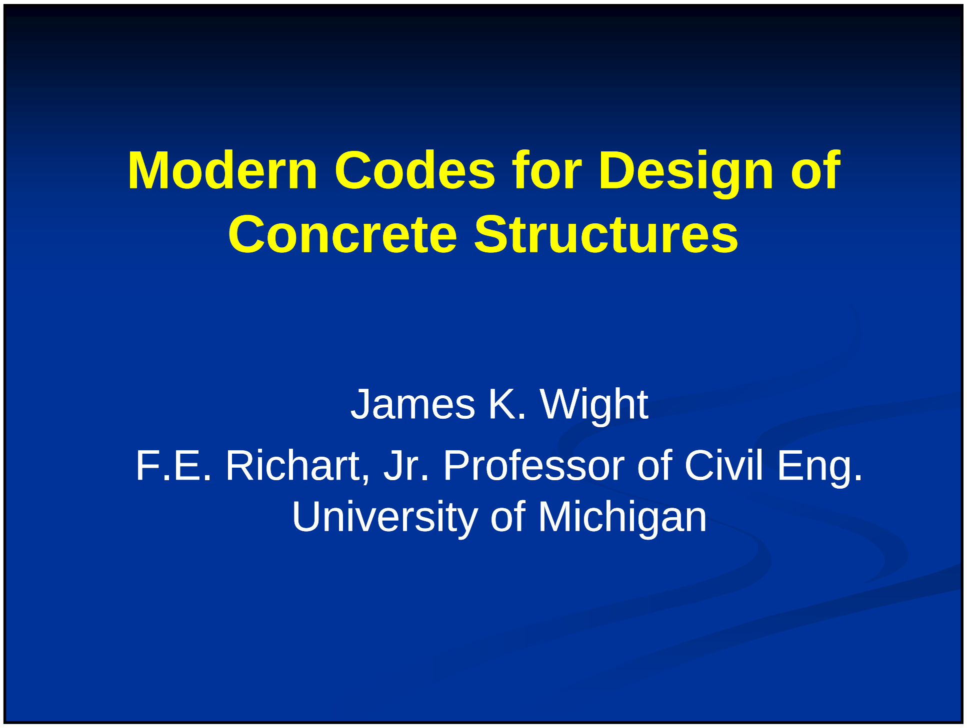

Modern Codes for Design of Concrete Structures

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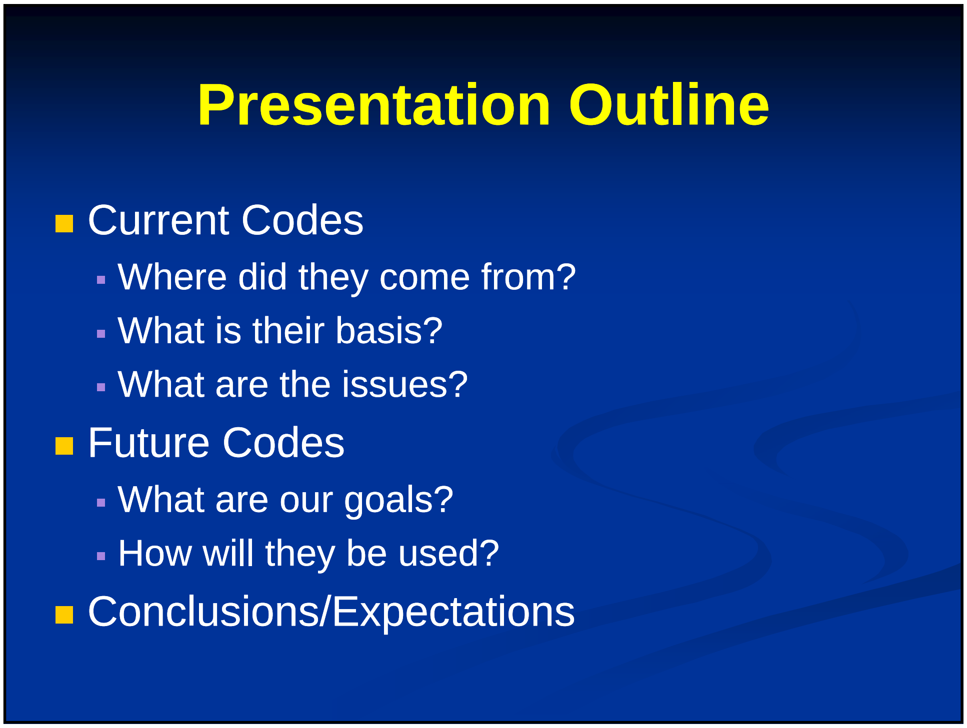
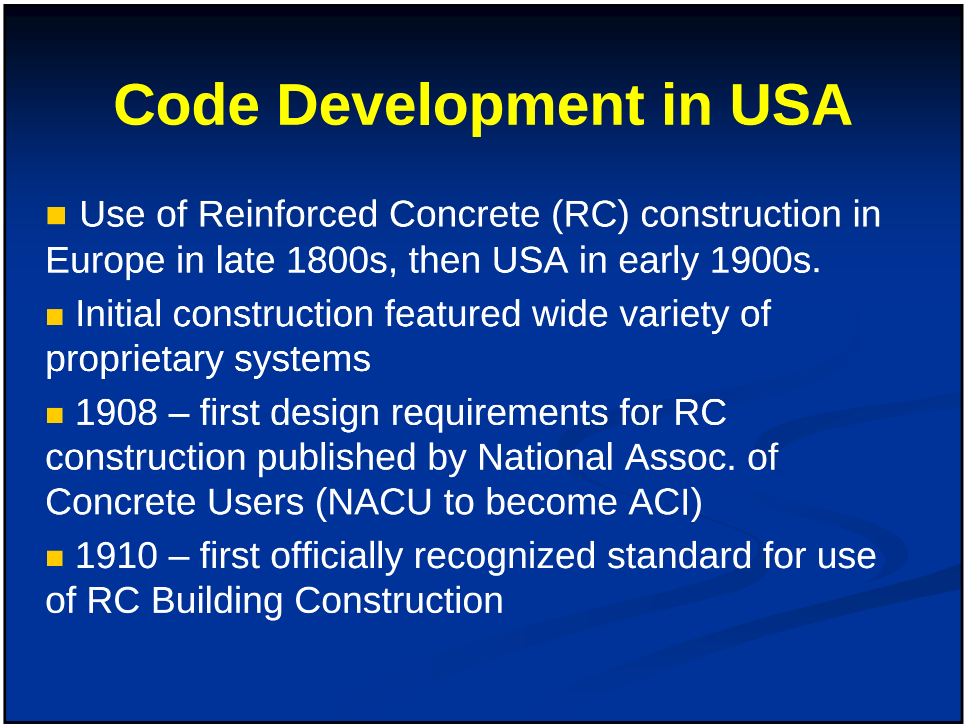


