Teaching Flexural Strength (Failure Modes) in Reinforced Concrete I

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Introduction

- Flexural strength is a fundamental topic for Concrete I
  - Maybe the most important
  - Foundational to the rest of the course
- Concrete tensile strength ignored and steel reinforcement added
- Need background in mechanics of materials and material behavior

Introduction

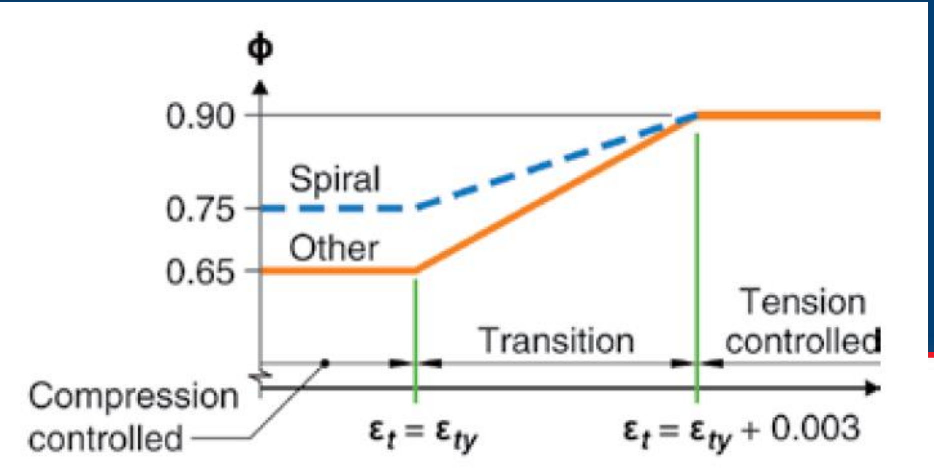
- Not just content, but how is it delivered?
  - Address different learning styles
  - Instructors often have little pedagogical training
  - Instructors tend to emulate their experiences
- This presentation is focused on an introductory Concrete Design course

Technical Content

- 2-4 lectures periods depending on the length
- Presentation of information should match textbook (notation)
- Need combination of theory and code requirements
- Failure mode depends on the amount of reinforcement
  - “Tension-controlled” or “under-reinforced”
  - “Compression-controlled” or “over-reinforced”
  - Defined based on strain in the steel

Technical Content

- Want steel to yield and produce a ductile failure ("tension-controlled")
  - Secondary compression
  - $\varepsilon_t \geq \varepsilon_{ty} + 0.003$
  - $\varphi = 0.90$ (ACI 318-19 21.2.1)
- "Compression-controlled" failure is sudden and catastrophic
  - Concrete crushes before steel yields
  - $\varepsilon_t \leq \varepsilon_{ty}$
  - $\varphi = 0.65$ (ACI 318-19 21.2.1)



Pedagogical Methods

- Combination of methods
  - Lecture
  - Active learning – think-pair-share, physical artifacts
  - Experiential learning – demonstrations and laboratory exercises
  - Creative Analogies – “transfer of learning” leverage familiarity with stories and fairy tales
- Should address multiple learning styles
- Depends on the course context

Presentation of Theory (lecture)

