Concrete Properties Considerations

Best Practices in Dam and Levee Safety Risk Analysis

Part E – Concrete Structures

Chapter E-1

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US Army Corps of Engineers®

U.S. Department of the Interior Bureau of Reclamation

Department of Energy Federal Energy Regulatory Commission

TVA

Outline

- Objectives
- Key concepts
- Evolution of concrete technology
- Concrete modulus
- Concrete compressive strength
- Concrete tensile strength
- Concrete shear strength
- Using concrete properties in a risk assessment

Objectives

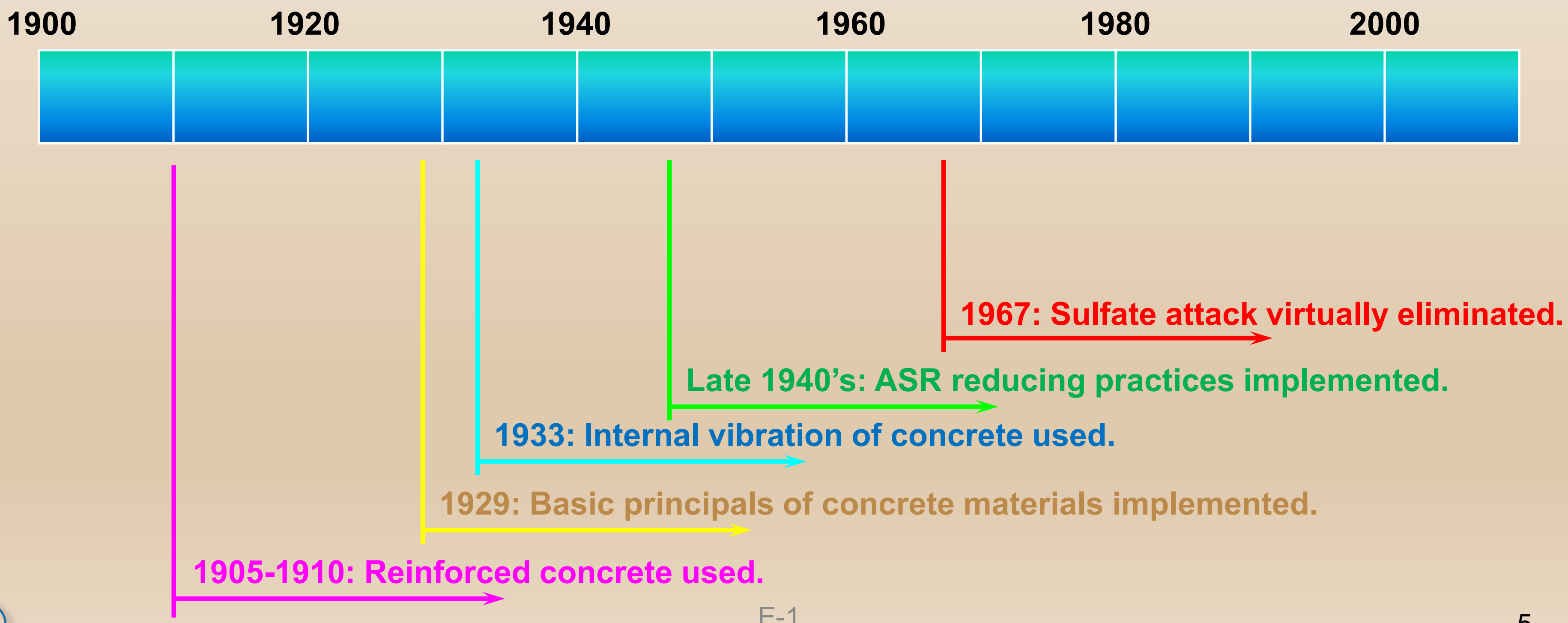
- Understand concrete properties that affect the evaluation of risk
- Understand how to select appropriate concrete properties for analysis and risk evaluation
- Understand conceptually how concrete properties will be used in a risk evaluation
- Note that this information was developed primarily for mass concrete, but may also be applicable for reinforced concrete

Key Concepts

- Concrete properties are needed to evaluate response of concrete structures to loading
- Risk analysis involves evaluating analysis results based on estimated in-situ properties, not design/code properties
- Mean values and variations can be important in understanding the probability of failure
- Compressive strength is typically not an issue, but many properties are correlated with compressive strength
- Tensile strength is often important, but currently no universally accepted method for determining – many factors are at play
- Shear strength is important for stability or shear evaluation, and is highly dependent on construction methods (joint clean up, placing, etc.)

Timeline for Historic Events in Concrete Construction

Timeline (sample of significant events)



Concrete Data For Risk Analysis

- Recent testing of cores
- Older core reports
- Field data from construction
- Construction information (materials/means/methods)
- Lab investigations from design

Concrete Modulus

- Stress-strain curves from standard lab tests typically used for dynamic loading
- 2/3 dynamic loading modulus typically used for static loading to account for long term creep
- Sensitivity analyses typically warranted to evaluate variability