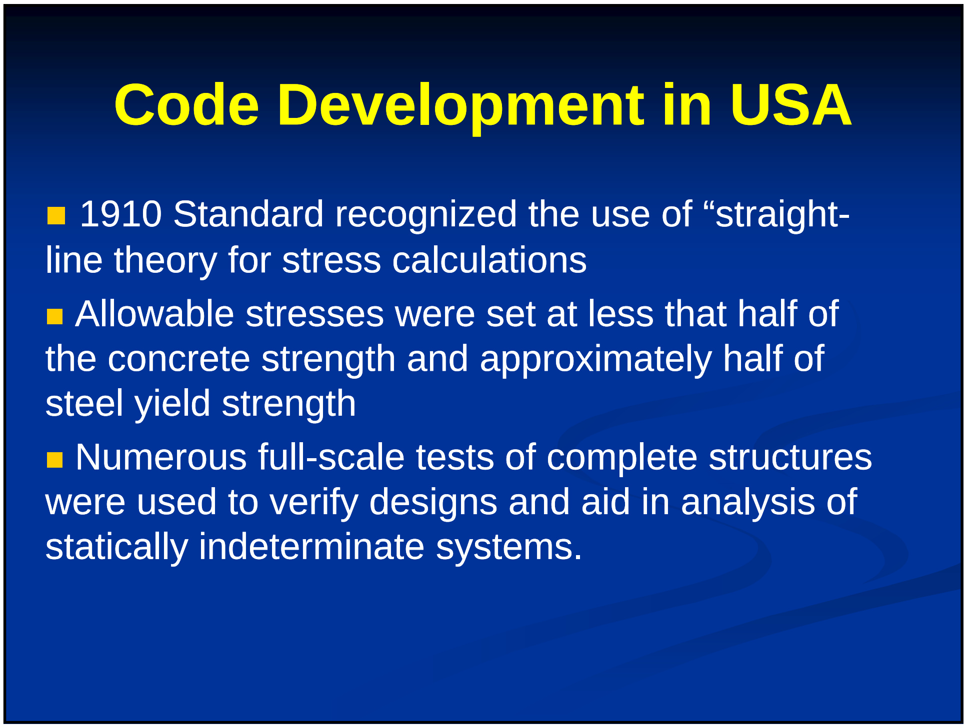
Presentation Outline

- Current Codes
  - Where did they come from?
  - What is their basis?
  - What are the issues?
- Future Codes
  - What are our goals?
  - How will they be used?
- Conclusions/Expectations



Code Development in USA

- Use of Reinforced Concrete (RC) construction in Europe in late 1800s, then USA in early 1900s.
- Initial construction featured wide variety of proprietary systems
- 1908 – first design requirements for RC construction published by National Assoc. of Concrete Users (NACU to become ACI)
- 1910 – first officially recognized standard for use of RC Building Construction



Code Development in USA

- 1910 Standard recognized the use of “straight-line theory for stress calculations
- Allowable stresses were set at less that half of the concrete strength and approximately half of steel yield strength
- Numerous full-scale tests of complete structures were used to verify designs and aid in analysis of statically indeterminate systems.

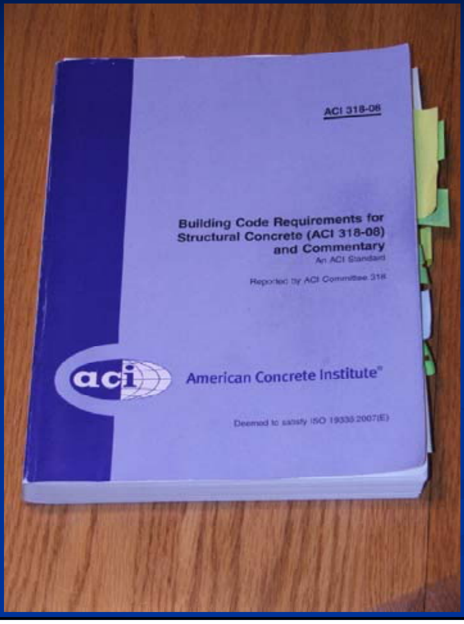
Code Development in USA

- Parallel effort on development of specifications organized by “Joint Committee” with representatives from ASCE, ASTM, AREA, PCA and NACU(ACI)
- 1916 – First Joint Comm. Report was issued; later called a standard specification
- 1920 – Second Standard Building Requirements for RC Const. from ACI
- 1928 – Reinforced Concrete Building Regulations and Specifications (combined effort)

Code Development in USA

- Code updated by ACI Committee every six to ten years based on Working Stress Design (WSD)
- 1941 Code was regarded as first modern and relatively complete standard
- 1963 Code introduced an option for Ultimate Strength Design (USD) and the first commentary
- 1971 Code for first full USD Code
- ACI Code has been periodically updated (6-yr. intervals) and expanded over the last 40 years without a significant change of format

Features of Current ACI Code



Features of Current ACI Code

- Twenty-two chapters plus four (two) appendices
- Used for all concrete construction: RC, PC, and plain concrete; either precast or cast-in-place.
- Includes materials specifications; construction tolerances; analysis and design requirements; special structural systems; and earthquake resistant design requirements
- Primary design limits states are for strength and serviceability
- Reliability-based load and resistance factors with some behavior-based strength reduction factors

Issues with Current ACI Code

- Too long and too complicated (it should be simplified)
- Prescriptive provisions as opposed to performance-based
- More behavior-based or capacity-based load and resistance factors
- Go an electronic format
- Include options for new materials, e.g. high-performance and ultra high-strength concretes

Issues with Current ACI Code

- Does not adequately address durability (sustainability); This is the third "S", strength, safety and serviceability.
- Does not address reparability; deconstructability; life-time CO_2 consumption.

Issues with Any Modern Code

- Whenever possible, base code provisions on scientifically sound mechanical models.
- If required, empirical constants or simplifying assumptions must be a clear as possible.
- If possible, define member behavior and standardize principles, not complex procedures.
- Good code provisions result from the combination of knowledge from two sources, research and practice (not an easy mixture)

Issues with Any Modern Code

- Codes must define minimum standards, but not over-specify and thus inhibit a designer's options.
- With the demands for codes to be more comprehensive, we need to avoid having them become too complex.
- Brevity and completeness are incompatible; usually brevity is lost when there is a conflict.
- Building codes must incorporate uncertainties and the effects of uncertainties in a rational manner.

Issues with Any Modern Code

- Tension between scientific theory and engineering judgment
  - Scientific theory offers elegant solutions that may not produce clear answers for real-world problems.
  - Engineering judgment is an invaluable asset, but limits on use of judgment must be defined.
- Code writing must involve government agencies to represent the public because a building code is a social contract based on acceptable risk.

Code Simplification ?

- “Everything should be made as simple as possible, but no simpler” (Albert Einstein)
- Simple; Reliable; Economical – you can have any TWO of these.
  - Usual choice is for reliable and economical, and thus, codes are not simple.
  - Some engineers/owners may want a reliable structure with a simple design, but it will not be cheap.
  - Simple and economical, i.e. not reliable, is not an acceptable option.

Code Simplification ?

- Two-tiered code has been suggested; simple code for common structures and complex code for special structures.
- The scope and applicability of a simple code would need to be very clearly defined in terms of material properties and types of structures.
  - This has been discussed; not easily achieved.
  - If a problem developed in a “common” structure, would the engineer be liable for damages if he/she knew that a more comprehensive code existed?

Performance-based Code ?