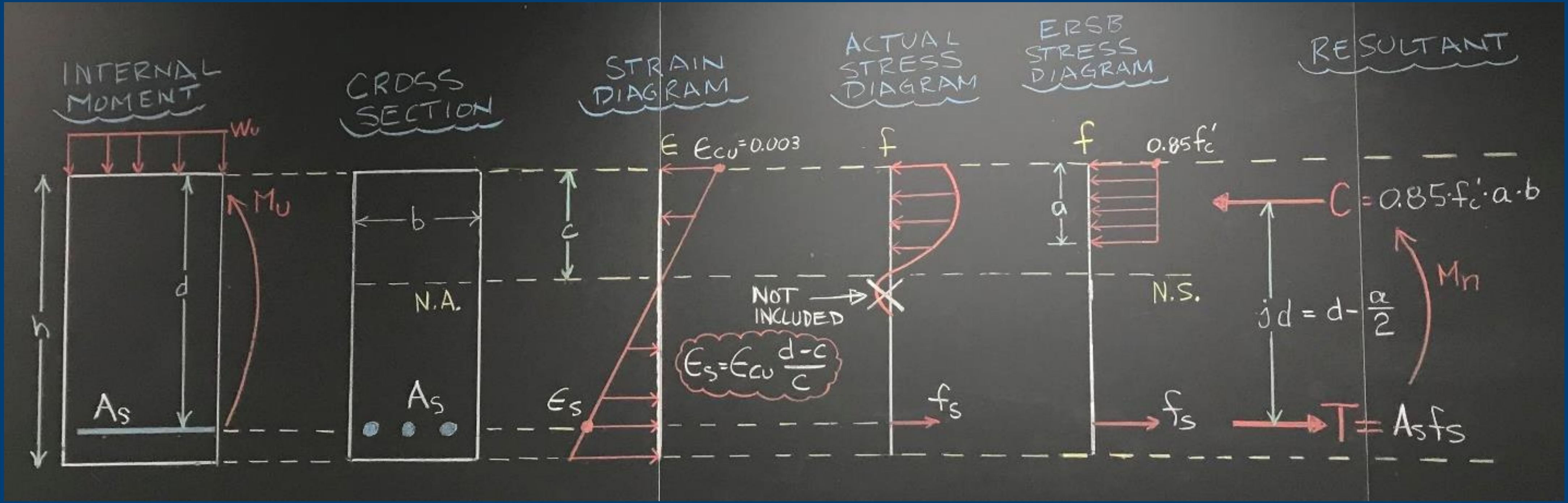
- Preparation time: 3-4 hours
- Activity time: approx. 1 hour of class time
- Start with homogenous beams and work to reinforced concrete
  - “Plane sections remain plane” – linear strain distribution
  - Neutral axis location – internal equilibrium
- Combine with physical models

Presentation of Theory (lecture)

- Required assumptions
  - Ultimate concrete strain, ε_{cu} is 0.003 (ACI 22.2.2.1)
  - Concrete tensile strength is not included (ACI 22.2.2.2)
  - Reinforcing steel behaves in an elasto-plastic manner (ACI 22.2.3.2)
  - Perfect bond between the steel and concrete
  - The Equivalent Rectangular Stress Block (RSB) (ACI 22.2.2.4)

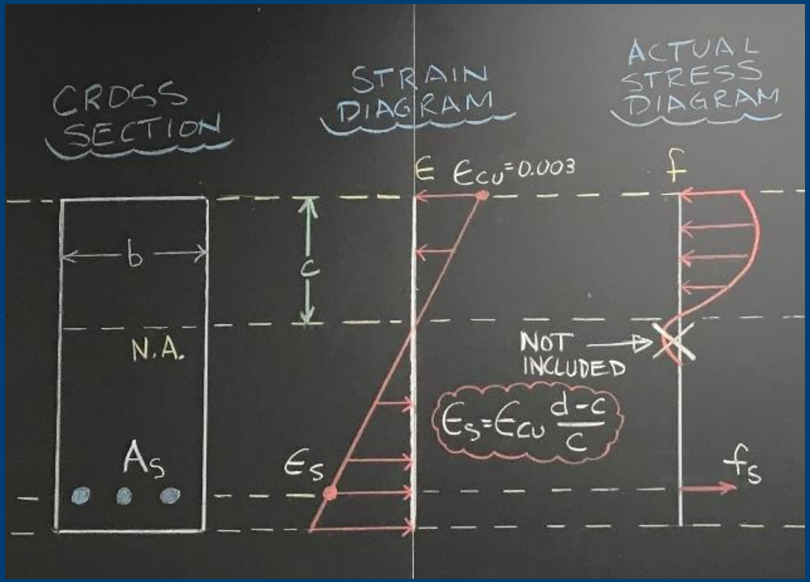
Presentation of Theory (lecture)

- Internal forces



Presentation of Theory (lecture)