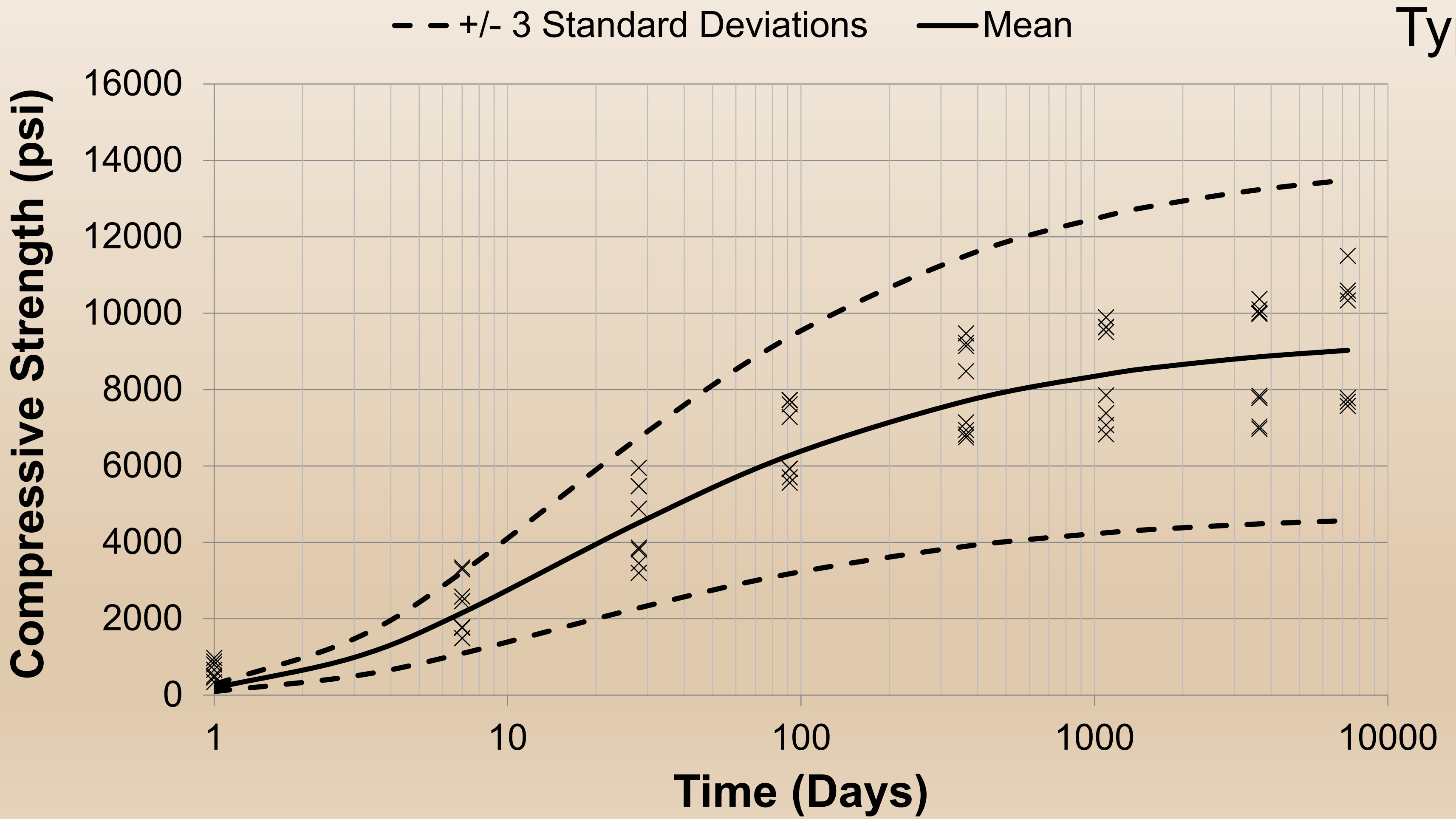
Concrete Compressive Strengths

Design Strength vs. In-Place Strength

- Design – f_c' means avg. of any 3 consecutive tests equal to or greater than specified value at 28 days and no tests less than 500 psi below specified value
- Design – to meet requirement, avg. strength typically f_c' + 1.34s (s= standard deviation)
- Strength gain beyond 28 days is significant
- Core tests typically higher than control cylinder tests (avg. ratio about 1.38 per USBR Concrete Manual from 136 comparisons)
- Therefore, using a design f_c' for risk analysis is typically too conservative

