NCST Investigation of the Champlain Towers South Collapse

Cross-Project Panel Theme 2: Analysis and Testing Updates

Fahim Sadek, James Harris, Christopher Segura, Kenneth Hover, Jack Moehle, Sissy Nikolaou

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

NIST has made no findings or recommendations based on the preliminary data and analyses presented, which are subject to change.

CTS Investigation: Analysis and Testing Updates

CTS Design and Construction

1. ***Structural Design Checks -- Tower***
   Fahim Sadek
2. ***Design Detail and Construction Issues***
   Jim Harris

Materials Testing and Degradation

3. ***Testing of Concrete and Reinforcing Bars***
   Christopher Segura
4. ***Concrete Mixtures and Corrosion of Reinforcement***
   Kenneth Hover

Structural and Geotechnical Testing and analysis

5. ***Structural Testing***
   Jack Moehle
6. ***Geotechnical Modeling and Testing***
   Sissy Nikolaou
7. ***Structural Collapse Modeling***
   Fahim Sadek

Structural Design Checks - Tower

Fahim Sadek

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U.S. DEPARTMENT OF COMMERCE

CTS Investigation: Structural Code Checks - Tower

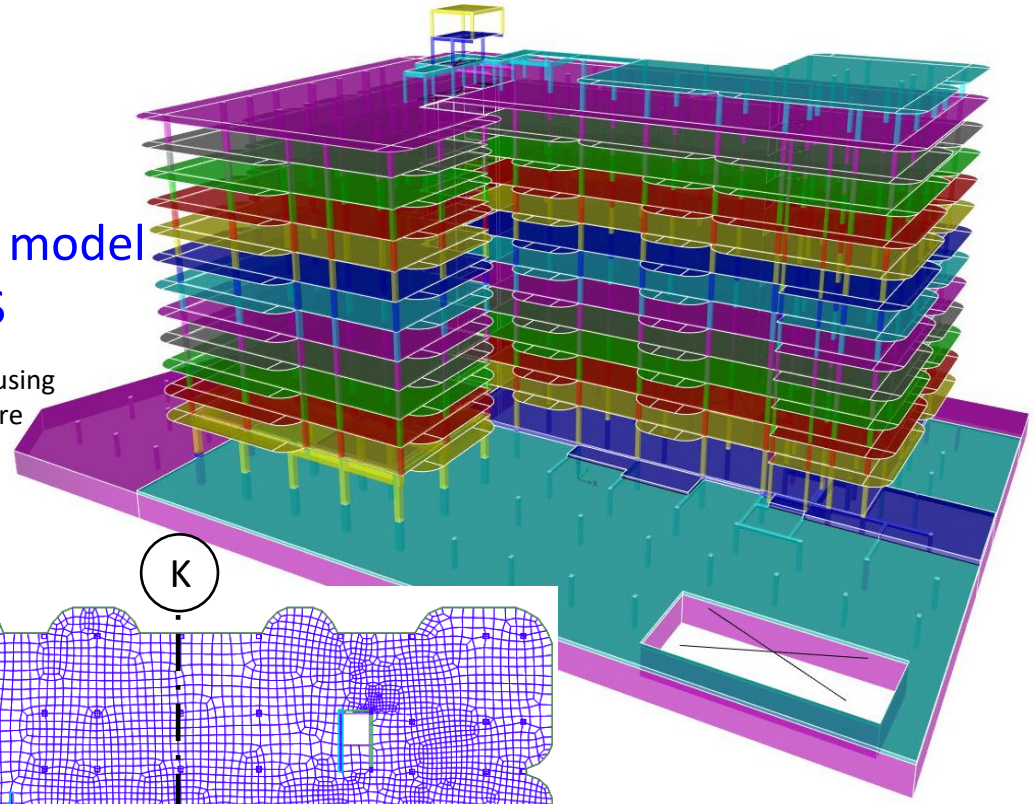
Scope

Conduct structural analyses and design checks for the CTS building in accordance with:

- Design codes, standards, and design practices at the time of the original building design:
  - SFBC* 79 / ACI^ 318-77
  - Columns and shear walls: gravity (tributary area calculations) and lateral loads (plane frame models)
  - Floors: equivalent frame model strips
- Current design codes, standards, and design practices:
  - ASCE† 7-22 / ACI 318-19
  - Columns and shear walls: ETABS FEA** model
  - Floor: ADAPT FEA models

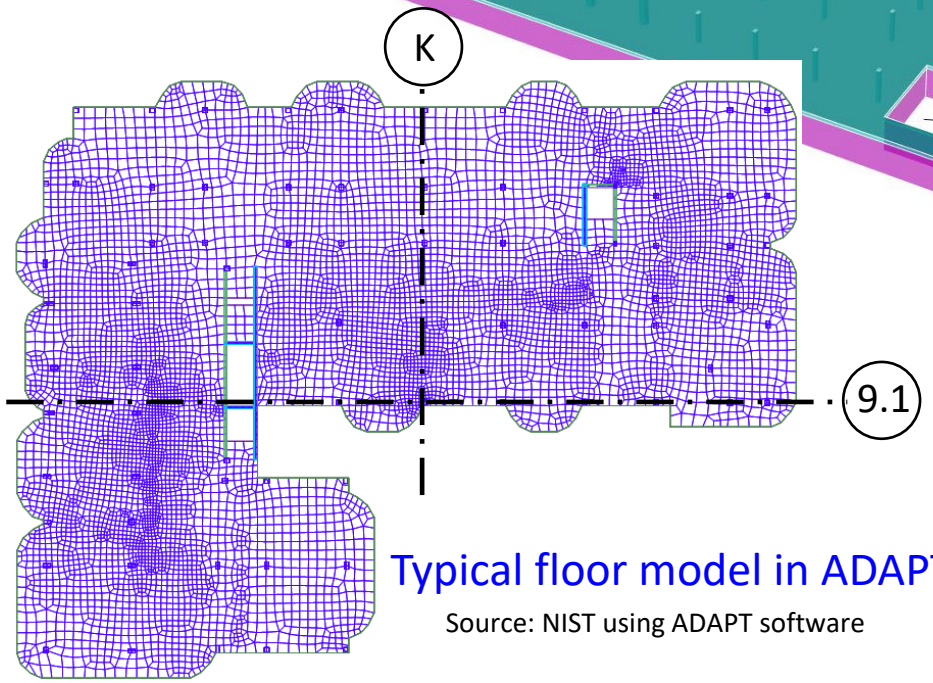
*South Florida Building Code
^American Concrete Institute
†American Society of Civil Engineers

** finite element analysis



Building model in ETABS

Source: NIST using ETABS software



Typical floor model in ADAPT

Source: NIST using ADAPT software

CTS Investigation: Structural Code Checks - Tower

Tower Columns Key Preliminary Observations:

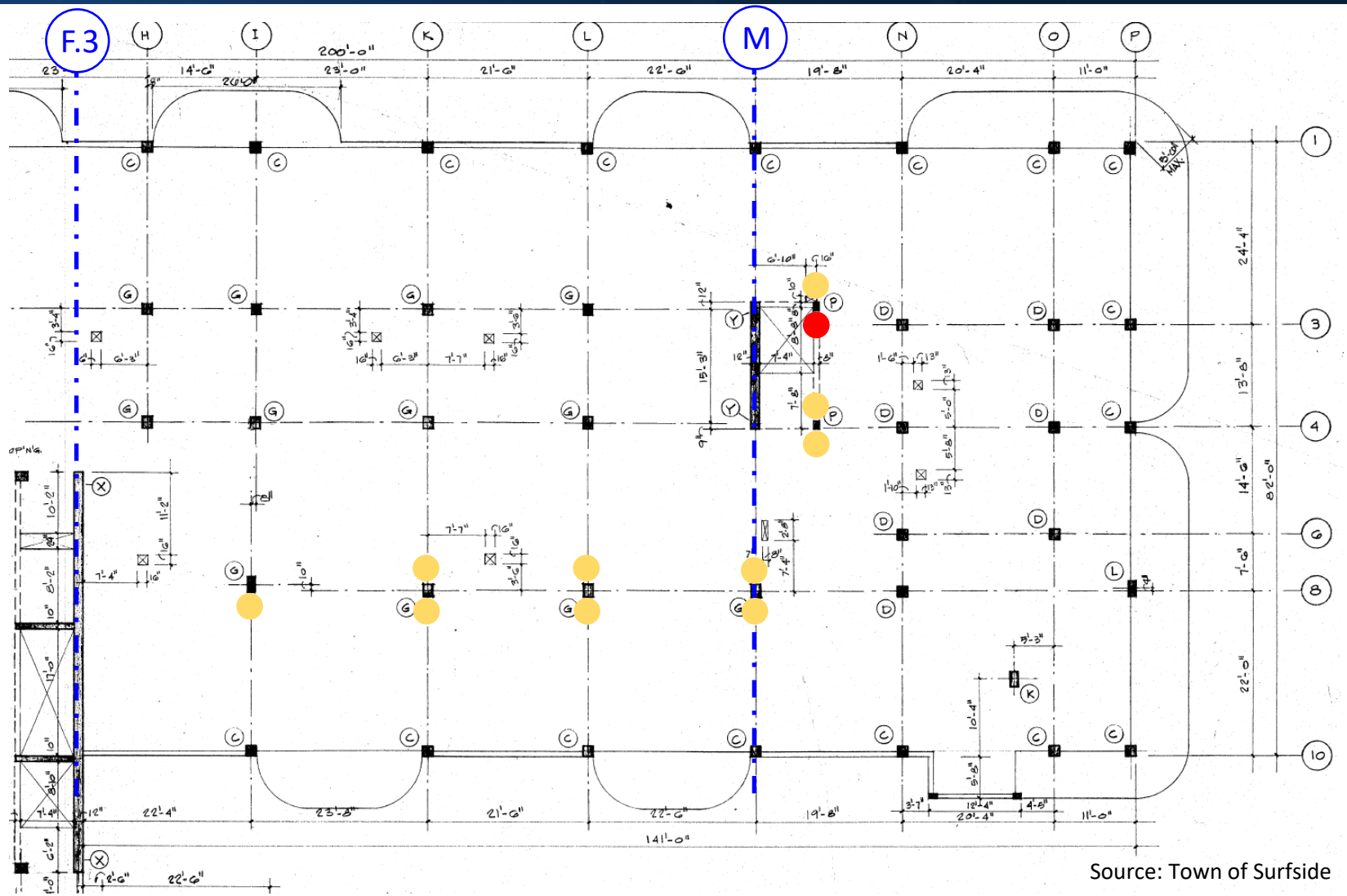
- Several columns have low to moderate strength deficiency, and their design strength does not comply with the original or current codes and standards.
- Lateral load resisting system:
  - *Original code:* wind load is resisted by shear walls and slab-column frame.
  - *Current code:* analysis shows that west-to-east wind load can be resisted by the slab-column frame, with no lateral resistance from the two short east-west walls of the western shear wall.

Figure Legend

Severe/moderate column understrength

Above column: First level

Below column: Basement level



Source: Town of Surfside

Tower Columns and Shear Walls

Locations where design strength does not meet original code (Demand-Capacity Ratio > 1.0)