- Moment capacity based on internal forces
  - $a = \frac{A_s f_y}{0.85 f_c' b}$
  - $M_n = A_s f_y \left(d - \frac{a}{2}\right)$
- Steel strain determined from similar triangles
  - $\frac{\varepsilon_{cu}}{c} = \frac{\varepsilon_s}{(d-c)}$
  - $a = \beta_1 c$ (ACI 22.2.2.4.1)
  - Used to determine failure mode and φ
- $\varphi M_n \geq M_u$



In-class Problem Solving (active learning)

- Preparation time: 4-6 hours
- Activity time: 2-3 hours of class time
- Progression of example problems to illustrate the concept
  1. Rectangular beam with “tensioned controlled” failure
  2. Rectangular beam with $\varepsilon_t \leq \varepsilon_{ty} + 0.003$ and $\varphi < 0.90$
  3. Rectangular beam with “compression-controlled” failure ($\varepsilon_t \leq \varepsilon_{ty}$)
  4. Rectangular beam with compression reinforcement
  5. T-beam with same conditions as Problem 1

In-class Problem Solving (active learning)

- Problem 1 can be used for inductive presentation
- Can use active learning strategies (best for problems 2 and 3)
  - Think-pair-share
  - Individual student work
- Students need to have the Code available

Analogies and Thought Experiments (creative analogies)

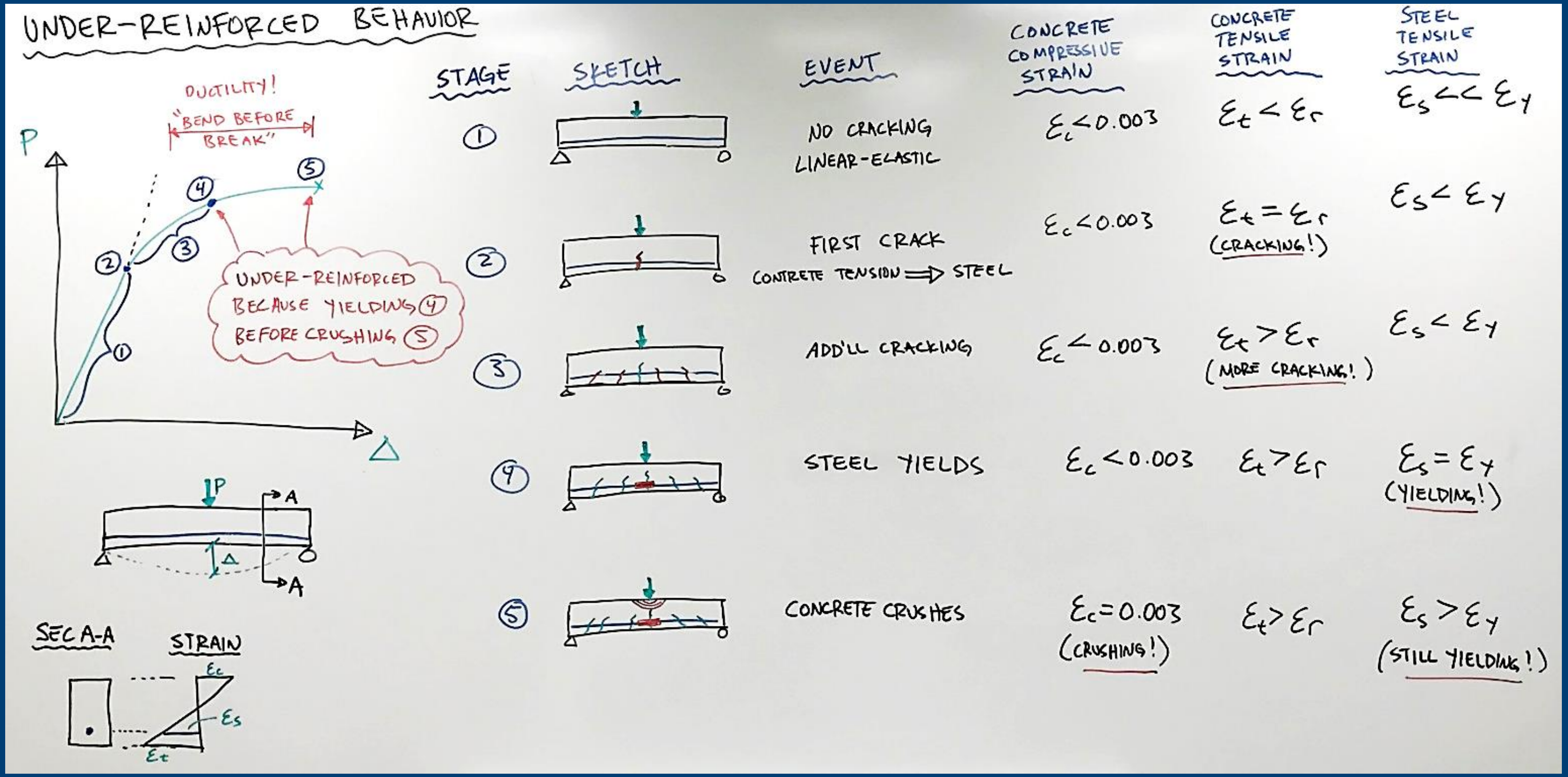
- Preparation time: 60 minutes
- Activity time: 50-75 minutes of class time
- Based on *Goldilocks and the Three Bears*
- Learning objectives
  - **Explain** the failure behavior of a reinforced concrete beam with "just right" amount of reinforcement
  - **Describe** reinforced concrete flexural behaviors associated with having too little and too much steel reinforcement
  - **Define** *over-reinforced*, *under-reinforced*, and *critically under-reinforced*