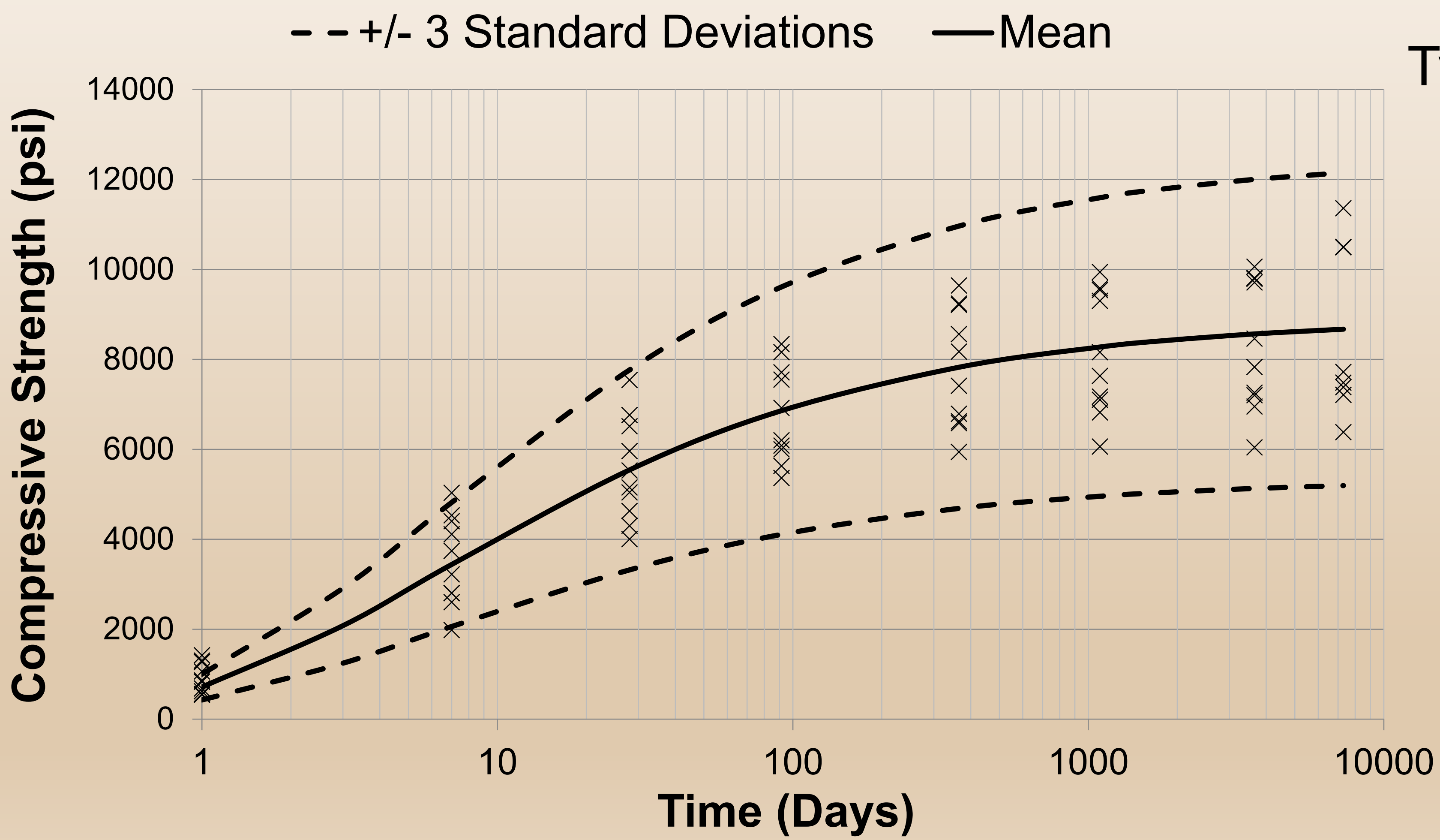
Concrete Strength Gain Beyond 28 Days

Type IV cement



Concrete Strength Gain Beyond 28 Days

Type II cement



Concrete Tensile Strength

Tensile Strength Concepts

- Tensile strength is often an important consideration for seismic analyses
- There are different ways to test for tensile strength, which typically produce different results
- Lift joint strength is typically less than parent concrete strength and often controls
- Most investigators have seen an increase in strength with increasing strain rate
- Cyclic fatigue may occur during dynamic loading above a threshold strength value
- Concrete stress-strain curves are nonlinear approaching failure – when using linear elastic analyses an apparent strength can be used
- Aggregate size and moisture conditions can affect the strength