PRELIMINARY ANALYSIS RESULTS

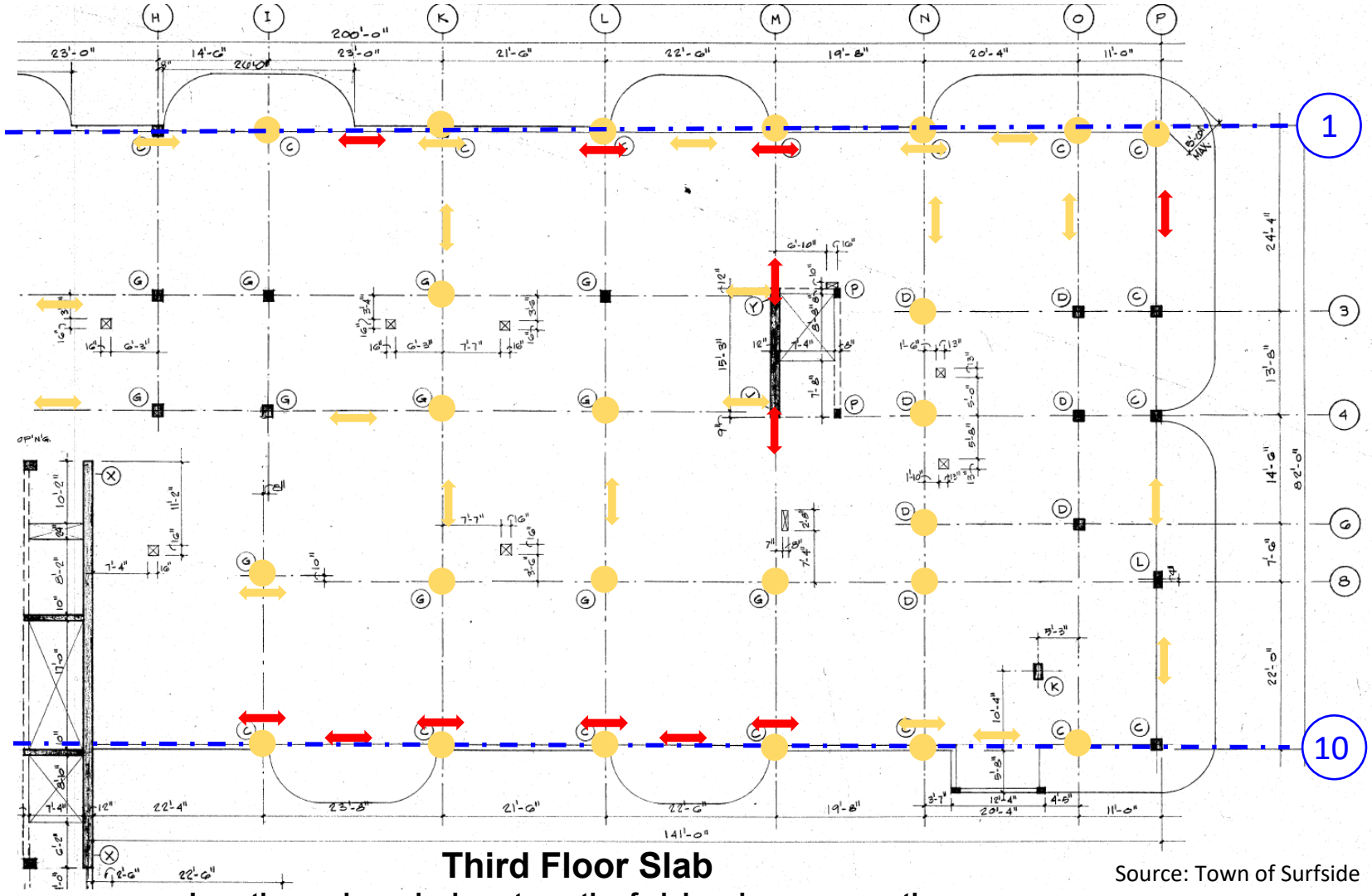
CTS Investigation: Structural Code Checks - Tower

Third Floor Key Preliminary Observations:

- Design strength does not comply with the original or current codes and standards, with many areas of strength deficiency.

Figure Legend

Degree of Understrength	Location of Understrength: slab-column connections	Location of Understrength: slab flexure
severe		⟷
moderate	●	⟷



Third Floor Slab

Source: Town of Surfside

Locations where design strength of slab-column connections and slab flexure does not meet original code (Demand-Capacity Ratio > 1.0)

PRELIMINARY ANALYSIS RESULTS

Design Detail and Construction Issues

James Harris

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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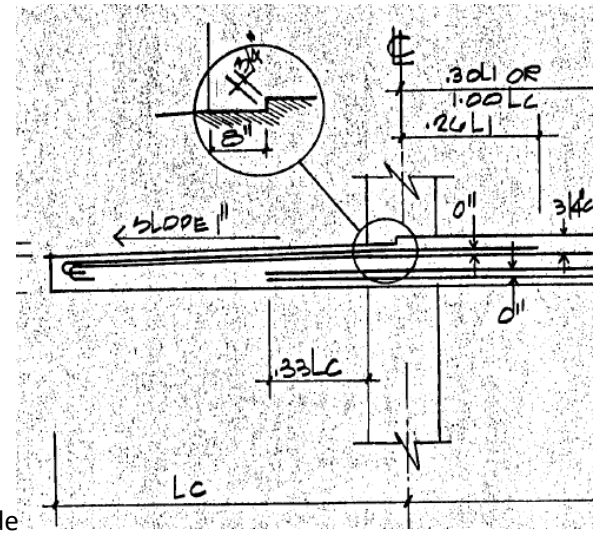
CTS Investigation: Design Detail Issues

Source: NIST

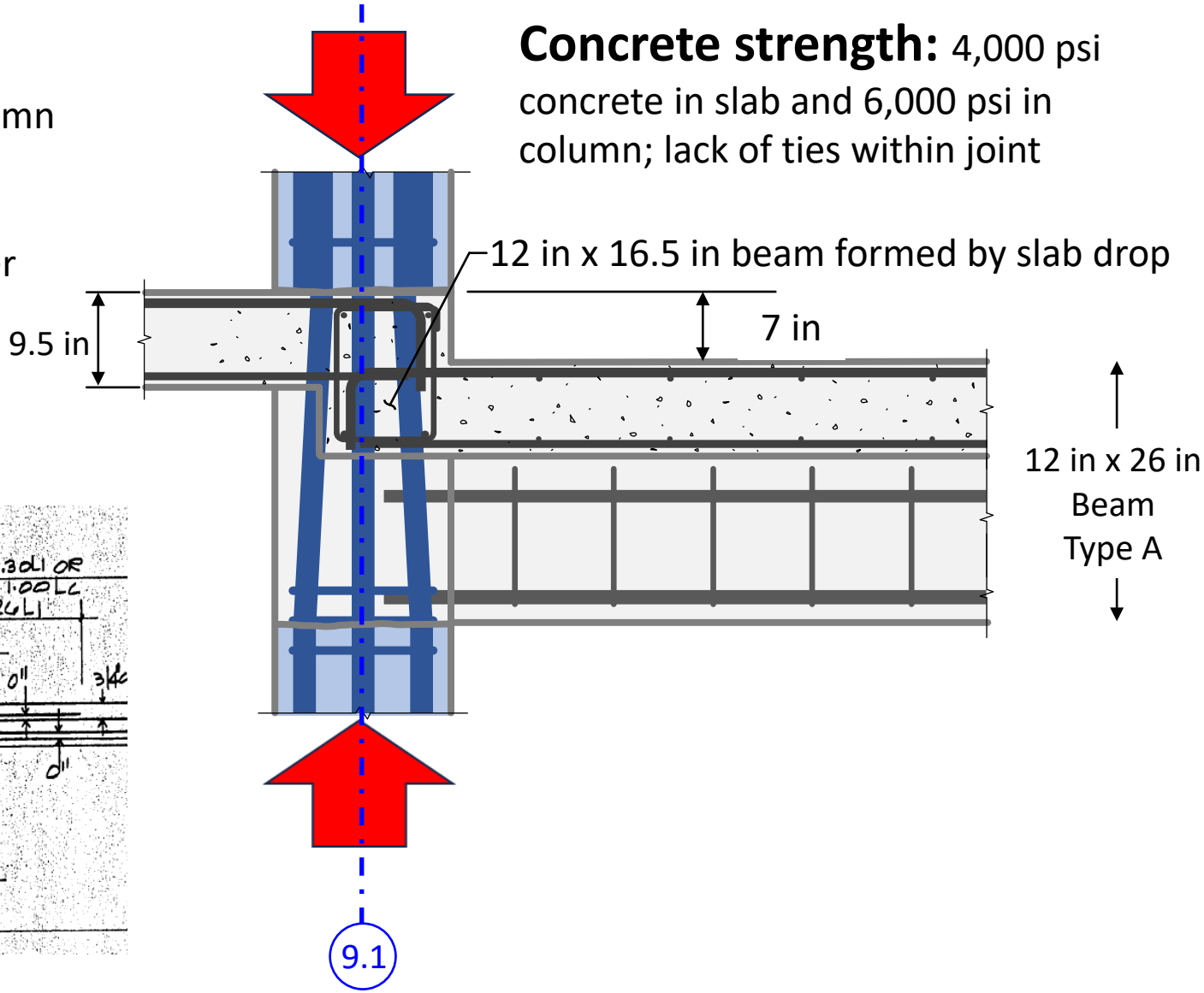
Congestion:
9.75 % vertical reinforcement in column at this splice, vs. 8 % maximum permitted (worst case at another column is 12.2 %)



Source: Town of Surfside

Inadequate cover: over reinforcement in balcony slabs exposed to weather

Concrete strength: 4,000 psi concrete in slab and 6,000 psi in column; lack of ties within joint



CTS Investigation: Construction Issues

Source: NIST

Source: Town of Surfside

Placement of top bars in column strips:

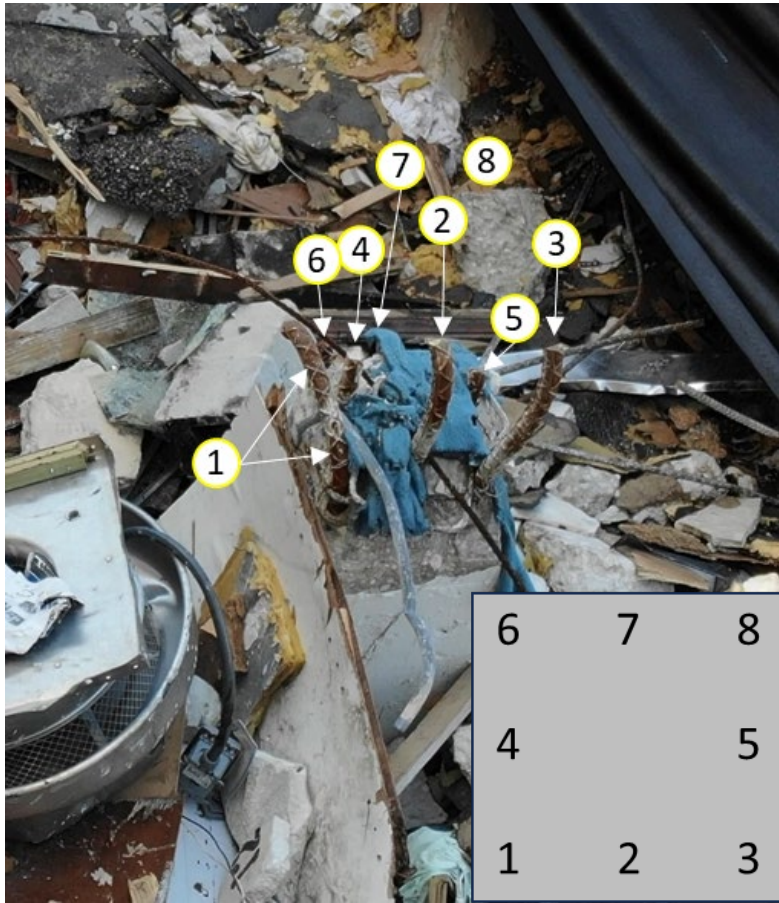
Example: measured 7 spaces between east-west top bars: average is 9.0 in; would be 5.75 in per drawings. Also have excessive cover on top bars

Source: NIST

Source: NIST

Position of reinforcing cage within columns:

Photos of top of basement column at Grid Line K on south face of tower: bars shifted to the north (excessive cover on near face, but ties against form on far side of column)



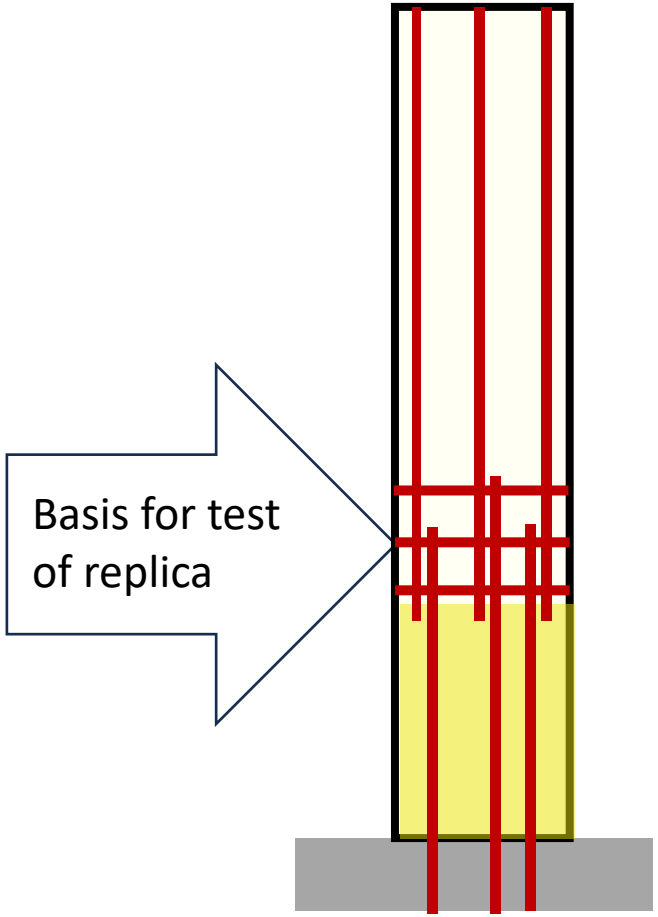
CTS Investigation: Construction Issues

Alignment of concrete:
Offset in column from story to story exceeds standard tolerances.