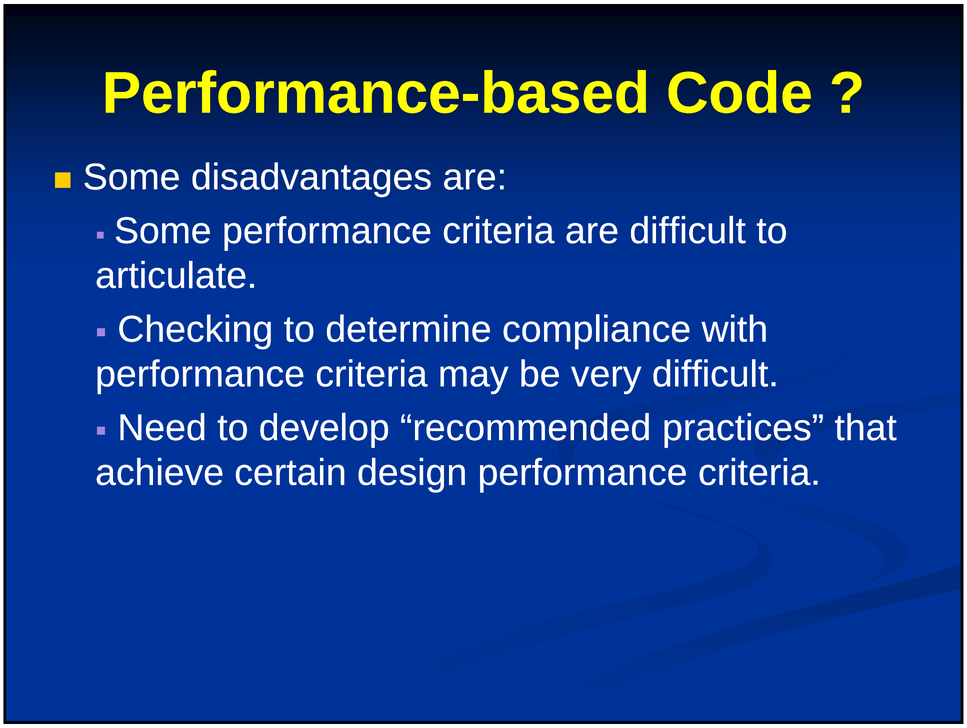
- Performance-based codes would define “what to do” as opposed to saying “how to do it”. This would give designers a wider set of options.
- A performance-based code would probably need to be supported by prescriptive minimum requirements.
- Would also need a separate document with recommended practices that satisfy the performance requirements.

Performance-based Code ?

- Performance standards are good for “products”, but less applicable for “structures” because each one is a unique product.
- A performance standard must define:
  - A performance objective relative to the intended use of a product.
  - The level of performance to be achieved by the product under a defined set of conditions.

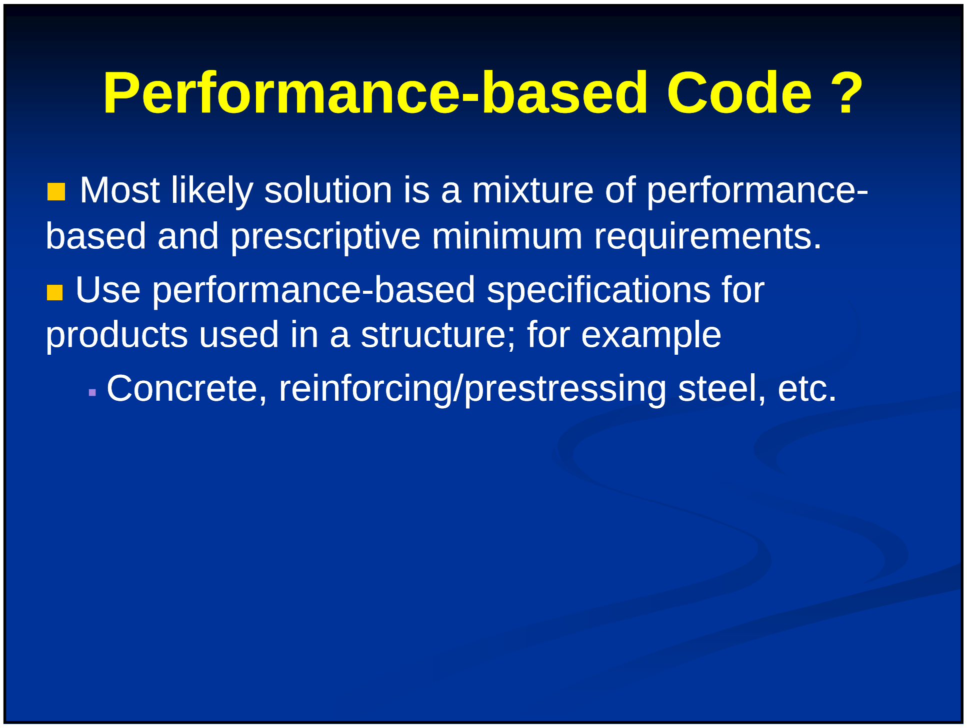
Performance-based Code ?

- Some advantages of performance-based code requirements are:
  - fewer restrictions placed on innovations in design and analysis procedures.
  - could allow more efficient (economical) designs
  - simplification of code language.



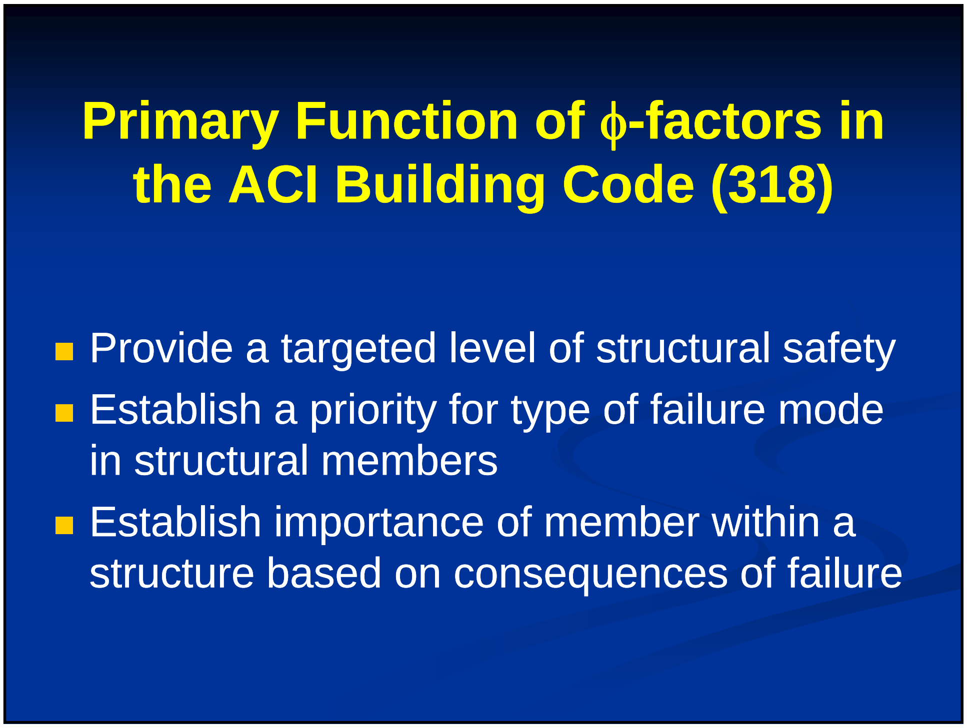
Performance-based Code ?

- Some disadvantages are:
  - Some performance criteria are difficult to articulate.
  - Checking to determine compliance with performance criteria may be very difficult.
  - Need to develop “recommended practices” that achieve certain design performance criteria.



Performance-based Code ?

- Most likely solution is a mixture of performance-based and prescriptive minimum requirements.
- Use performance-based specifications for products used in a structure; for example
  - Concrete, reinforcing/prestressing steel, etc.