Concrete Tensile Tests

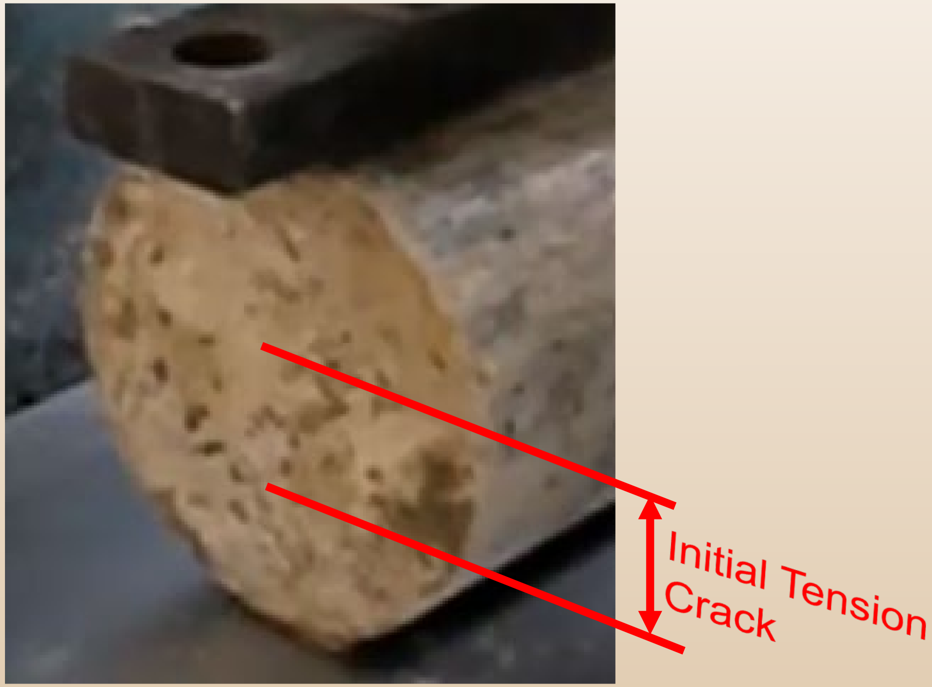
Splitting Tension

Flexure or Modulus of Rupture

Direct Tension

Direct Tension Test

Splitting Tension Test

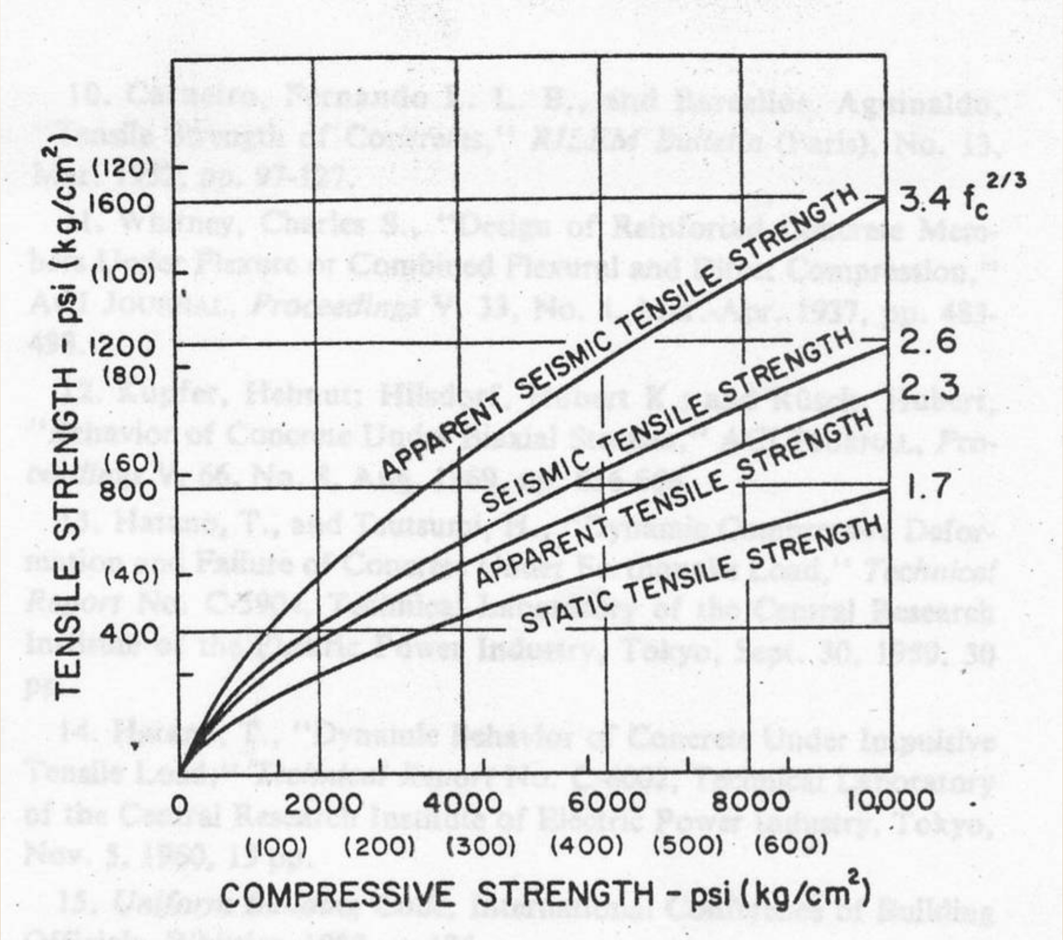


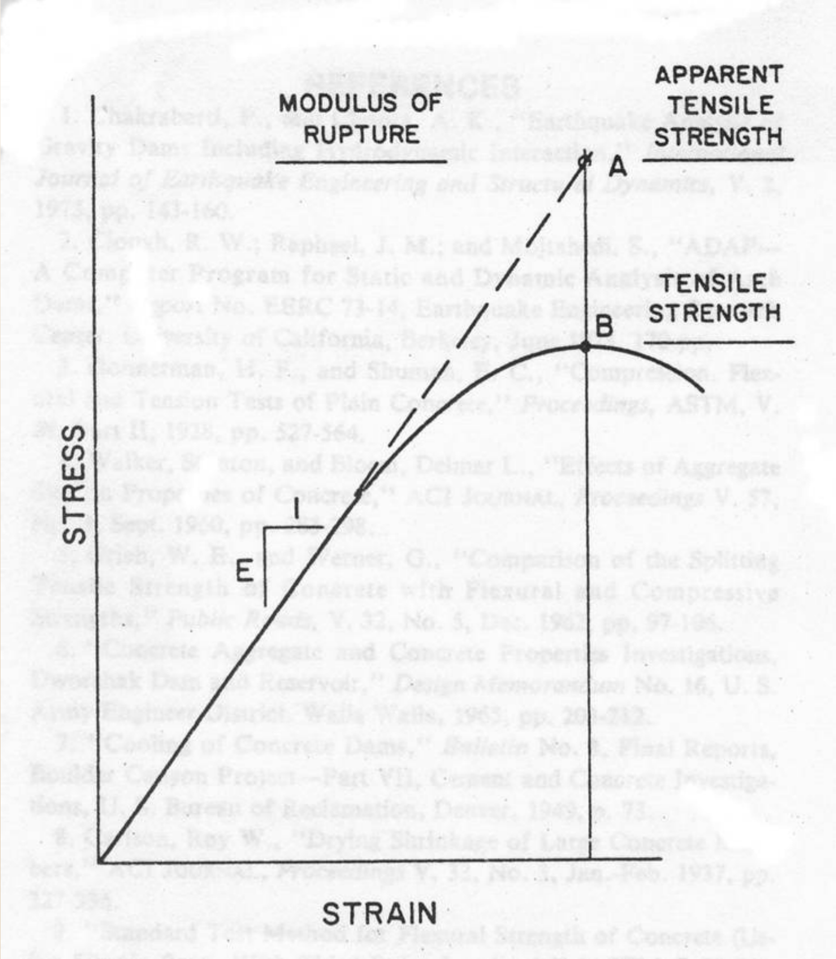
Concrete Tensile Tests

Differences of Opinion

- There are some differences of opinion as to when to use splitting tension results or direct tension results, as well as factors to apply for different loading rates.
- These should be discussed as part of the risk analysis process.
- However, the information presented here results from a thorough review of a number of testing programs from various agencies, and is considered “best practices” at this time.