Analogies and Thought Experiments (creative analogies)

1. Tell the story of *Goldilocks and the Three Bears*
   - Make it interesting: “Bald-i-locks” at Clemson
   - Have students help
   - Emphasize the extremes of porridge, chair, and bed
   - Goldilocks’s preference for “just right” is analogous to selecting flexural reinforcement
2. Dispel misconception of “under-reinforced” being a bad thing
   - Use different terminology (tension controlled)
   - Have students vote

Analogies and Thought Experiments (creative analogies)

3. Show “just right” load-displacement response on the board

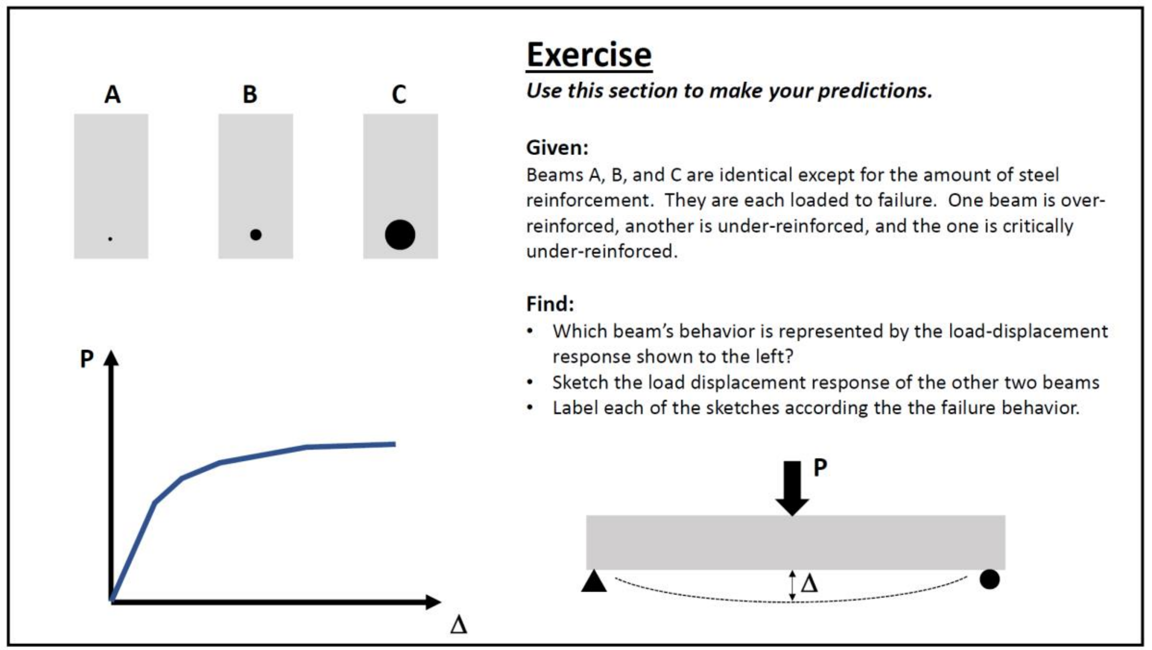


Analogies and Thought Experiments (creative analogies)