Primary Function of ϕ-factors in the ACI Building Code (318)

- Provide a targeted level of structural safety
- Establish a priority for type of failure mode in structural members
- Establish importance of member within a structure based on consequences of failure

Targeted Level of Structural Safety

- Load and ϕ-factors for strength design were tuned to obtain member designs similar to those from WSD
- Statistics were developed for loads and material properties for use in standard structural reliability calculation procedures
- The target structural reliability index, β, was set to be at or above 3.5

Establish Member Failure Priority Based on Type of Failure

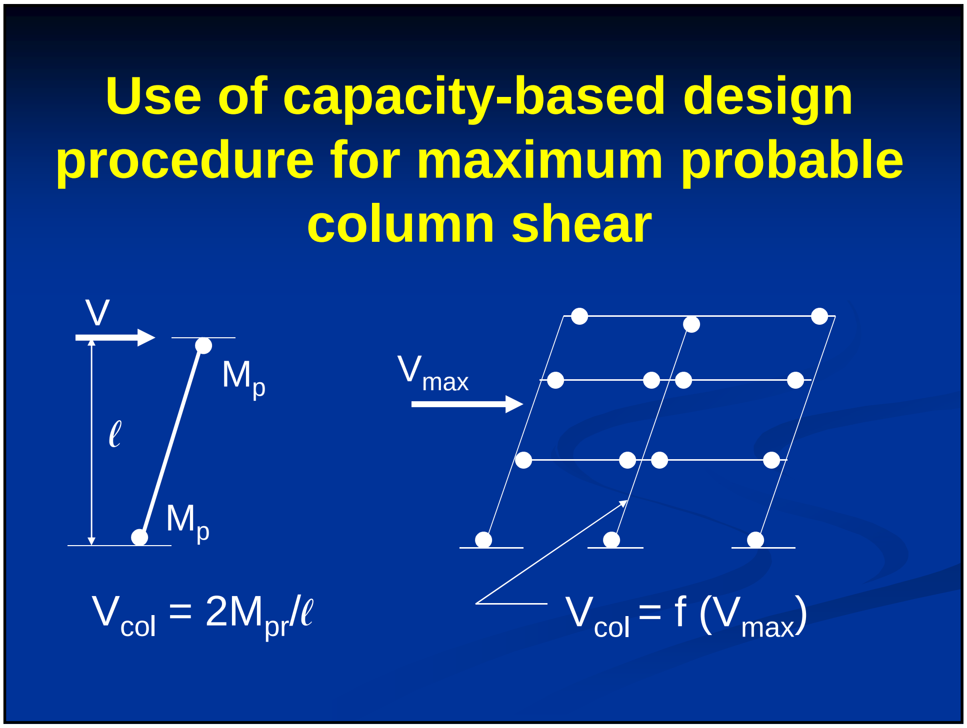
- Ductile failure mode is preferred over a brittle failure mode
- Beam flexural design should result in a ductile (tension-controlled) failure mode; Use $\phi = 0.90$
- To lower the probability of a brittle shear failure, beam shear design uses $\phi = 0.75$

Establish Member Failure Priority Based on Consequences of Failure

- Axial load and flexure, ϕ = 0.9 for beams and ϕ = 0.65 tied columns (or 0.75 for spiral columns.
- Essentially results in a higher structural reliability index for columns.

Do current ϕ-factors correctly effect potential failure modes?

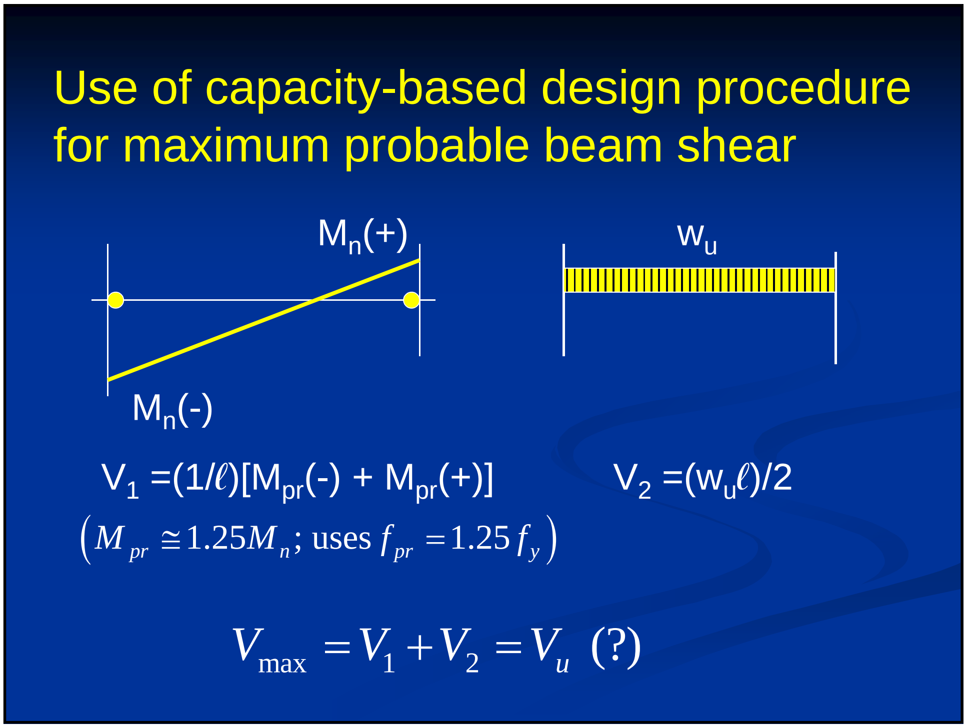
- Should we use a capacity-based design procedure (mechanism analysis) to establish a preferred priority of flexure vs. shear failure modes?
- If yes, should we modify (increase) the ϕ-factors for shear?
- A precedent exists in seismic design procedures in ACI Code Chapter 21



Use of capacity-based design procedure for maximum probable column shear

$V_{col} = 2M_{pr}/\ell$

$V_{col} = f\ (V_{max})$



Use of capacity-based design procedure for maximum probable beam shear

$V_1 = (1/\ell)[M_{pr}(-) + M_{pr}(+)]$

$V_2 = (w_u\ell)/2$

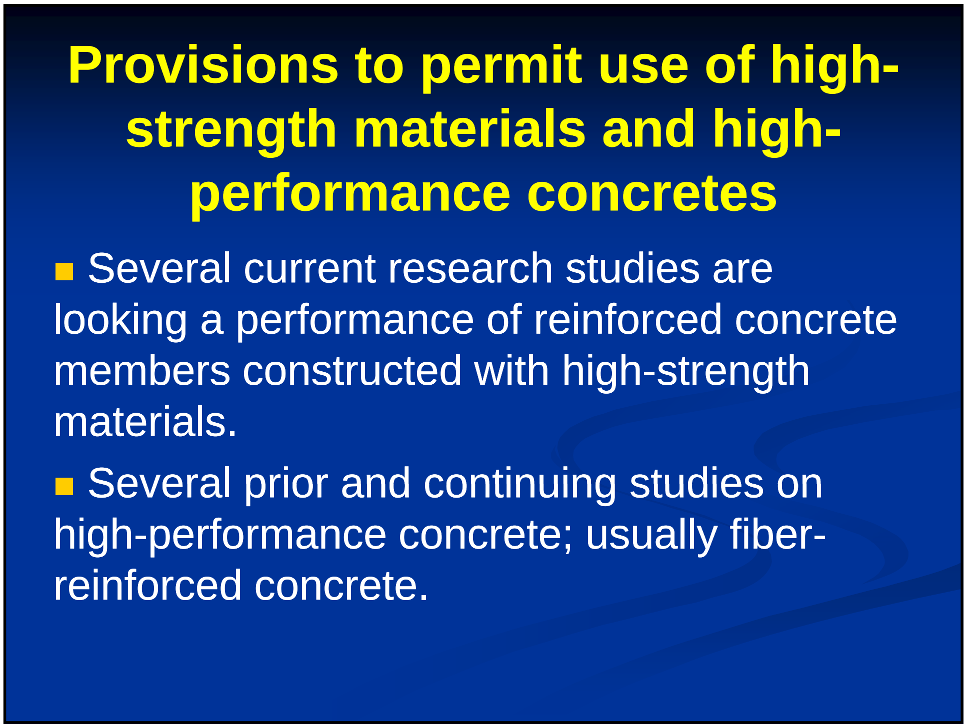
$\left(M_{pr} \cong 1.25 M_n;\ \text{uses } f_{pr} = 1.25 f_y\right)$

$$V_{\max} = V_1 + V_2 = V_u \ \ (?)$$

Should we use the normal strength requirement for shear design?