Concrete Tensile Strength (Raphael 1984)





Concrete Tensile Strength (Cannon 1995)

- In depth evaluation by Bob Cannon (1995) confirmed that splitting tensile strength is a good starting point but has some issues with Raphael's recommendations
- Adjustment for large size aggregate (10% reduction)
- Adjustment for direct tension and anisotropy (20% reduction)
- Confirmed a 50% increase for dynamic tensile strength
- Recommendations for RCC
- See Corps of Engineers EP 1110-2-12, 30 Sep 95, Appendix E
- Not valid for ASR-affected concrete or otherwise damaged concrete

Lift Joint Strength

- Lift joints tend to be the weak link in a concrete structure
- Joints often placed at changes in geometry where stress concentrations occur
- Lift joint strength dependent on joint preparation, clean-up, placement methods, and curing
- Green-cut joints, water curing, low w/c mix, rich mix with smaller aggregate adjacent to joint, good concrete layering and vibration can result in joint tensile strength approaching the parent concrete (joint strength = 92% parent concrete strength at Hoover Dam)
- Poor practice can result in lower joint tensile strength

Concrete Placing

Concrete Placement

Tensile Strength Estimation

To convert from avg. compressive strength, f_c, to splitting tensile strength: ST = $1.7f_c^{2/3}$

Correct from	To	Multiply by:
ST	DT	0.8
RM	DT	0.75
Small Aggregate	Large Aggregate	0.9
Parent Concrete	Well Prepared Lift Joint	0.85
Static Loading	Rapid Loading	1.5
Nonlinear Strength	Apparent Linear Strength	1.3

Where: ST = splitting tension strength

DT = direct tension strength

RM = modulus of rupture (flexure strength)

Note: Although moisture affects strength, there is currently no practical way to account for this in a prototype dam

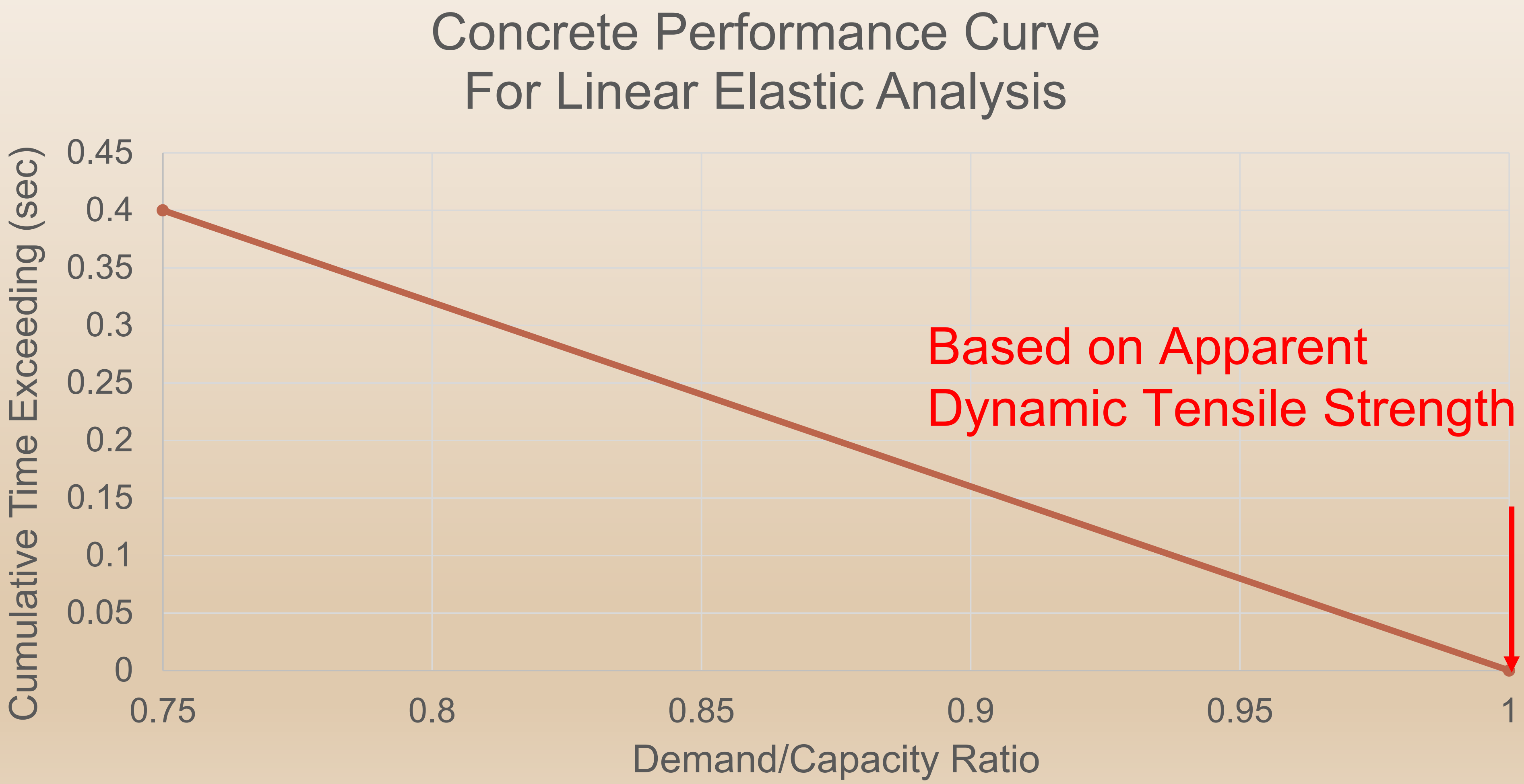
Cyclic Fatigue

- There is no definitive study of the effects of cyclic loading on the fatigue tensile strength of concrete.
- The closest is a series of tests on dry specimens described in Corps of Engineers Report C-77-6.
- No specimens failed when cycled to 60% of the estimated strength.
- 24 percent of specimens cycled to 80% of the estimated strength failed.
- (Note that strength gain under rapid loading was only observed for wet specimens, which throws some uncertainty into the results.)