4. Define the failure modes in an accessible way
   - **Under-reinforced (tension-controlled)**: A beam in which steel reinforcement yields prior to concrete crushing in compression. This is the "just right" amount of reinforcement.
   - **Over-reinforced (compression-controlled)**: A beam in which the steel reinforcement does not yield before the concrete crushes. This happens when there is too much reinforcement.
   - **Critically under-reinforced**: A beam in which the steel reinforcement does not have capacity to support the tension force which causes the concrete to crack. This happens when there is too little reinforcement.

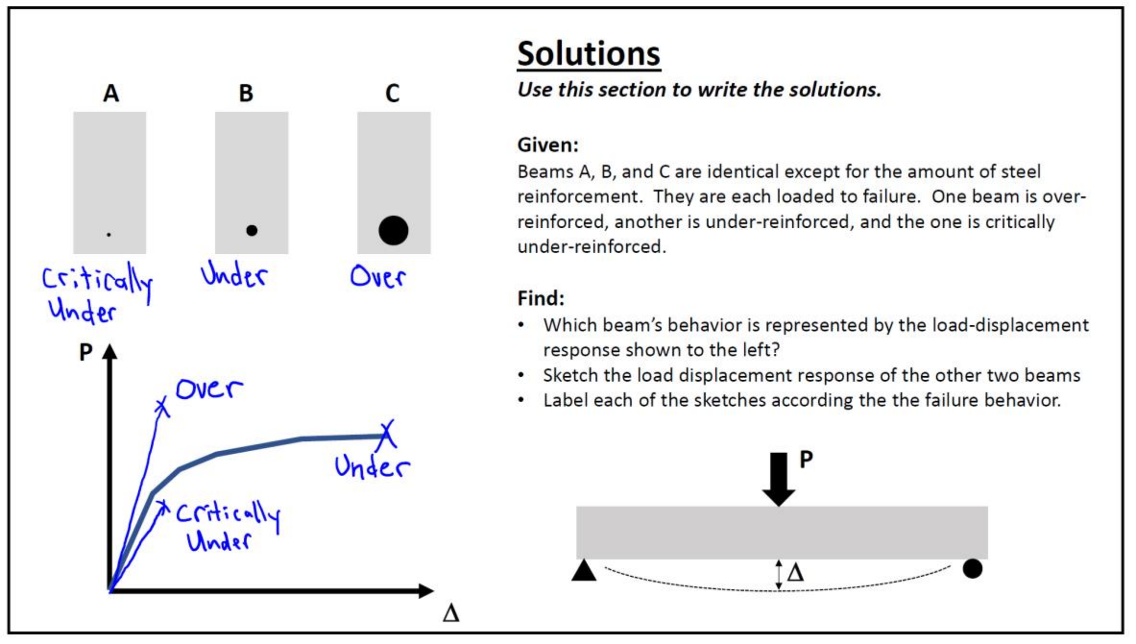
Analogies and Thought Experiments (creative analogies)

5. Thought experiment
    - Students given a handout and asked to draw load-displacement for over-reinforced and under-reinforced



Analogies and Thought Experiments (creative analogies)

5. Thought experiment
   - Provide correct curves and give students a clean copy to record them
   - Note the lack of ductility