Source: NIST

Misplaced/short splice:
Several columns found with longitudinal bars where the lap splice is shorter than specified.

Source: NIST



Testing of Concrete and Reinforcing Bars

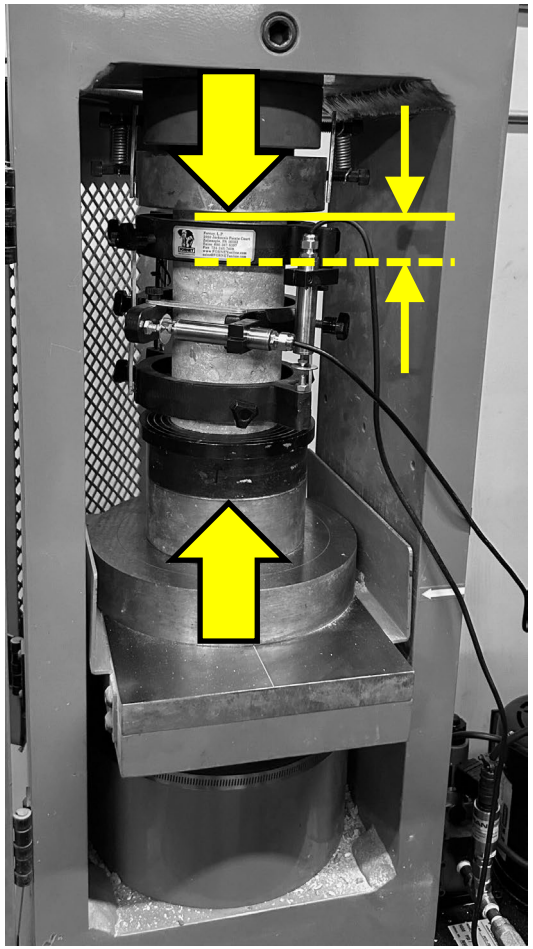
Christopher Segura

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Source: Town of Surfside

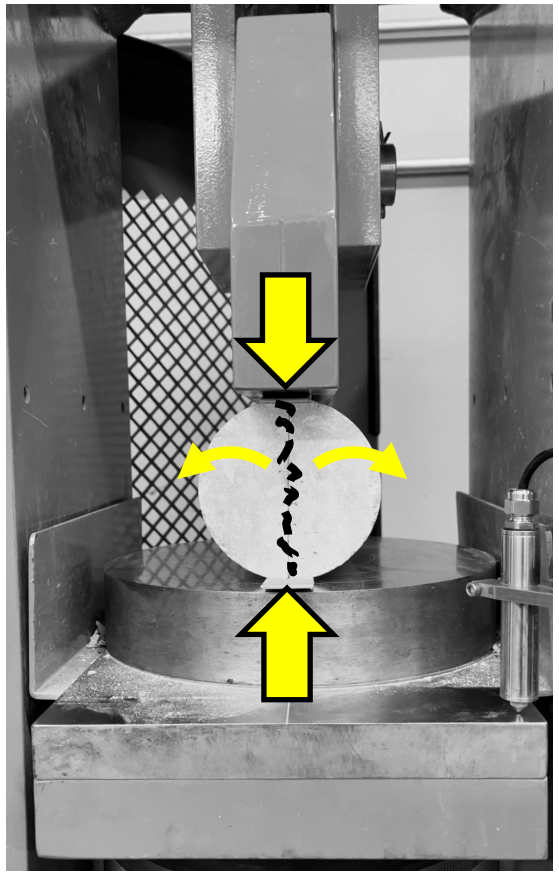
CTS Investigation: Mechanical Tests on Concrete & Steel Reinforcing Bars

Concrete Compression Strength & Modulus of Elasticity
(ASTM C39, C42, C469)



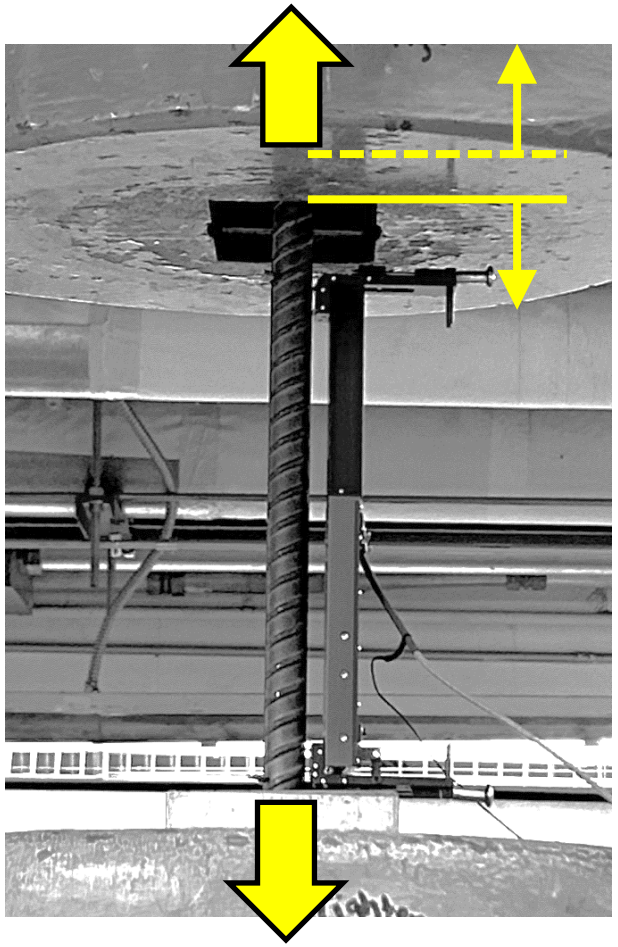
Source: NIST

Concrete Splitting Tensile Strength
(ASTM C496)



Source: NIST

Steel Reinforcing Bar Tensile Properties
(ASTM A370)



Source: NIST

CTS Investigation: Extraction and Testing Progress

Concrete: 497 cores extracted

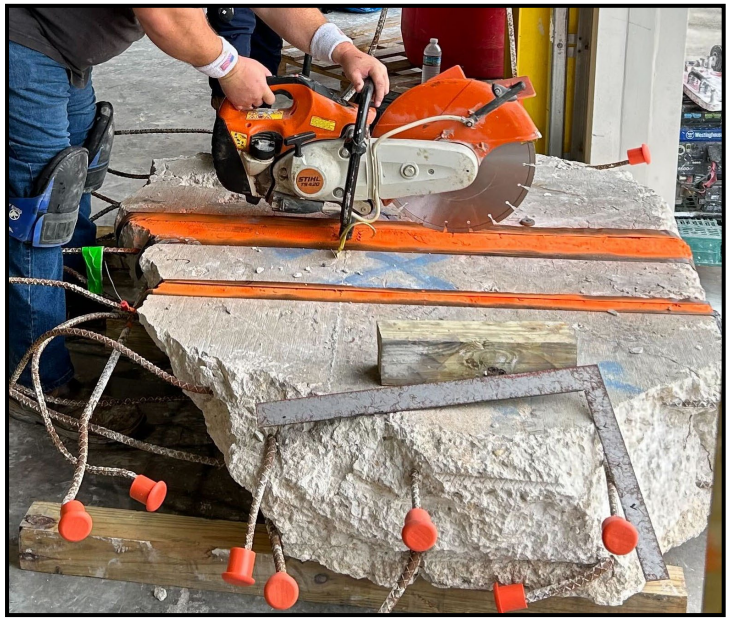
417 mechanical tests planned

- Compressive strength: 274/302 completed
- Modulus of elasticity: 22/35 completed
- Splitting tensile strength: 72/80 completed