Evaluating Linear Elastic Dynamic Analysis Results

- Estimate appropriate average dynamic tensile strength (use apparent strength for linear elastic material properties)
- If envelope of stresses shows no (or only limited) areas that exceed 75% of the tensile strength, then likelihood of cracking is minimal
- If envelope of stresses exceed the tensile strength over more than 20% of the area of concern, significant cracking can be expected
- In between these two cases, use the performance curve (shown on the next slide) which accounts for cyclic fatigue to estimate the likelihood of cracking – if the performance curve is exceeded over 20% of the area, significant cracking can be expected, otherwise limited cracking would be likely

Dynamic Concrete Performance Curve



Concrete Cracking Models

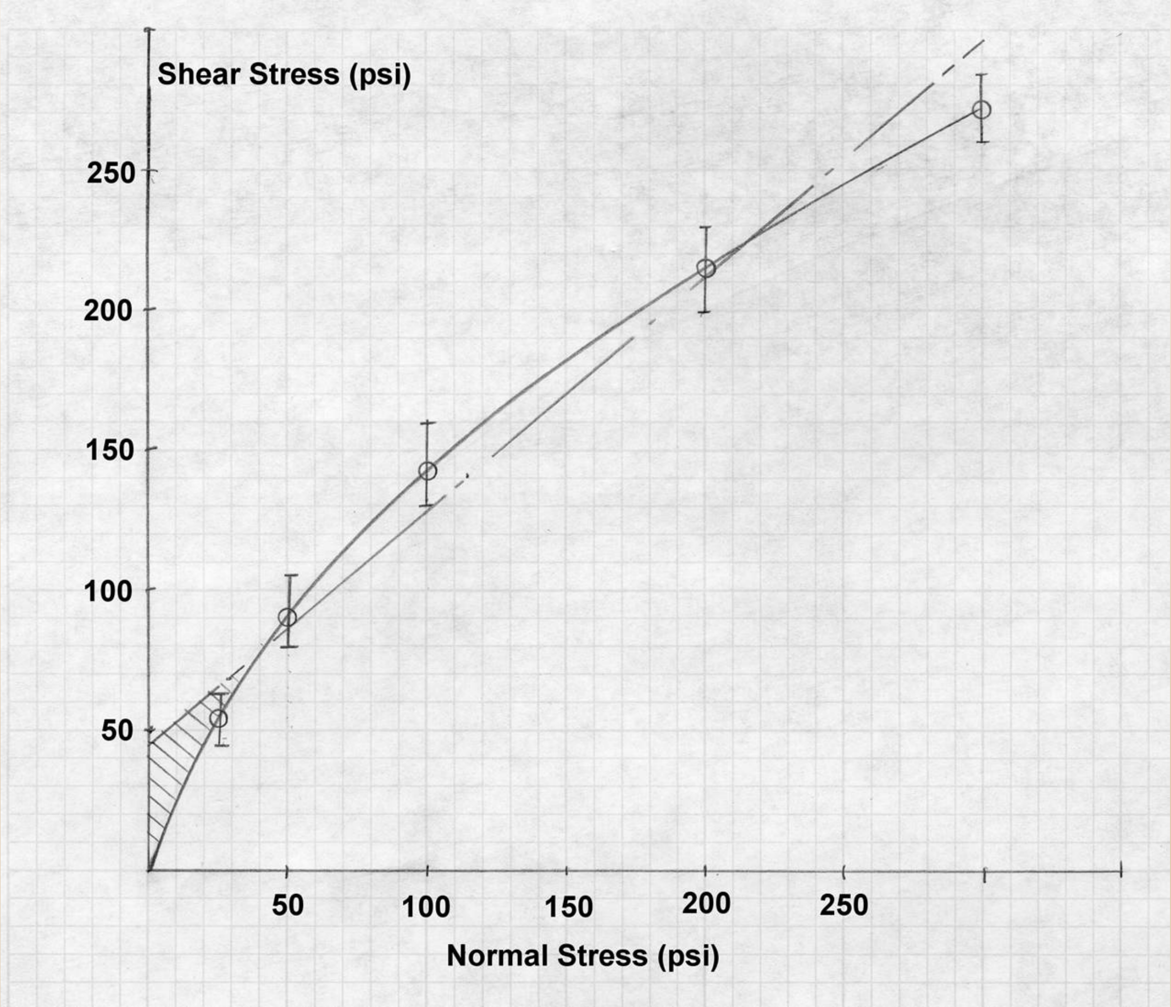
- Most nonlinear finite element programs have the option to use concrete cracking models.
- If these are used, it is essential to perform a linear elastic analysis first to form a baseline from which to judge the reasonableness of the results.
- These cracking models often require input parameters that are not obtained as part of routine concrete testing, so the implications are not always obvious or predictable.
- More than one cracking model should be used to show that similar results are obtained.

Concrete Shear Strength

Concrete shear strength is needed to evaluate the potential for sliding or shear failure of concrete members.