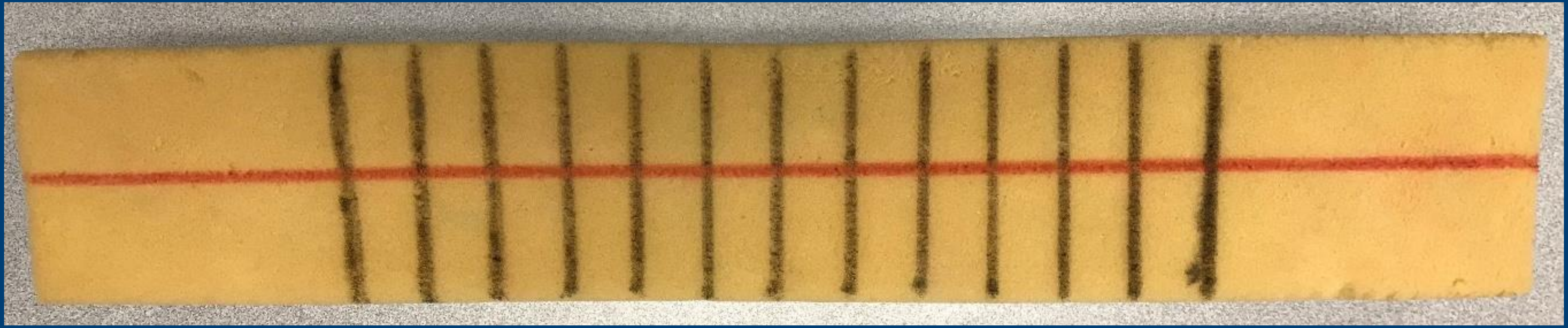
Analogies and Thought Experiments (creative analogies)

6. Assessments
   - Use learning objectives as test questions
   - Explain a beam failure scenario and have students interpret

   "You are assigned to investigate a failure that occurred in a simple span reinforced concrete floor beam. The beam failed suddenly at relatively small loads. Evidence collected from the failure showed the beam had very little reinforcement and failed immediately upon the first crack forming in the concrete. The first crack was located near midspan on the tension (bottom) side of the beam. What type of failure is this? Your answer should use the terminology discussed in lecture. What could the original designer have changed in order to prevent this type of failure?"

Physical Models (active learning)

- Foam Beam
- Preparation time: 15 – 30 minutes
- Activity time: 5 minutes
- Materials at local craft store



Physical Models (active learning)

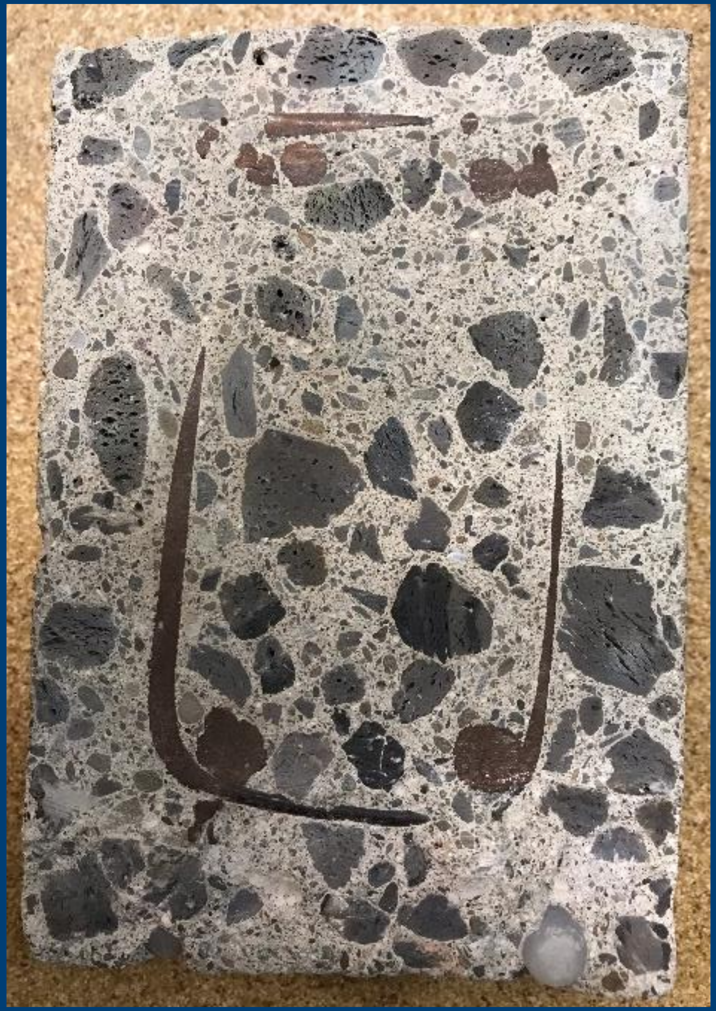
- Steel Samples
- Preparation time: 10 – 20 minutes
- Activity time: 5 – 10 minutes
- Available at conferences, CRSI, research, hardware store