Reinforcing steel: 369 reinforcing bars extracted

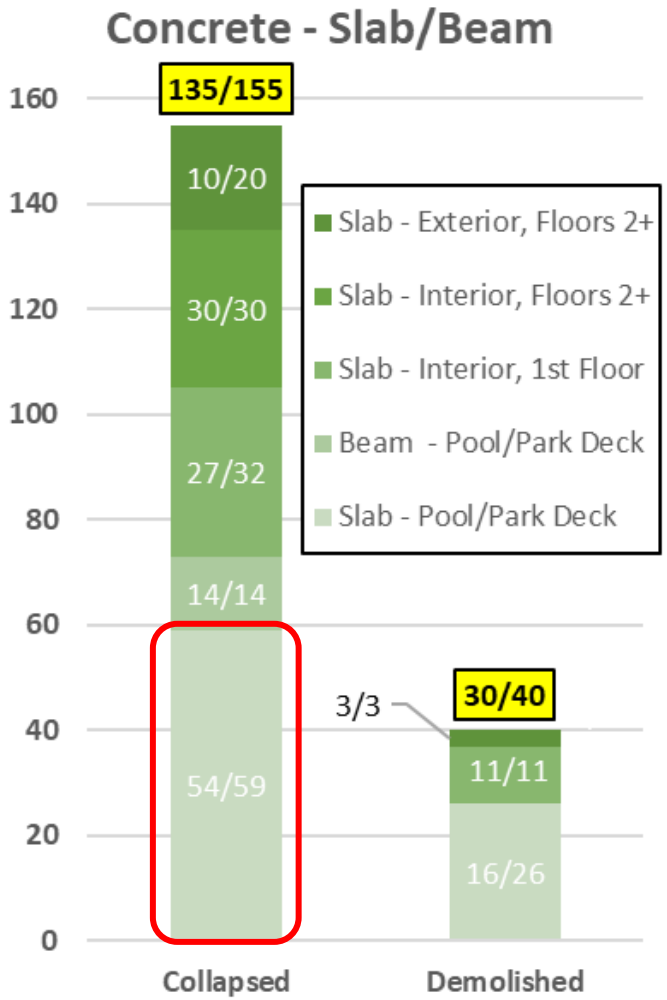
- Tensile properties: 40/156 completed

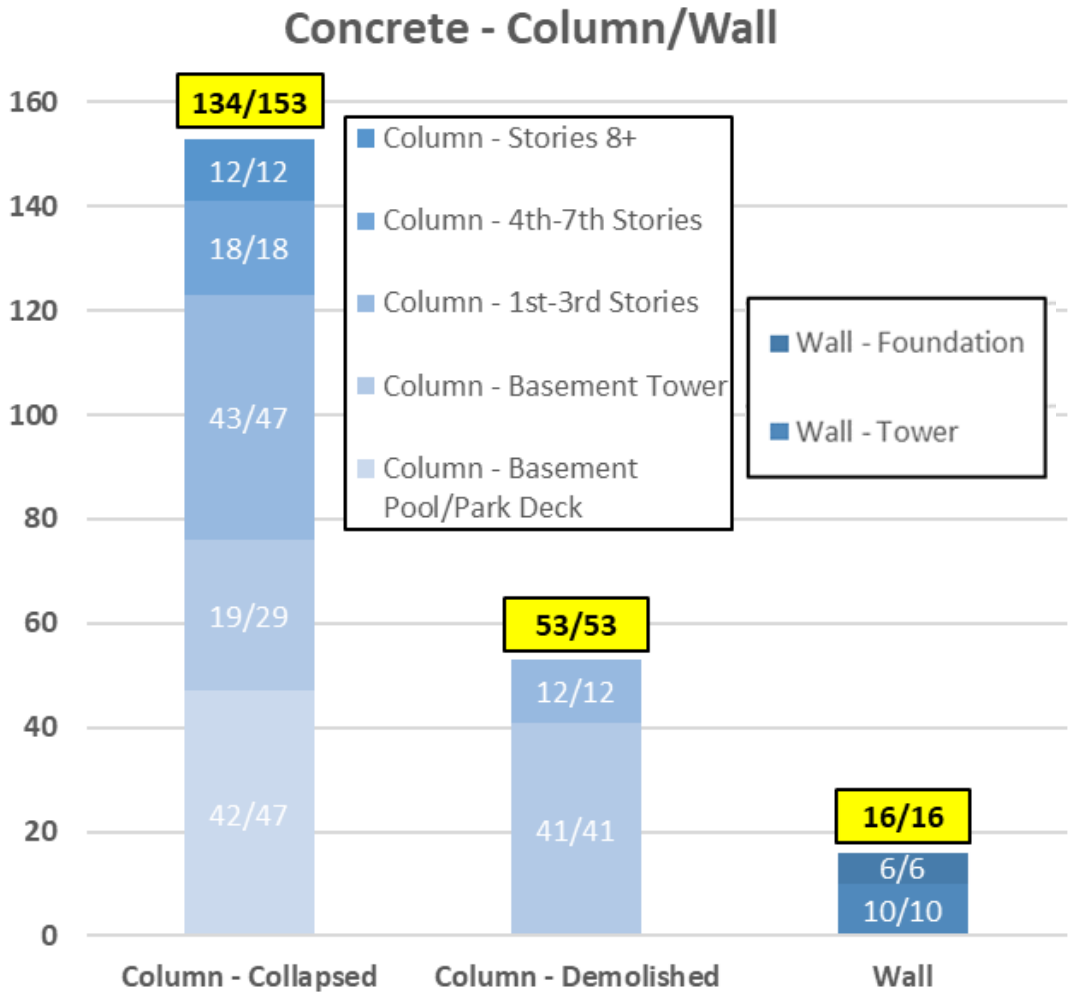
Source: NIST



Source: NIST

CTS Investigation: Concrete and Reinforcing Bar Testing





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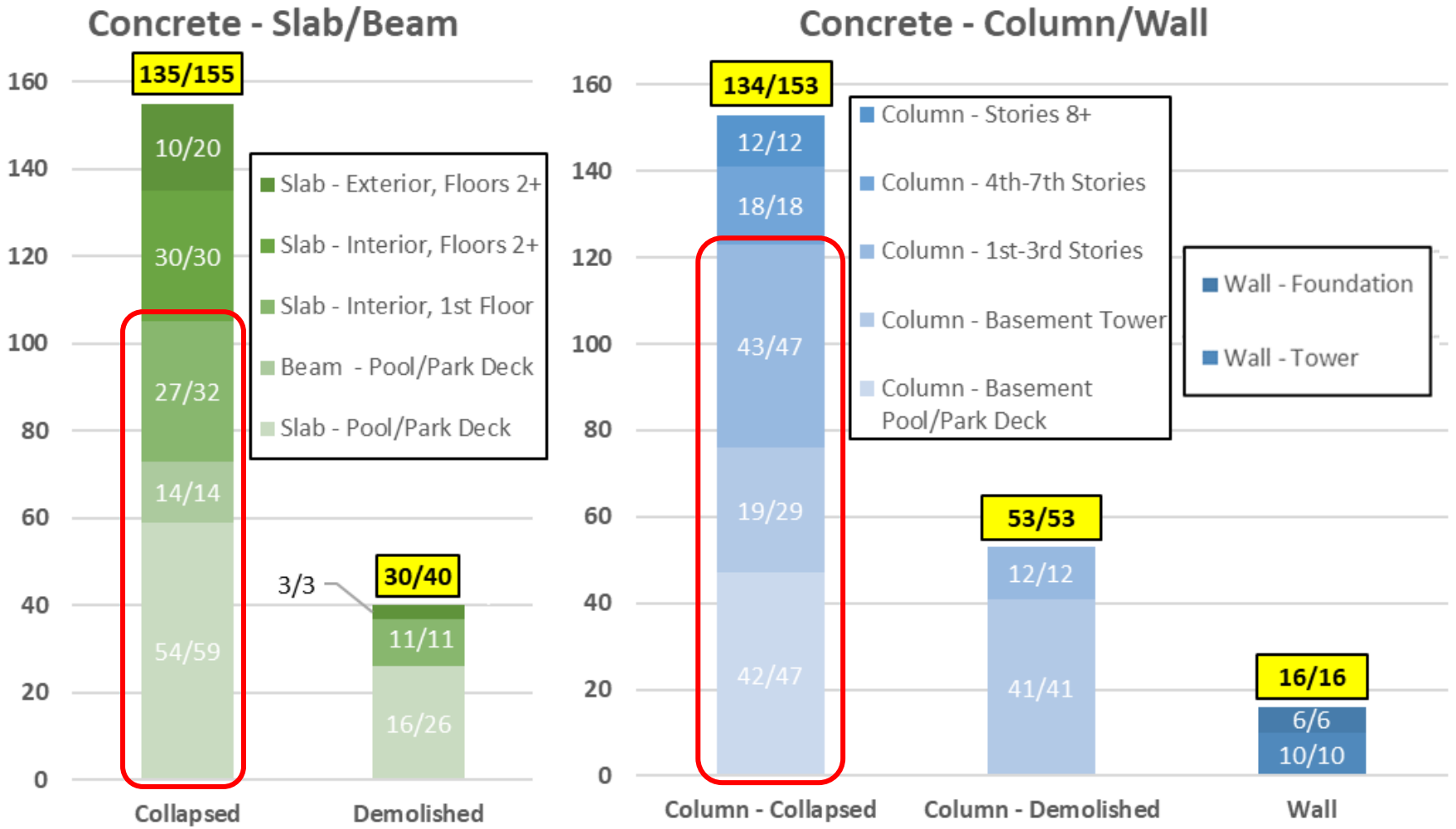
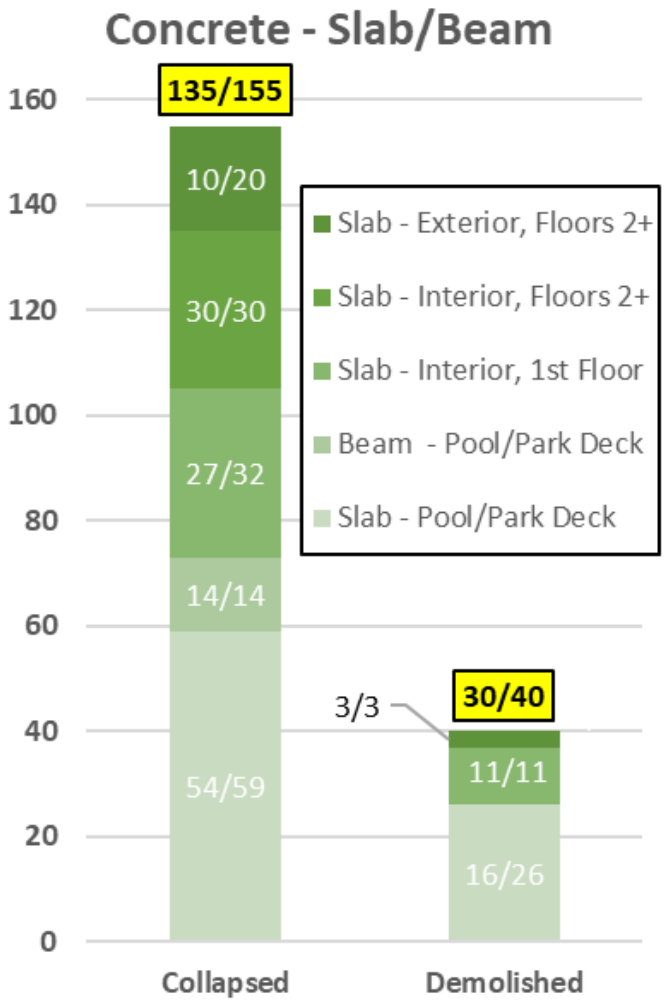
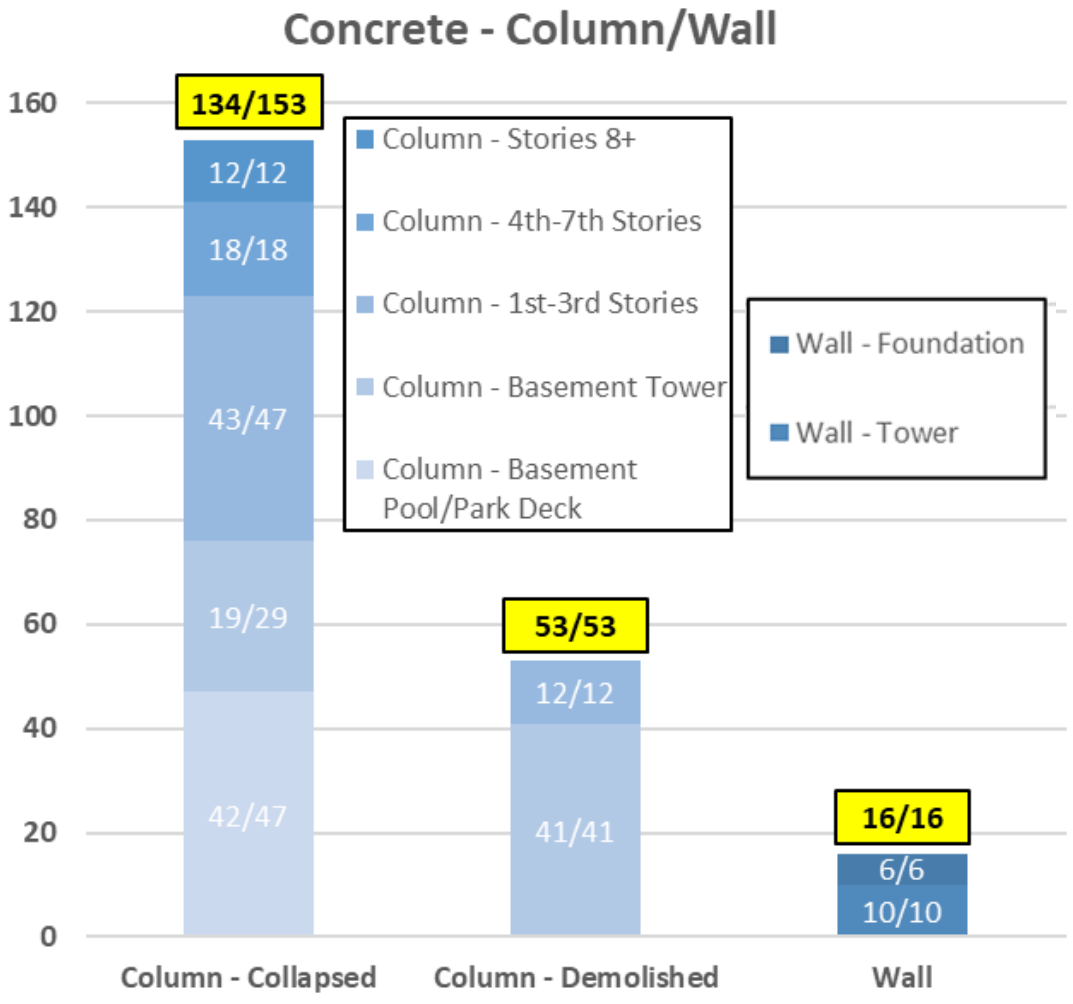
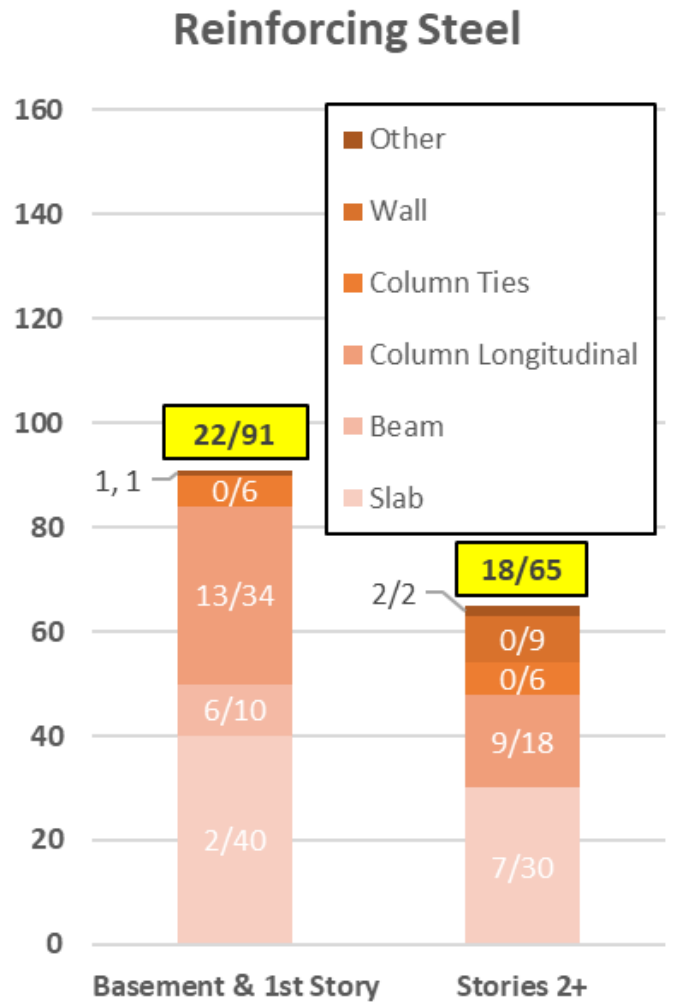