$$\phi V_n \geq V_u$$

If yes, what value should we use for ϕ?

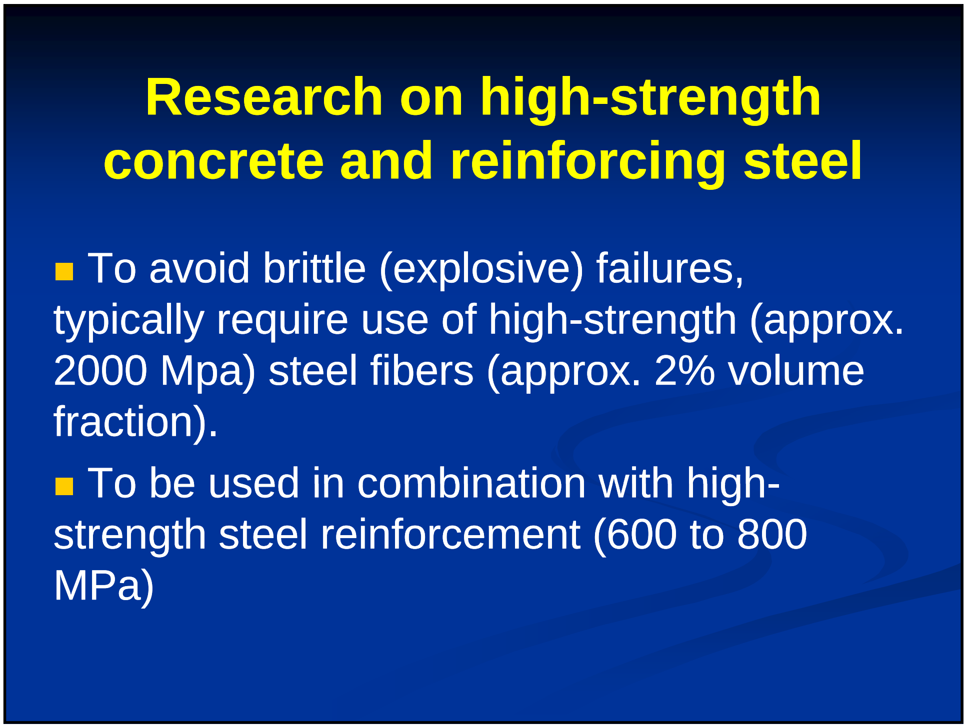


Provisions to permit use of high-strength materials and high-performance concretes

- Several current research studies are looking a performance of reinforced concrete members constructed with high-strength materials.
- Several prior and continuing studies on high-performance concrete; usually fiber-reinforced concrete.

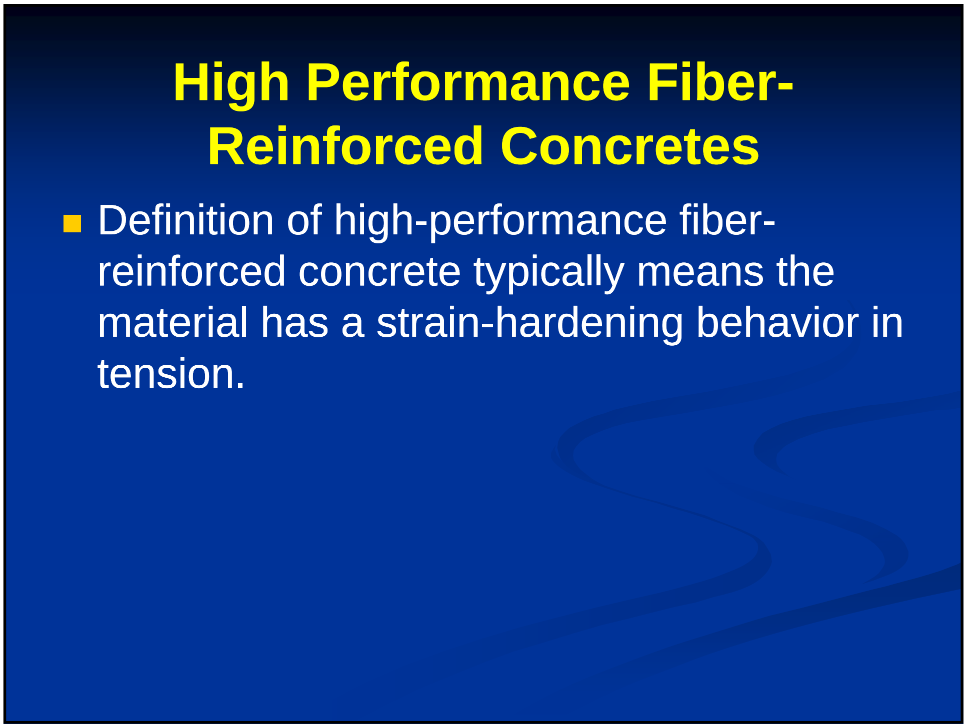
Research on high-strength concrete and reinforcing steel

- Current investigations in Europe, North America and Japan on ultra-high-strength concrete (150 MPa and higher).
- Requires very dense packing of sand and cement particles and typically results in a flowable, self-consolidating mixture.



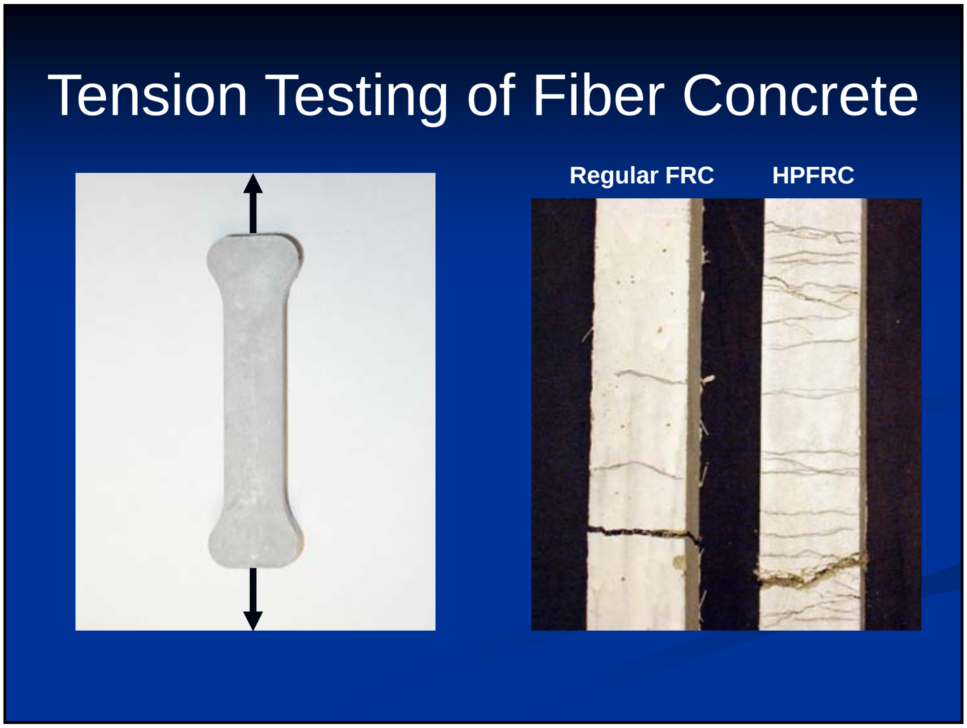
Research on high-strength concrete and reinforcing steel

