstrations (variety of learning styles)

- Cracking behavior
  - Photos or videos are easy to prepare
  - Can provide a connection to active research



(a)

(b)

Physical Artifacts/Demonstrations (variety of learning styles)

- Punching Shear
  - Foam padding or Styrofoam

Experiential Learning (variety of learning styles)

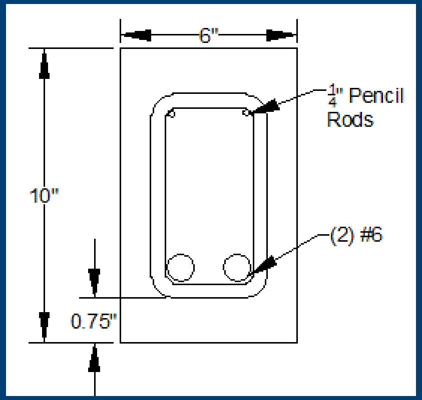
- Preparation time: widely variable
- Activity time: 20 minutes to several class meetings
- Description
  - Students participate in construction and/or testing of physical specimens
  - Laboratory sections often included with design courses
- Recommendations
  - Laboratory activities require significant time, funds, and facilities
  - Best to include in a class with a lab section
  - Can scale to available time and facilities

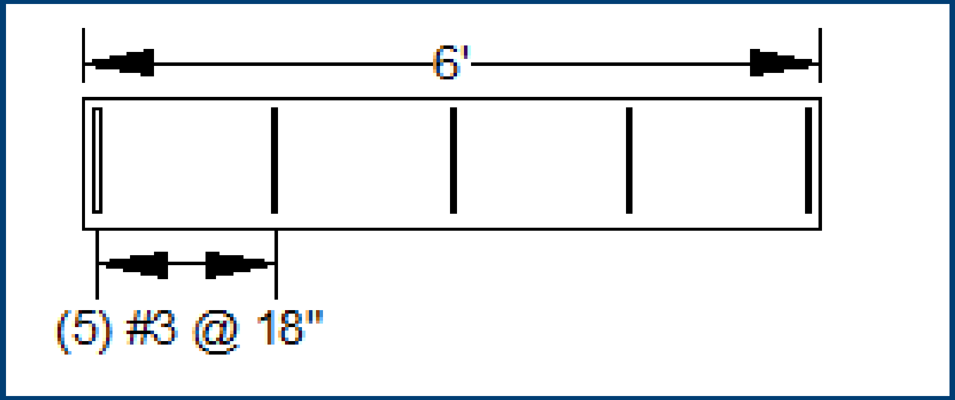
Experiential Learning (variety of learning styles)

- Pattern loading
  - Students form the “uniformly distributed load”
  - Discuss effect of different loadings on shear forces

Experiential Learning (variety of learning styles)

- Lab Example 1
  - Students build and test beams over two class periods
  - Minimal stirrups to show brittle failure





Experiential Learning (variety of learning styles)

- Lab Example 2
  - Students are assigned a failure type and must design for that failure
  - Shear failure is typically spectacular and memorable

Lab Group	Failure/Behavior Type	Minimum Load	ACI 318-19 Section
Team 1	Tension Controlled	12 kips	21.2.2
Team 2	Compression Controlled	12 kips	21.2.2
Team 3	Shear	12 kips	22.5
Team 4	Bond	12 kips	25.4.2
Team 5	Doubly Reinforced	20 kips	
Team 6	T-Beam	20 kips	6.3.2

Simulation and Computations (higher order thinking)

- Preparation time: < 30 minutes to create the assignment
- Activity time: Approx. 2 weeks for student work and instruction
- Description
  - Student built or instructor provided spreadsheet or “App”
  - Streamline the design process for consideration of alternatives
- Recommendations
  - Be aware of student skills with the proposed software
  - Can be used with other active learning strategies
  - Students can be asked to identify limitations

Simulation and Computations (higher order thinking)