Physical Models (active learning)

- Concrete Cylinders
- Preparation time: 60 – 90 minutes
- Activity time: 5 – 15 minutes
- Cylinders and video of testing
- Illustrate compressive strength and brittle failure

Physical Models (active learning)

- Beam Cross-Section
- Preparation time: 1 – 3 hours
- Activity time: 5 – 15 minutes
- Previous research or specifically cast and cut
- Visual cue for drawn diagrams



Physical Models (active learning)

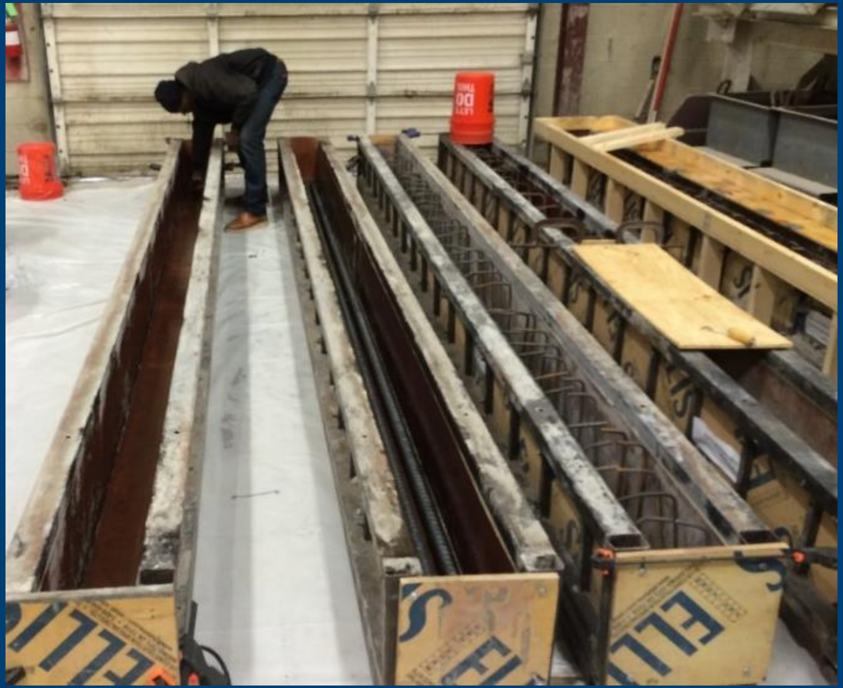
- Small-Scale (2 in. x 2 in.) Beams
- Preparation time: 2 – 4 hours
- Activity time: 15 – 30 minutes
- Plain mortar or reinforced with threaded rod

Laboratory Exercise (experiential learning)

- Activity time: 10 – 12 hours total
  - Student teams design for a failure mode (or are assigned a design)
  - Construct and test in the lab
  - Can be adjusted to available facilities
  - Students write a report with prediction and observations

Lab Group	Failure/Behavior Type	Minimum Load	ACI 318 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

Laboratory Exercise (experiential learning)



Laboratory Exercise (experiential learning)

Lessons Learned

- Three rules for classroom demonstrations
  1. Keep demonstrations simple
  2. Make demonstrations quick
  3. Make it memorable (think Goldilocks)
- Student comments indicate a laboratory experience (or at least photos) is very helpful
- Students need perspective on rebar size, spacing, congestion, etc.
- Be willing to try new things, but not too many at once
- Ask for feedback on new activities

THANK YOU!

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