- To avoid brittle (explosive) failures, typically require use of high-strength (approx. 2000 Mpa) steel fibers (approx. 2% volume fraction).
- To be used in combination with high-strength steel reinforcement (600 to 800 MPa)

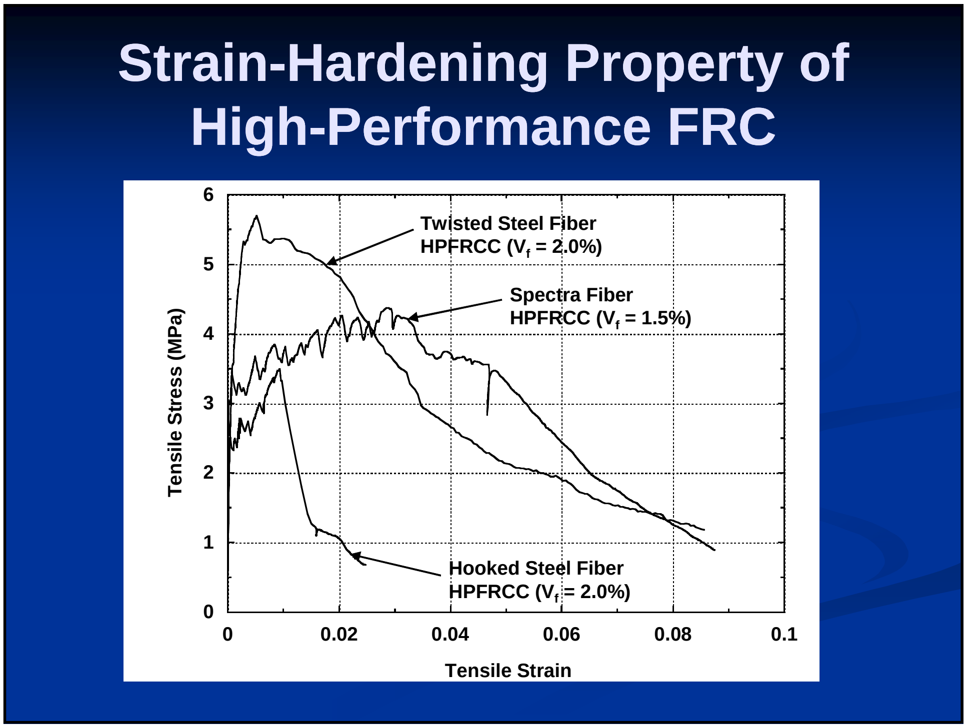


High Performance Fiber-Reinforced Concretes

- Definition of high-performance fiber-reinforced concrete typically means the material has a strain-hardening behavior in tension.

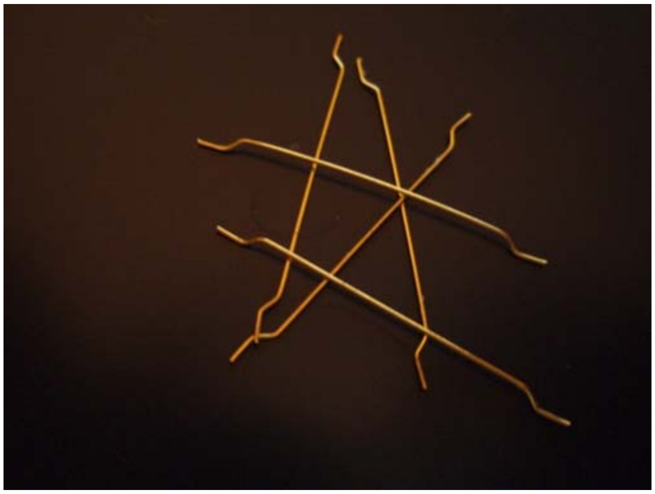


Tension Testing of Fiber Concrete



Strain-Hardening Property of High-Performance FRC

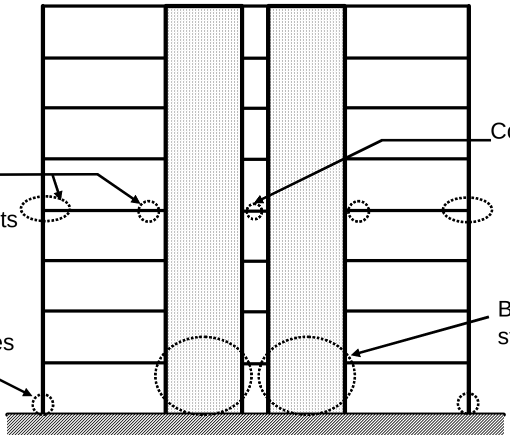
Example of hooked fibers



Earthquake-Resistant Design Applications

- The ductility and stiffness retention of HPFRC members under inelastic load reversals make them an excellent candidate for use in earthquake-resistant design of reinforced concrete buildings.

Potential locations for use of HPFRC



Coupling beams

Plastic hinges at beam ends and beam-column joints

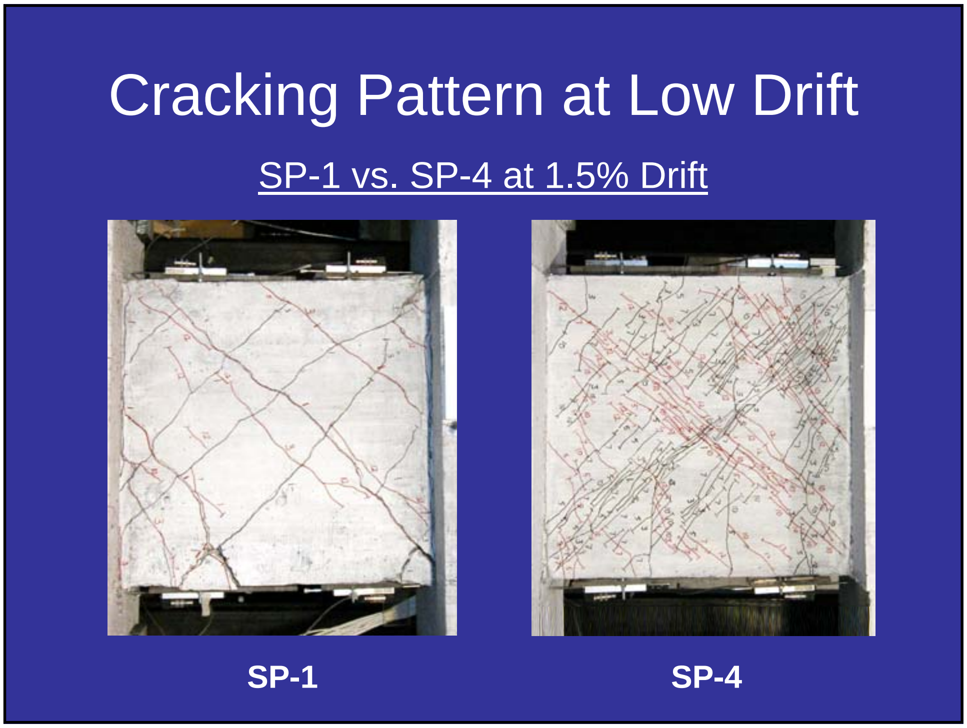
Base of structural walls

Plastic hinges at column bases

Construction Issues

Research Objectives

- Investigate the use of precast HPFRC coupling beams in earthquake-resistant coupled wall systems
- Reduce transverse and diagonal reinforcement requirements in coupling beams
- Develop information on shear strength and damage tolerance of HPFRC members subjected to large displacement reversals