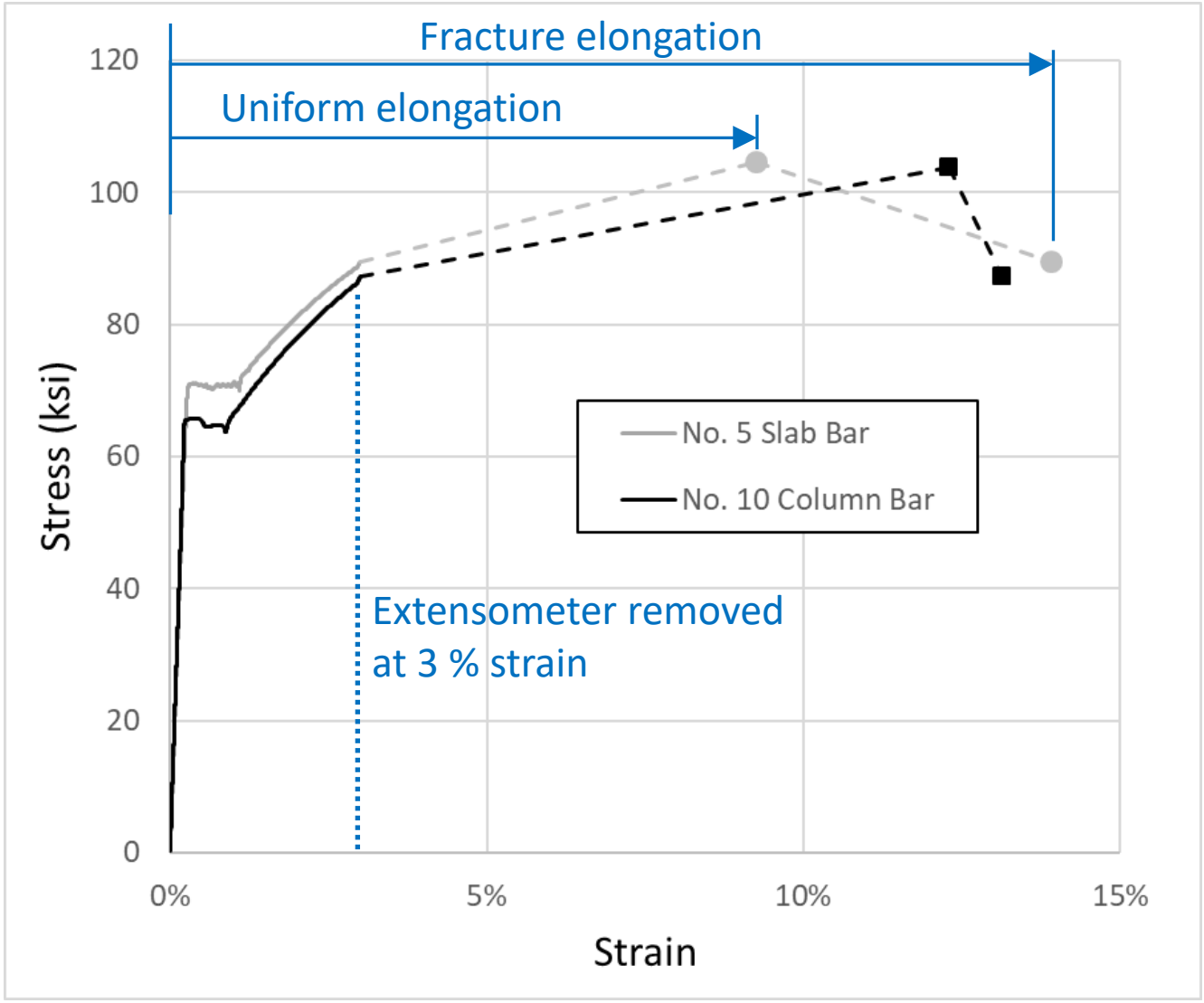
CTS Investigation: Concrete and Reinforcing Bar Testing

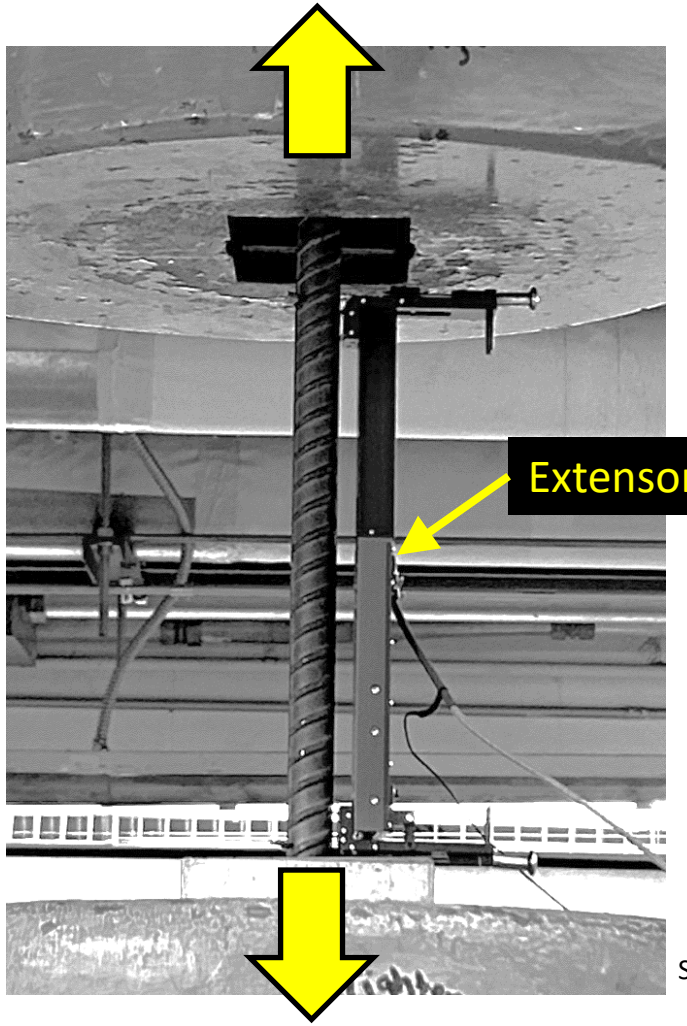






CTS Investigation: Steel Reinforcing Bar Testing

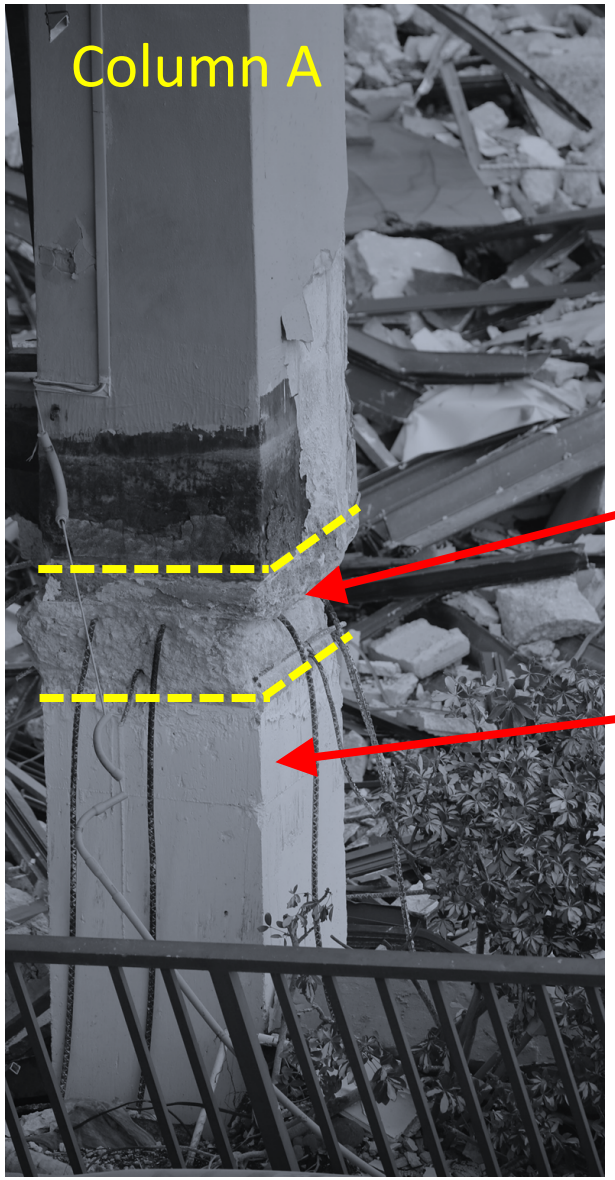




Source: NIST

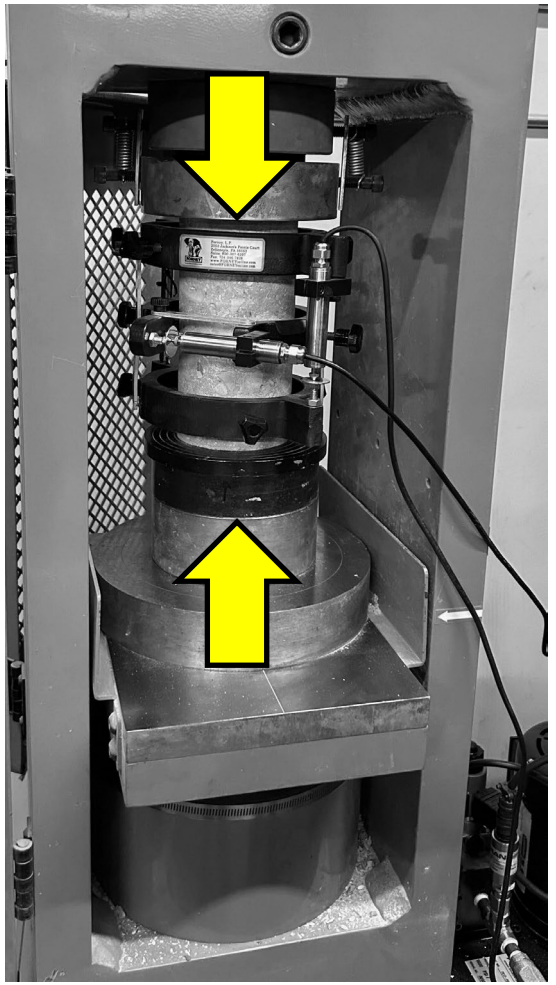
PRELIMINARY DATA ANALYSIS

CTS Investigation: Concrete Testing



	Column A
Slab – First Floor	4,420 psi 4,480 psi
Column – Basement	8,360 psi 8,680 psi

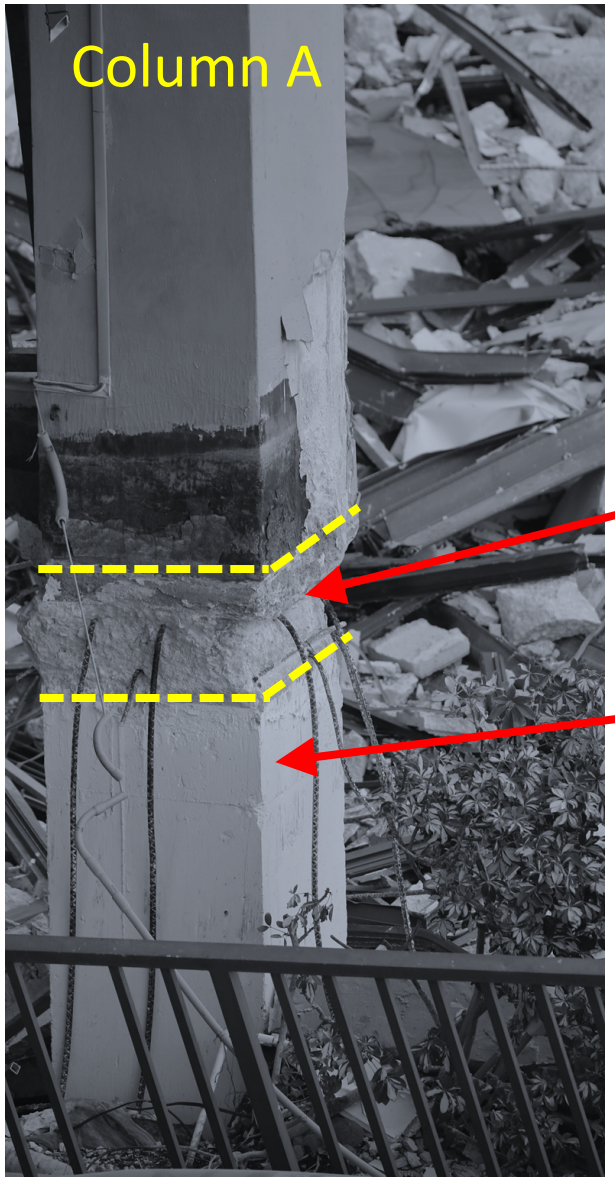
Source: NIST



Source: NIST

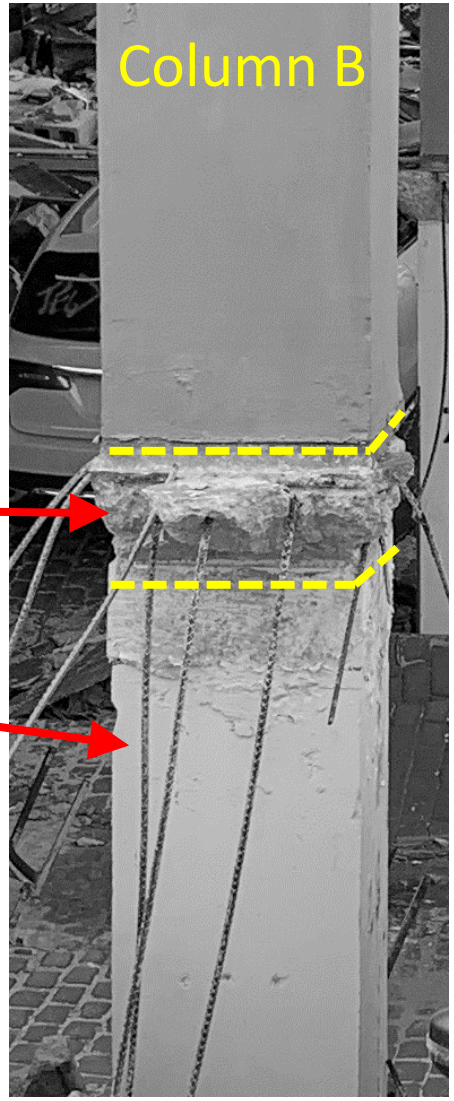
PRELIMINARY DATA ANALYSIS

CTS Investigation: Concrete Testing



	Column A	Column B
Slab – First Floor	**4,420 psi** 4,480 psi	**5,310 psi**
Column – Basement	8,360 psi **8,680 psi**	5,580 psi 5,600 psi **5,290 psi** **6,900 psi**