- Example spreadsheet for determining spacing with $V_u(x)$

Shear Stirrup Calculator

Correction needed for new size effect factor

Span	38	feet
Ru left	110	Kips
wu	5	Kips/ft
Increment	100	

bw	12	in
beam depth h	21	in.
bar cover to stirrup	1.5	in.
flex bar size	9	#

f'c	4000	psi
fy	60	ksi

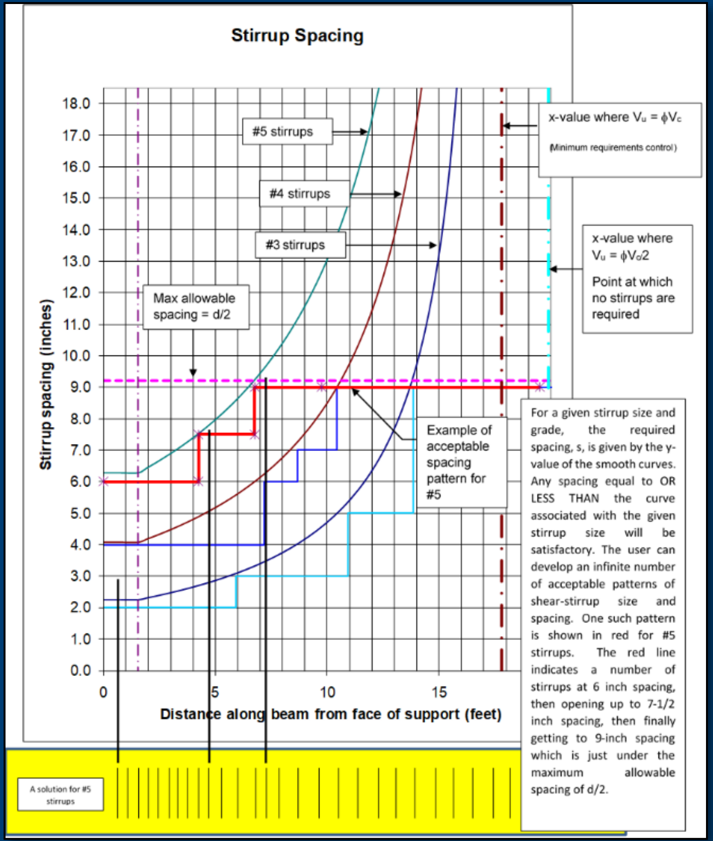
Strp	#3	#4	#5	
d	18.6	18.4	18.3	in
phi Vc	21.1	21.0	20.8	kips
phi Vc/2	10.6	10.5	10.4	kips

x @ Vu = ϕV_c	17.8	ft
x @ Vu = $\phi V_c/2$	19.9	ft

	#3	#4	#5
As (in^2)	0.11	0.2	0.31
No. legs	2	2	2
Av (in^2)	0.22	0.4	0.62
Smax (in)	22.0	40.0	62.0
d/2 (in)	9.2	9.2	9.2
Control	9.2	9.2	9.2

			d=	18.6	18.4	18.3
Point	x feet	Vu Kips	Strp #	3 s inches	4 s inches	5 s inches
0	0	102.3		2.3	4.1	6.3
1	0.77	102.3		2.3	4.1	6.3
2	1.54	102.3		2.3	4.1	6.3
3	1.92	100.4		2.3	4.2	6.4
4	2.30	98.5		2.4	4.3	6.6
5	2.68	96.6		2.4	4.4	6.7
6	3.06	94.7		2.5	4.5	6.9
7	3.44	92.8		2.6	4.6	7.1
8	3.82	90.9		2.6	4.7	7.3
9	4.20	89.0		2.7	4.9	7.5
10	4.58	87.1		2.8	5.0	7.7
11	4.96	85.2		2.9	5.2	7.9
12	5.34	83.3		3.0	5.3	8.2
13	5.72	81.4		3.0	5.5	8.4
14	6.10	79.5		3.1	5.7	8.7
15	6.48	77.6		3.3	5.9	9.0
16	6.86	75.7		3.4	6.1	9.3
17	7.24	73.8		3.5	6.3	9.6
18	7.62	71.9		3.6	6.5	10.0
19	8.00	70.0		3.8	6.8	10.4
20	8.38	68.1		3.9	7.0	10.8

Spreadsheet continues to compute "s" over the balance of the length of the beam



Lessons Learned

- **Hands-on hands-down** – student comments indicate laboratory experience and physical models are particularly useful to students
- **Application before theory** – show the application first and use it to inform the theory, especially if time is limited
- **Reinforcement detailing** – students think no reinforcement is required within d from the support and general confusion about minimums and maximums
- **Know your *b*** – web width for shear, never flange width
- **Beware the φ foul-up** – multiple possible mistakes by students
- **Assessment** – combine homework, open-ended projects, and exam

THANK YOU!

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