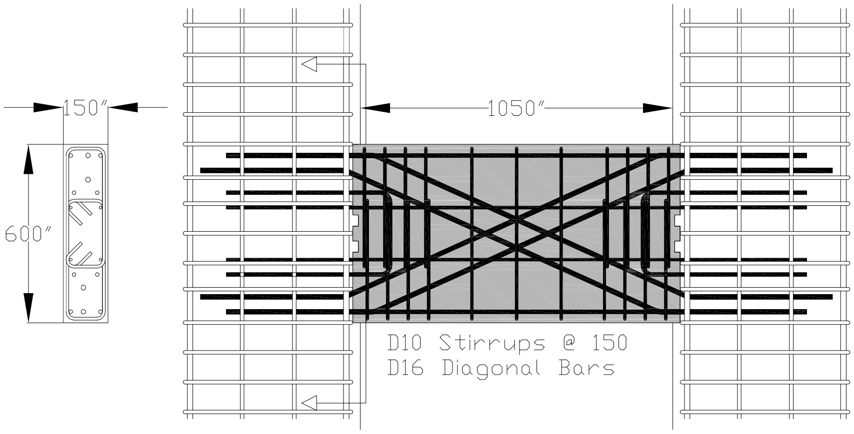
Cracking Pattern at Low Drift

SP-1 vs. SP-4 at 1.5% Drift

SP-1 **SP-4**

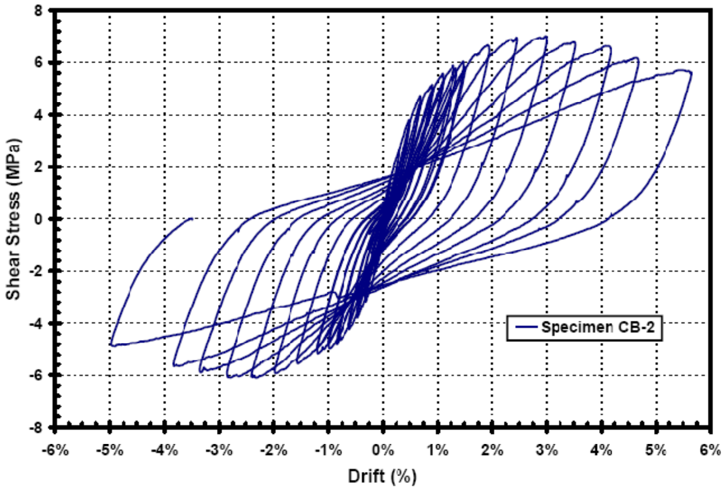
Construction of Coupled Wall System

CB-2 design (L/d = 1.75)

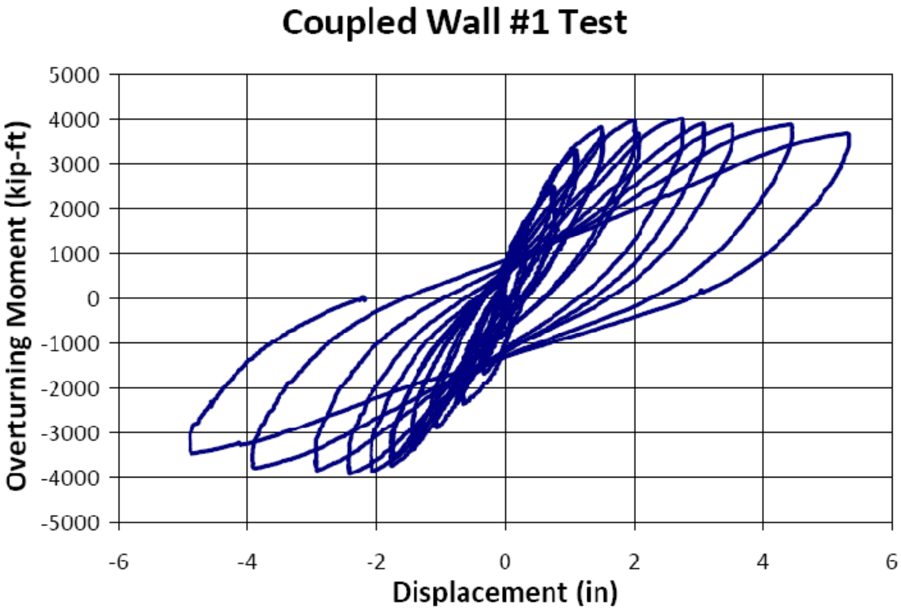


Precast Coupling Beam

CB-2 behavior



Four story coupled-wall specimen



Electronic Format:
Example of shear strength

$$V_n = V_c + V_s$$

$$V_c = 0.17\lambda\sqrt{f_c'}\, b_w d$$

Lightweight Agg. Conc.?

Yes or No $(\lambda = 1)$

Electronic Format:
Example of shear strength

Type of Lightweight Conc.

Sand-lightweight (λ=0.85)

All-lightweight ($\lambda = 0.75$)

$$V_c = 0.145\sqrt{f_c'}\, b_w d$$

Electronic Format:
Example of shear strength

Axial load effects?

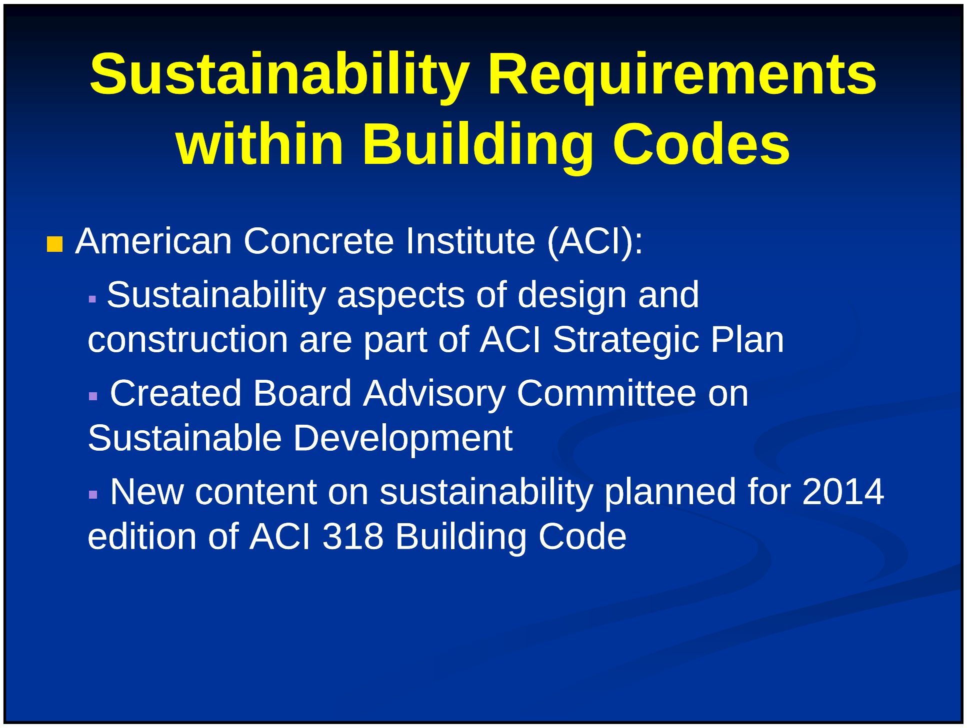
Compression?