Blue text: Lowest measured value for floor/story
Green text: Highest measured value for floor/story



Source: NIST

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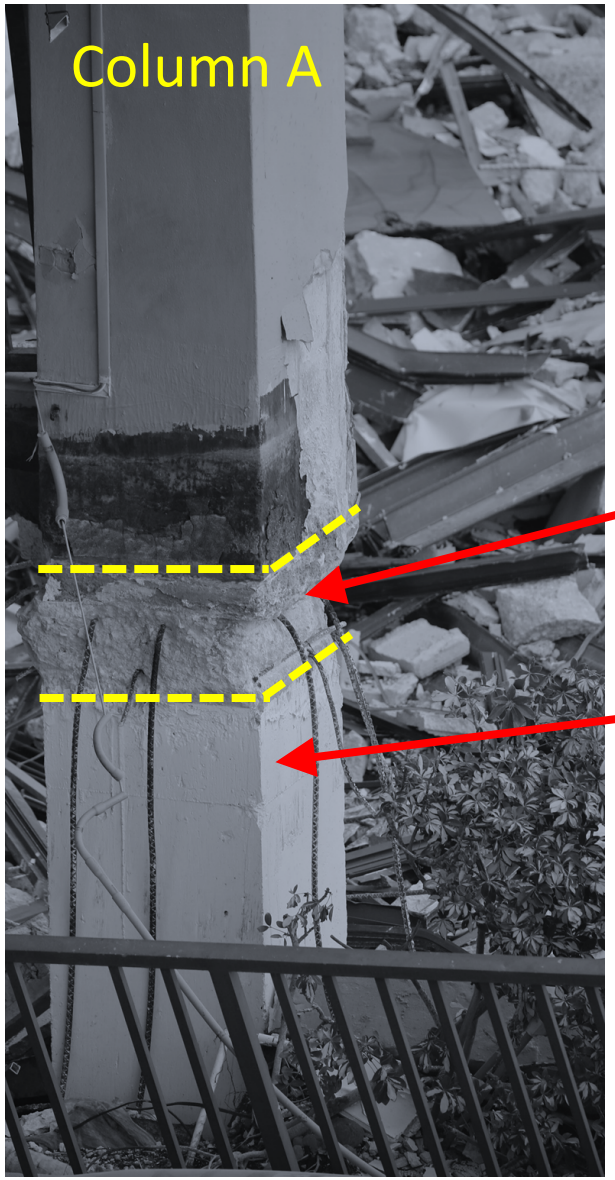
PRELIMINARY DATA ANALYSIS

CTS Investigation: Concrete Testing



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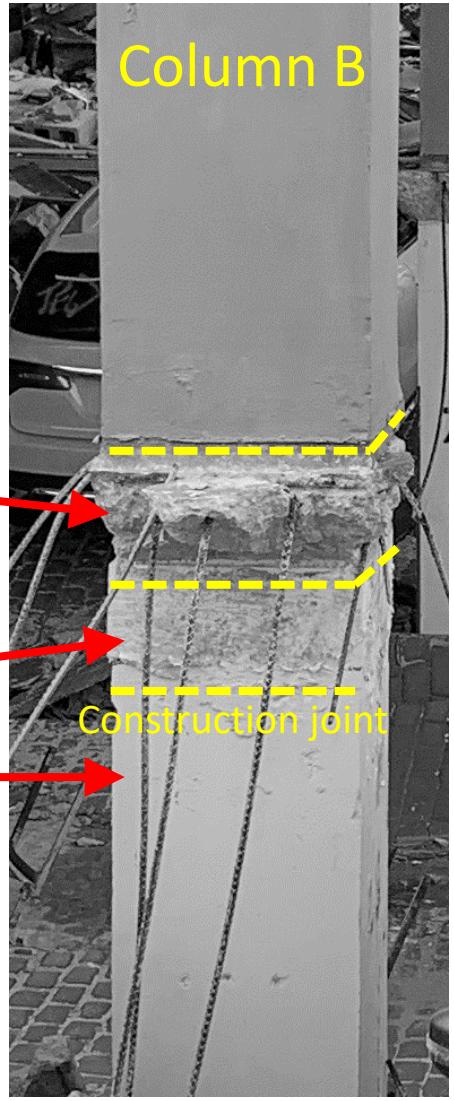


Source: NIST

PRELIMINARY DATA ANALYSIS

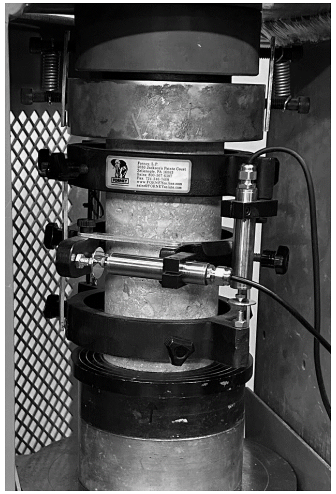
Concrete Mixtures and Corrosion of Reinforcement

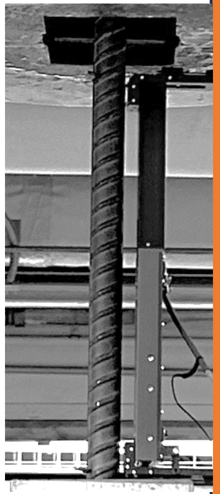
Kenneth Hover

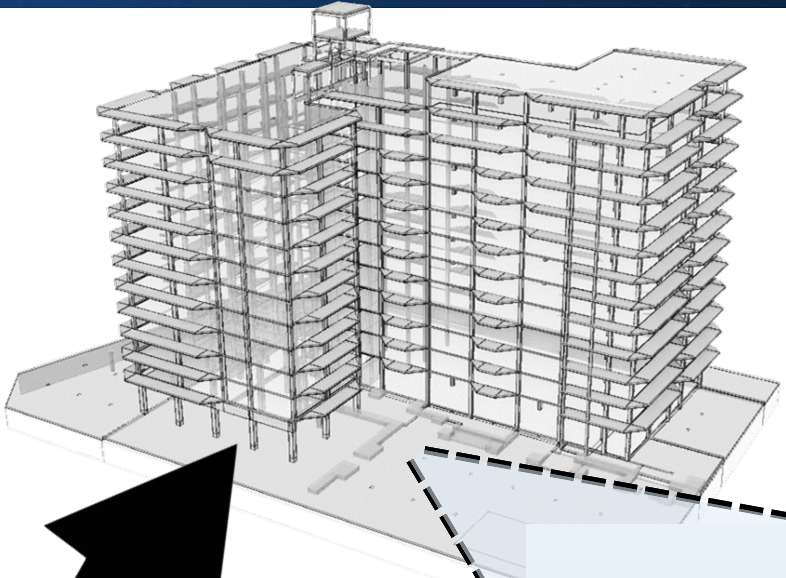
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Source: Town of Surfside

CTS Investigation: Concrete Mixtures & Corrosion







Understanding:
- Material properties & conditions at failure
- Influence on structural behavior

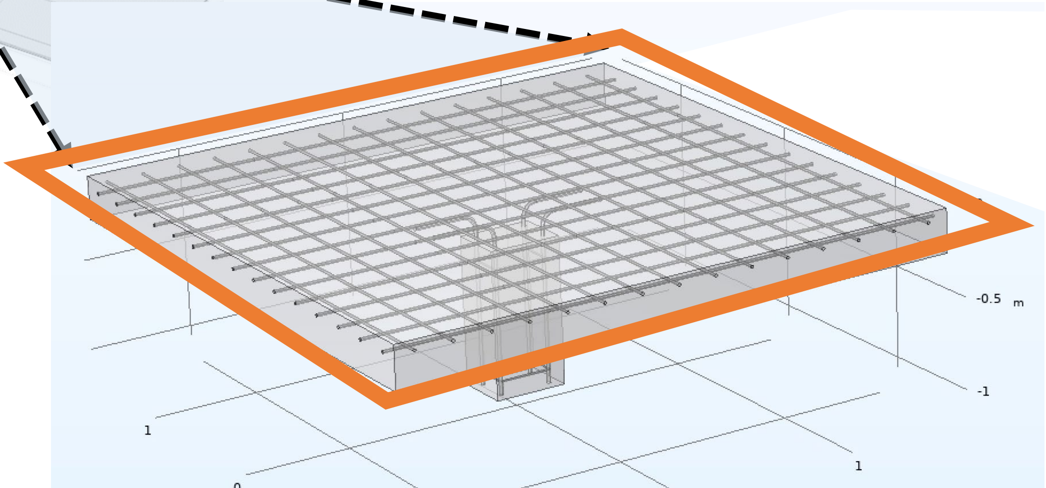
Mechanical Properties
- Compressive Strength
- Splitting Tensile Strength
- Modulus of Elasticity
- Steel strength & elongation
- Density

Steel Condition
- Distribution of corrosion
- Degree of Corrosion
- Impact on mechanical properties

Concrete Composition
- Aggregate types, sources, blends & proportions
- Cement type & proportion
- Ratio of water to cement
- Air content
- Admixtures
- Variability

Concrete Condition
- Distribution of mixtures
- Macro-cracking
- Microcracking
- mical change
-
- Ca
- Chloride penetration
- Deleterious reactions

Transport Properties
- Absorption
- Permeability
- Diffusivity
- Resistivity



Large Scale Structural Tests

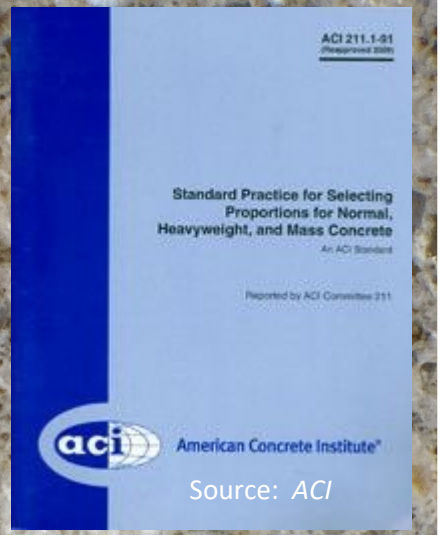
With and without accelerated corrosion

All sources: NIST

CTS Investigation: Concrete Mixtures for Large Scale Tests

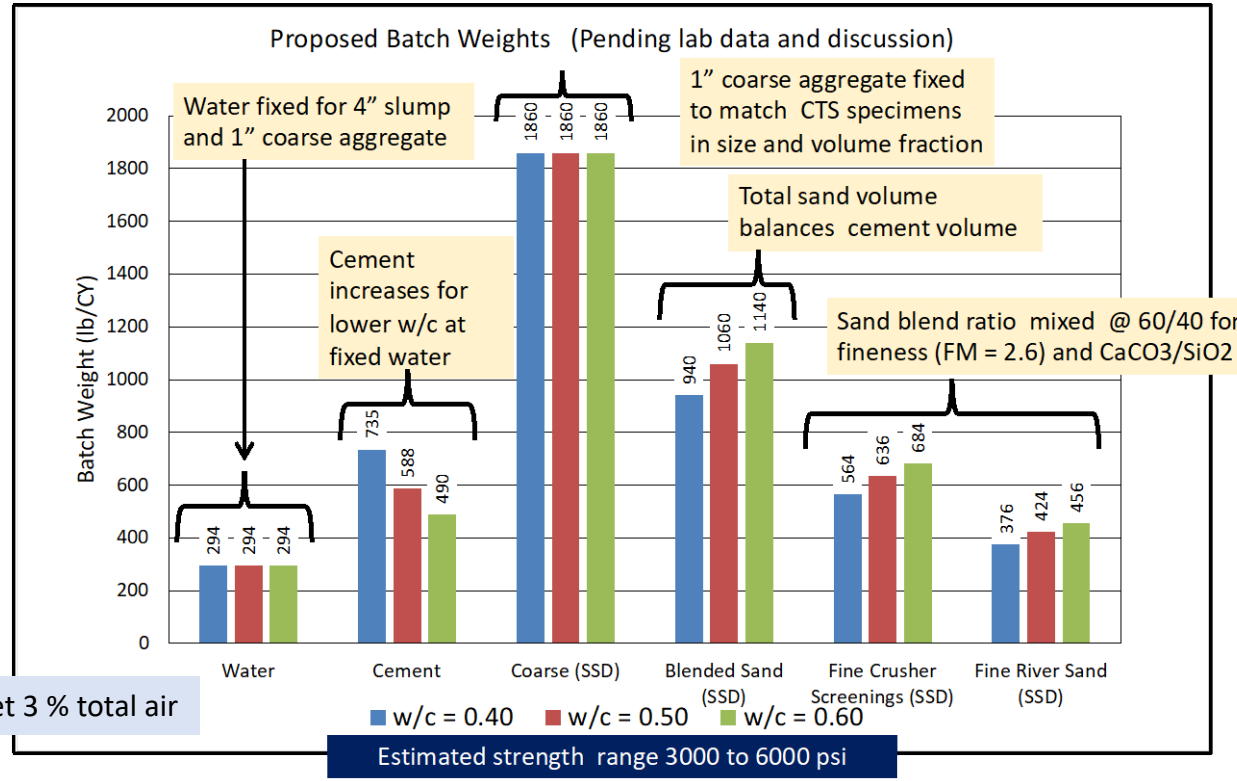
As reported in June 2023:

ACI* 211.1
Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete



Petrographic & compositional analyses

Source: NIST



Target 3 % total air

Mixture proportions

*American Concrete Institute

CTS Investigation: Concrete Production & Construction


Source: NIST

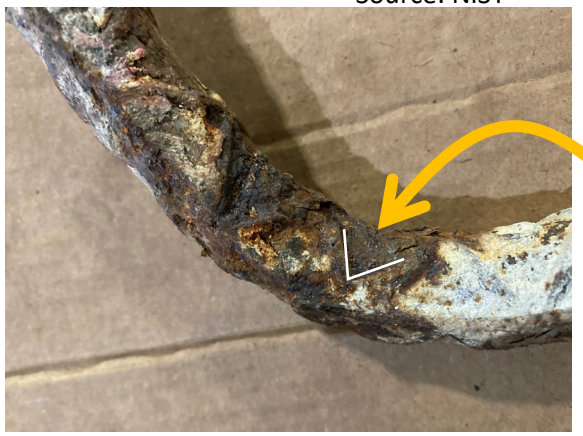

"Super-Sacks"

Source: NIST


Source: NIST

CTS Investigation: Corrosion of Reinforcing Steel

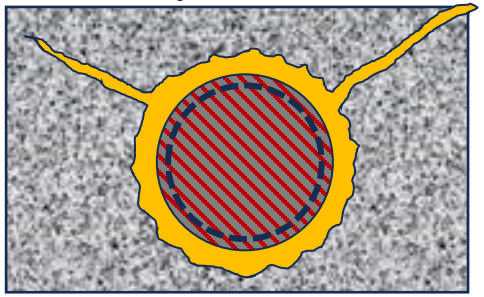
Source: NIST



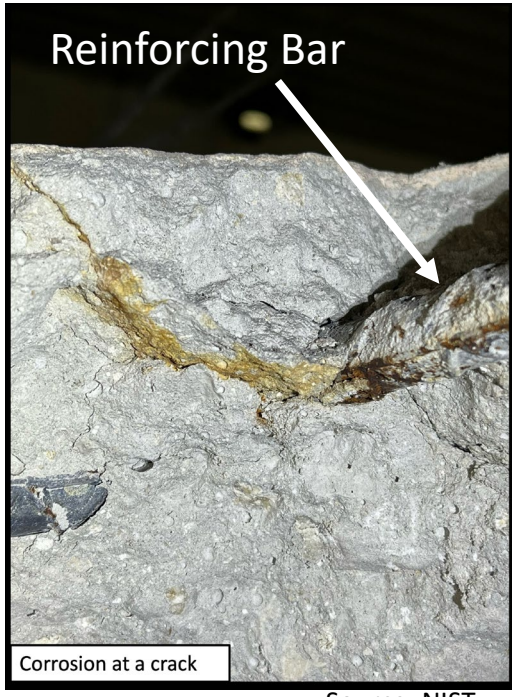
Source: NIST

Expansion of Corrosion Products

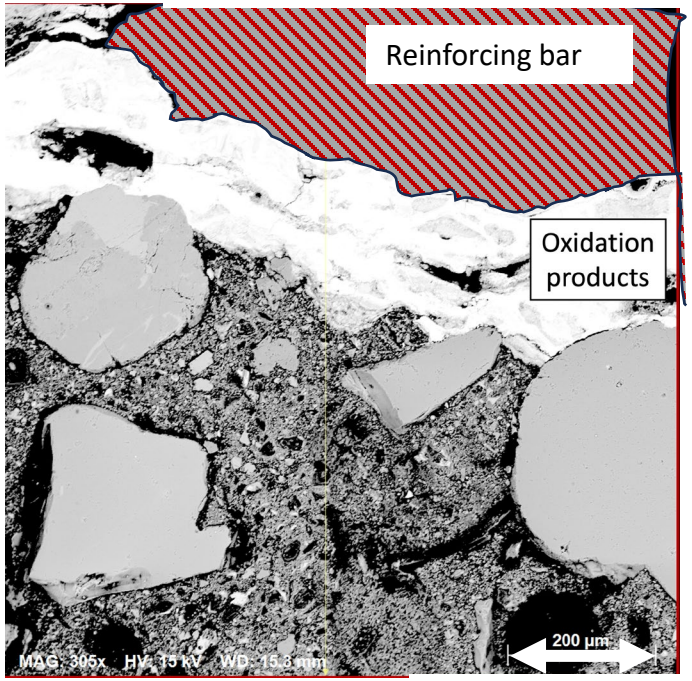
"Rust" volume occupies up to 6 times vol. of parent metal



- Bursting stresses can crack concrete
- Reduced area of steel



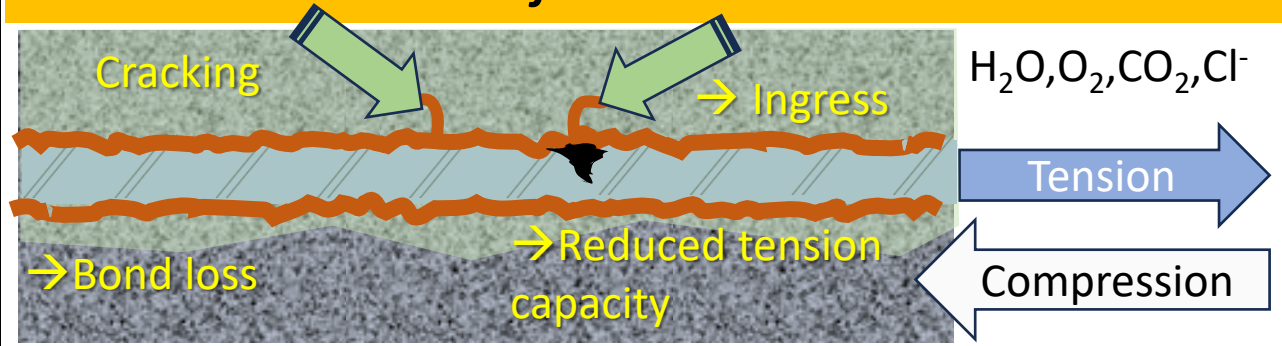
Source: NIST



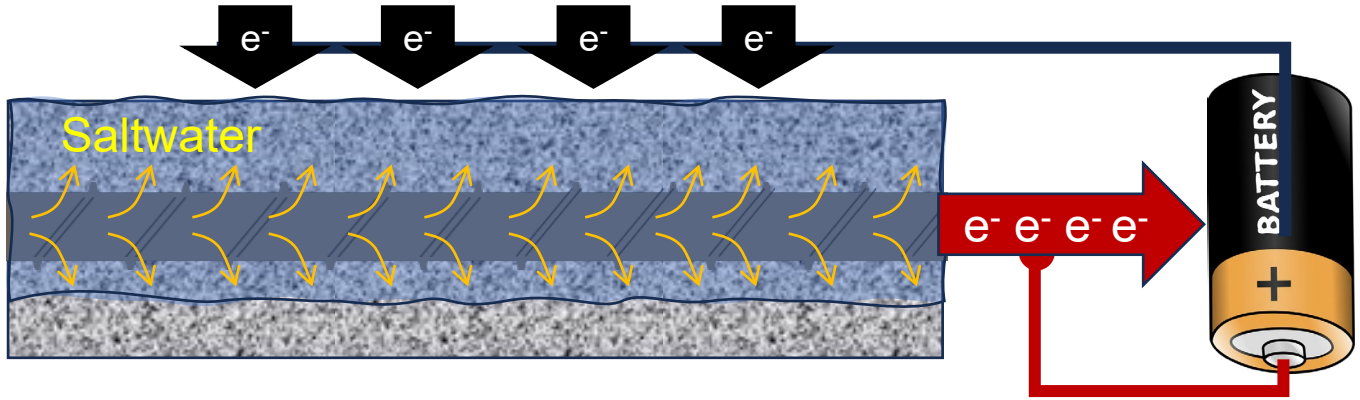
Source: NIST

0.2 mm = 0.008 in,

How corrosion influences structural behavior



CTS Investigation: Evaluating Influence of Corrosion of Reinforcing Steel

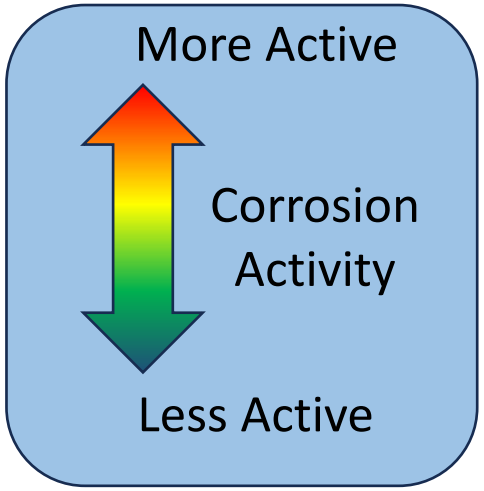


Corrosion is an electrochemical reaction:
Two electrons leave bar per corroding iron ion.

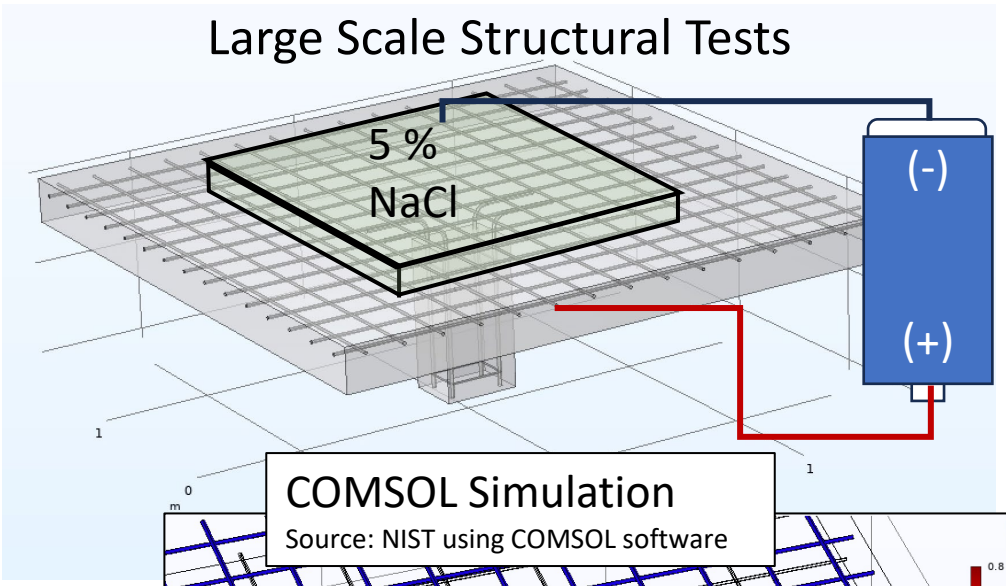
Simulations inform:

- Size of saltwater pond
- Distribution of electrical current & driving voltage
- "Current density" at key locations