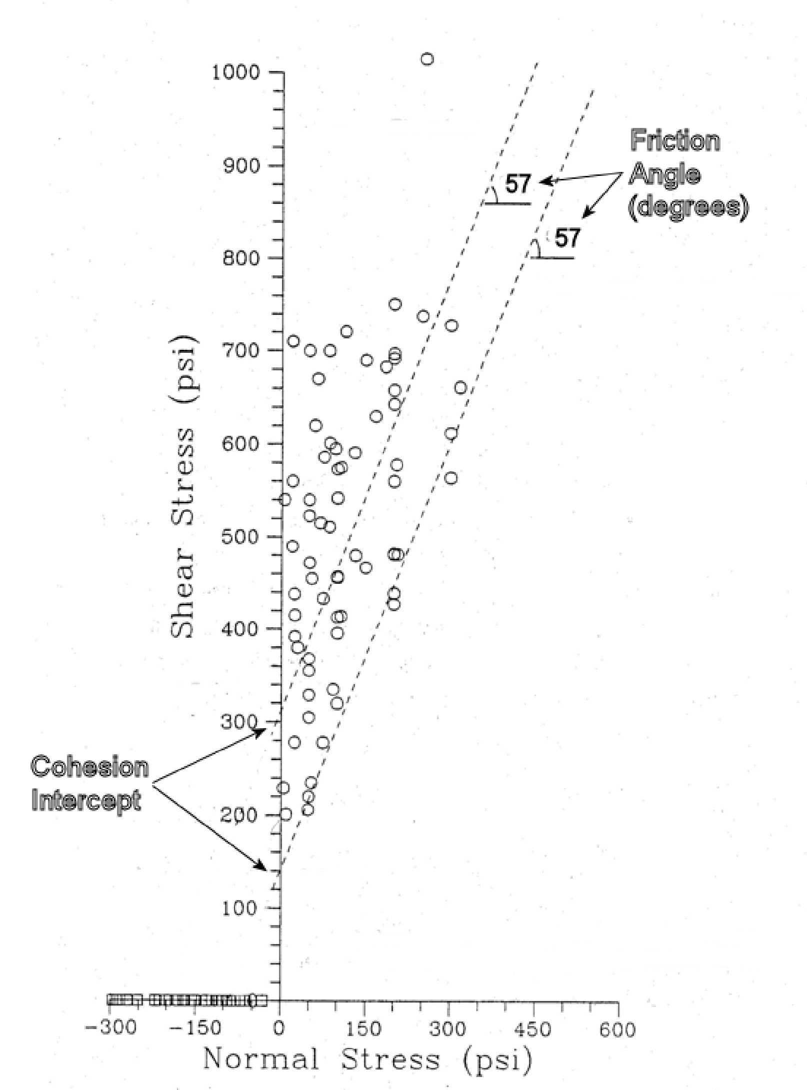
Beware of Apparent Cohesion on Open Joint

Strength is often over-estimated by straight line fit (at low normal stress typical of gravity dams)