Tension?

Electronic Format:
Example of shear strength

$$V_c = 0.145\left(1+\frac{N_u}{14A_g}\right)\sqrt{f_c'}\,b_w d$$

Where N_u/A_g has units MPa

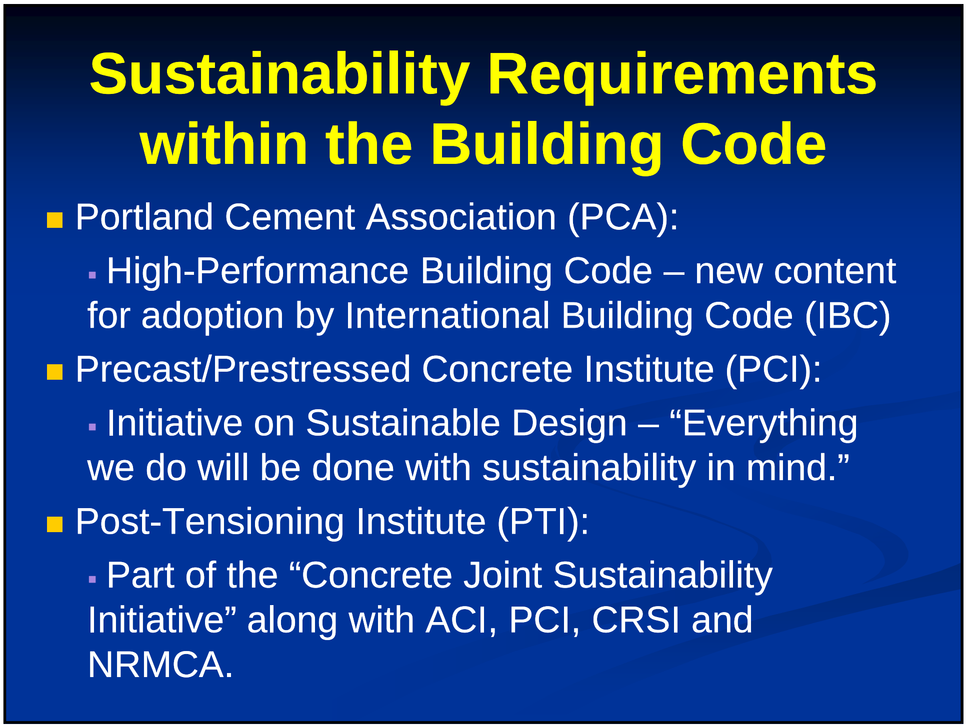


Sustainability Requirements within Building Codes

- American Concrete Institute (ACI):
  - Sustainability aspects of design and construction are part of ACI Strategic Plan
  - Created Board Advisory Committee on Sustainable Development
  - New content on sustainability planned for 2014 edition of ACI 318 Building Code

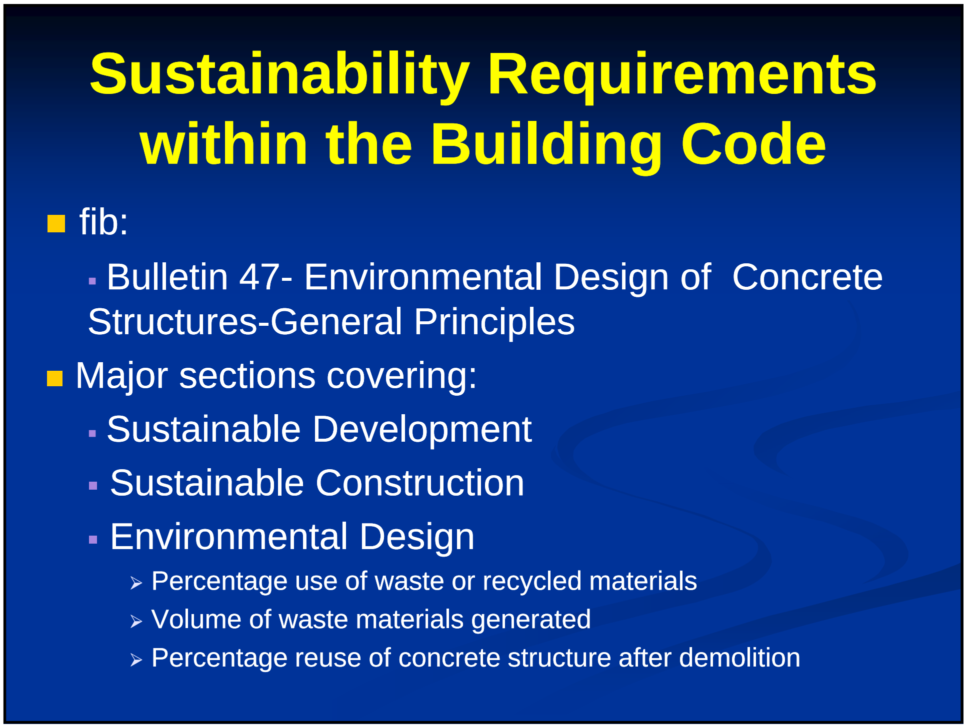
Sustainability Requirements within Building Codes

- American Concrete Institute (ACI):
  - TC-71 SC8 to develop new ISO Standard on Concrete and Sustainability
  - Annual forums on Concrete Sustainability at ACI Conventions



Sustainability Requirements within the Building Code

- Portland Cement Association (PCA):
  - High-Performance Building Code – new content for adoption by International Building Code (IBC)
- Precast/Prestressed Concrete Institute (PCI):
  - Initiative on Sustainable Design – “Everything we do will be done with sustainability in mind.”
- Post-Tensioning Institute (PTI):
  - Part of the “Concrete Joint Sustainability Initiative” along with ACI, PCI, CRSI and NRMCA.



Sustainability Requirements within the Building Code

- fib:
  - Bulletin 47- Environmental Design of Concrete Structures-General Principles
- Major sections covering:
  - Sustainable Development
  - Sustainable Construction
  - Environmental Design
    - Percentage use of waste or recycled materials
    - Volume of waste materials generated
    - Percentage reuse of concrete structure after demolition

Conclusions/Expectations

- Need to establish a balance between performance-based and prescriptive provisions.
- Performance-based clauses will reduce some complexity, but there are real limits to simplification
- Will continue to use a combination of behavior-based and reliability-based load and resistance factors.
- Must be open to acceptance of new materials, including new high-performance and high-strength concretes.

Conclusions/Expectations

- Must more thoroughly address sustainability issues for the good or our industry and the good of the planet.
- Will evolve into an electronic format to fit into the working-style of the modern engineer.

Thank You