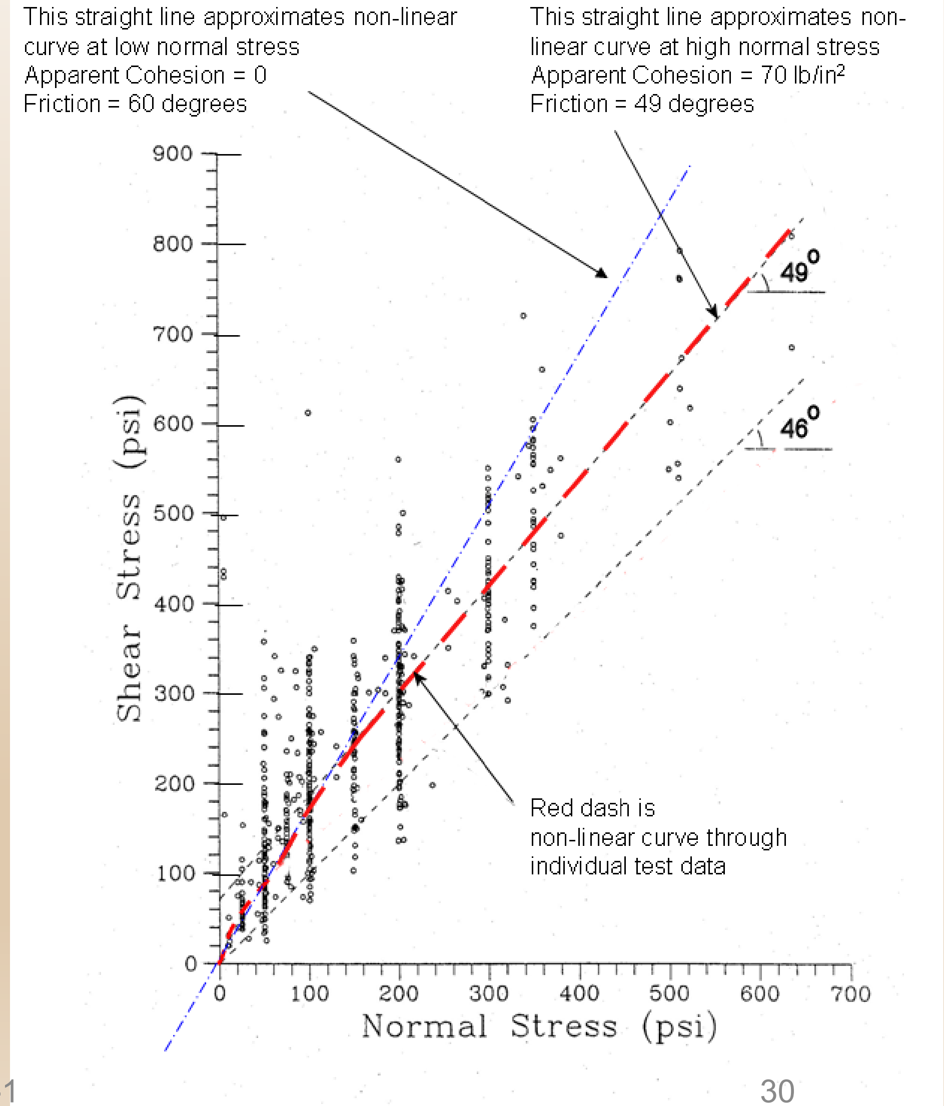
Concrete Shear Strength

Bonded Lift Line or Construction Joint



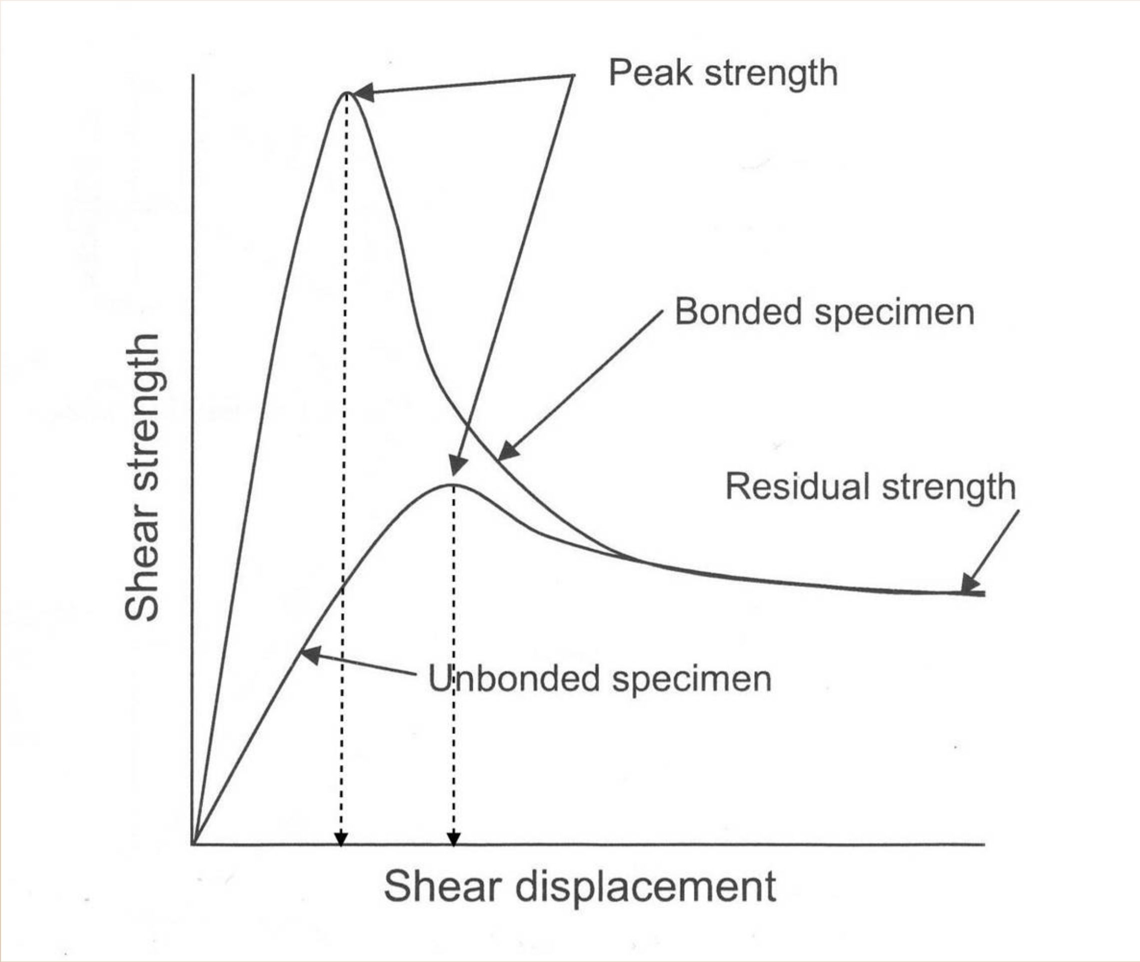
Peak Shear Strength of Concrete-Lift Joints

Unbonded Lift Line or Construction Joint



Sliding Friction Shear Strength of Concrete-Lift Joints (Unbonded joints)

Shear Strength



- Make sure added strengths are developed at compatible displacements

Concrete Property Distributions

- For static analyses of shear/sliding or moments, probabilistic Monte-Carlo analyses may be appropriate. In these cases, a mean and standard deviation can be estimated from available test data or by estimating values using information contained in this section and from testing on other similar concrete materials.
- For seismic analyses, probabilistic analyses are possible in special cases, but practically speaking due to the large number of analyses required, it is more expedient to perform analyses based on mean properties and then perform sensitivity analyses on key parameters to estimate probabilities.

Using Concrete Strengths in Risk Analysis – Takeaway Points

- Concrete modulus is needed for finite element analyses. Sensitivity studies can often lead to settling on use of a mean value.
- It is often necessary to estimate concrete strengths as a distribution for use in Monte-Carlo analyses to obtain the probability of instability for static analyses – dynamic analyses typically focus on mean values.
- Demand-capacity ratios of tensile stress/tensile strength are often needed to estimate the potential for cracking.
- Once cracking initiates and progresses, the shear strength becomes important for estimating the probability of excessive displacements.

Questions or Comments?