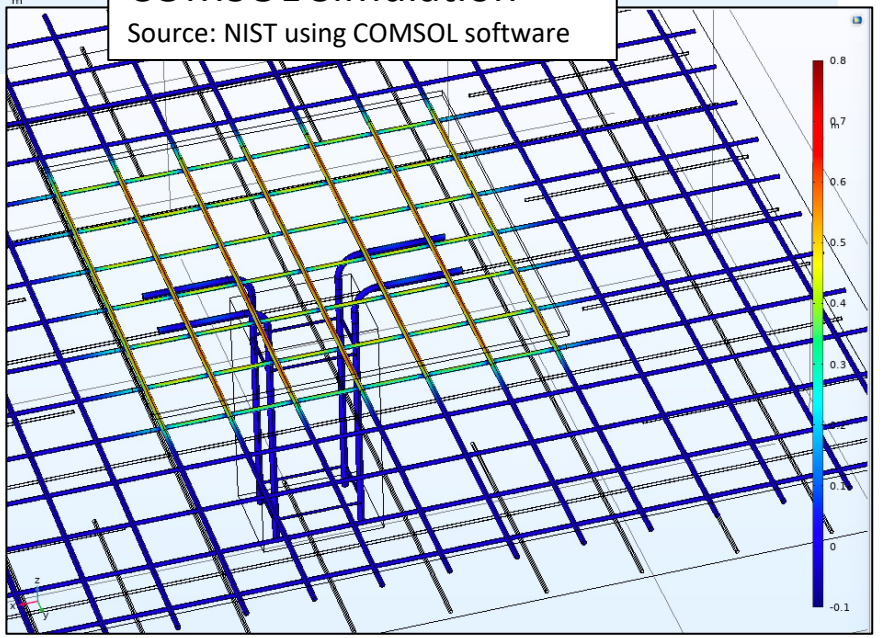
For large scale tests



Large Scale Structural Tests

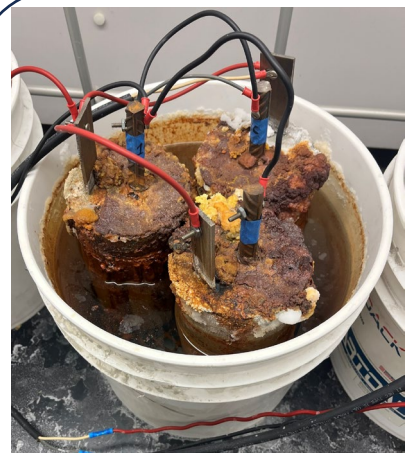


COMSOL Simulation
Source: NIST using COMSOL software



Source: NIST unless otherwise noted

CTS Investigation: Accelerated Corrosion of Reinforcing Steel



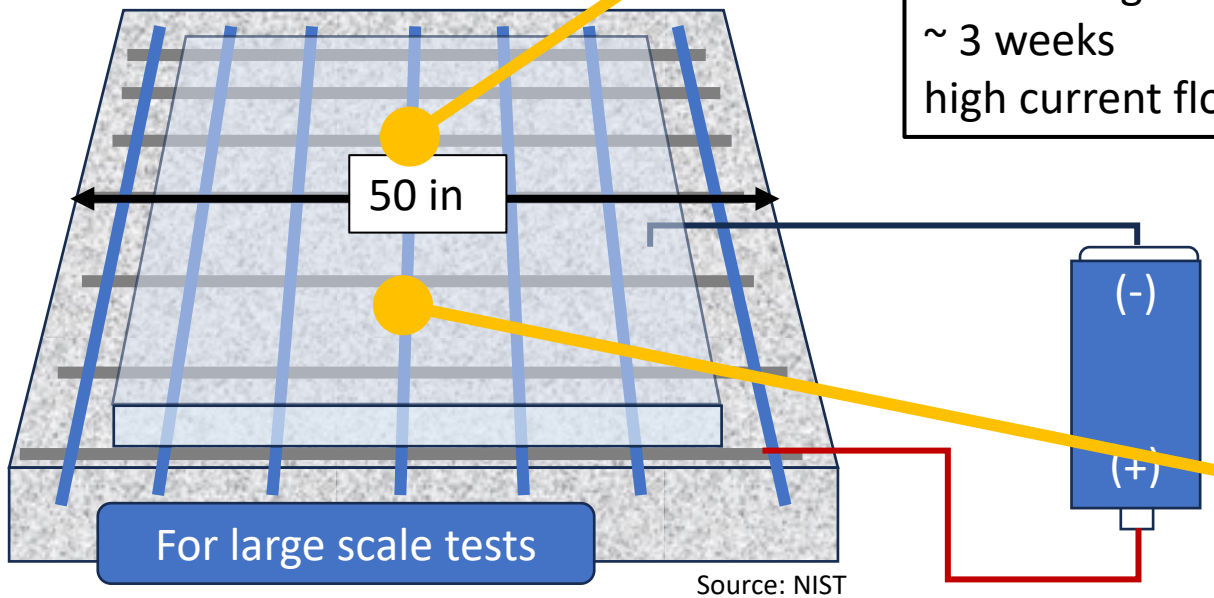
Source: NIST

Accelerated corrosion:
steel-in-concrete “Lollipops”

½-in diameter reinforcing bars
in 4-in diameter cylinders

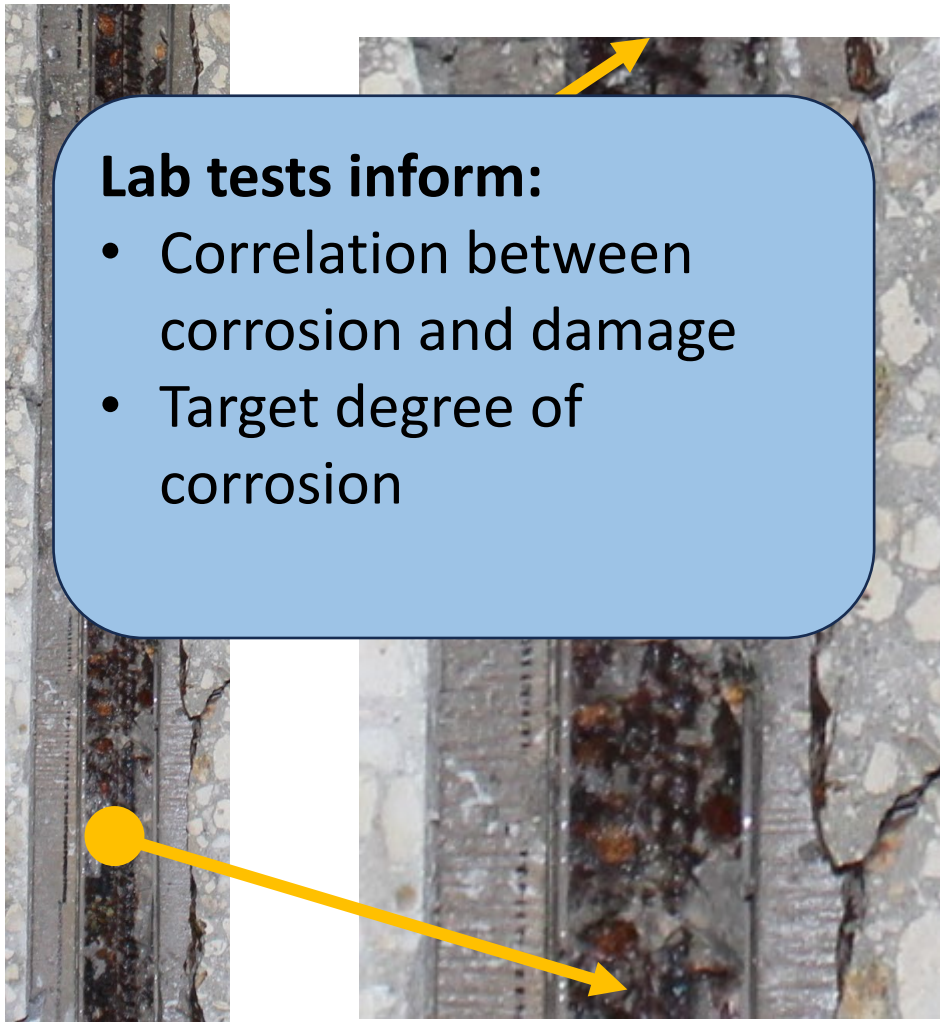
127 days, low current flow
20-25 % mass-loss

Accelerated corrosion: small slab



Source: NIST

Reinforcing bar
~ 3 weeks
high current flow



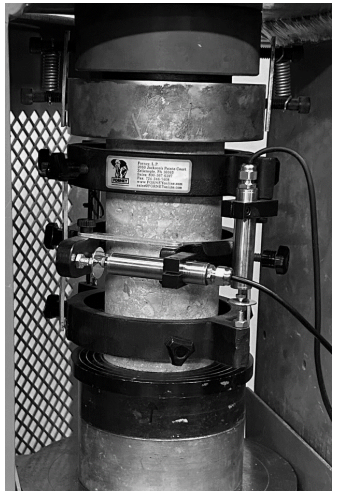
Source: NIST

Source: NIST

Lab tests inform:

- Correlation between corrosion and damage
- Target degree of corrosion

CTS Investigation: Concrete Mixtures & Corrosion



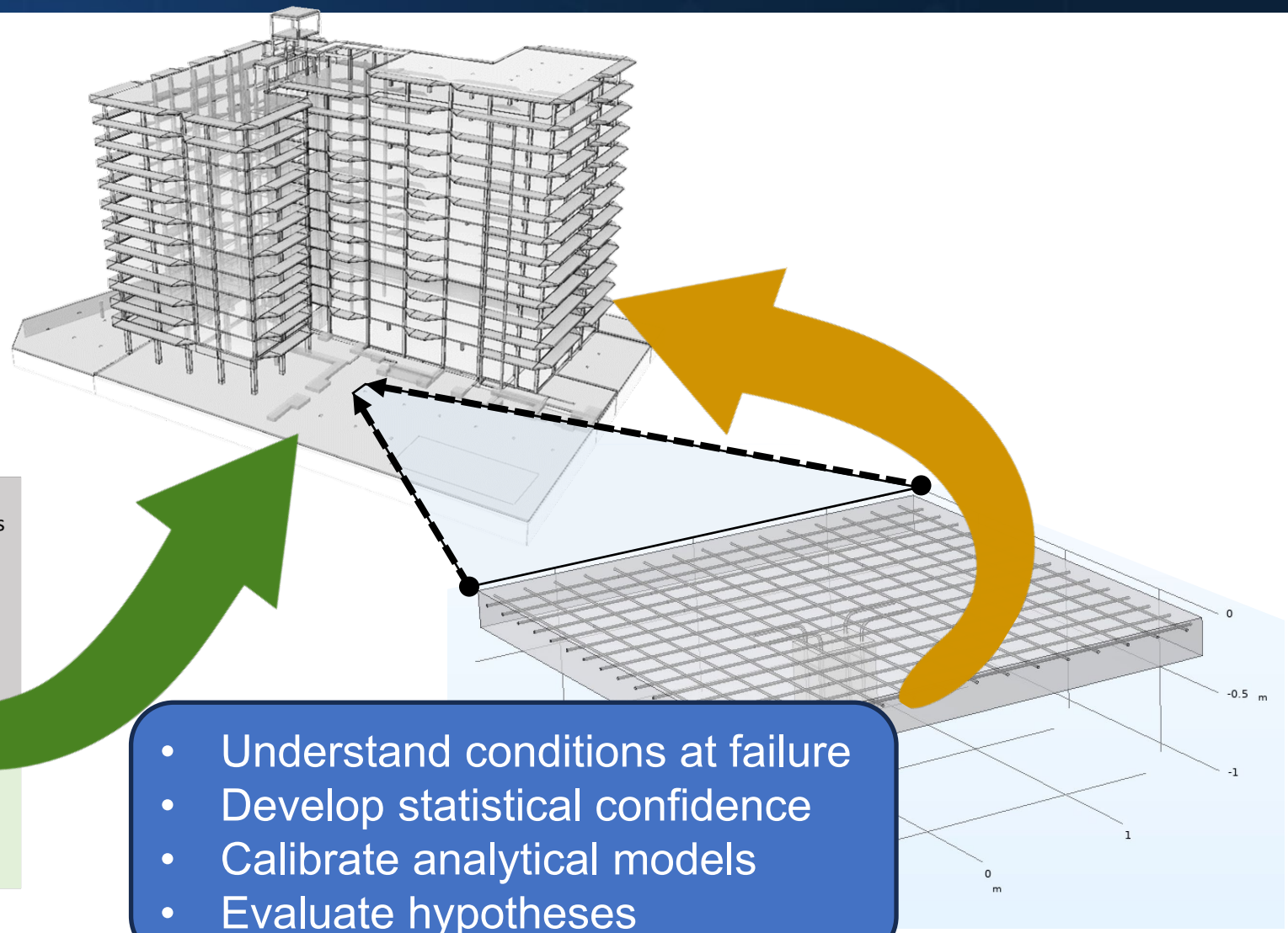
Mechanical Properties
- Compressive Strength
- Splitting Tensile Strength
- Modulus of Elasticity
- Steel strength & elongation
- Density

Steel Condition
- Distribution of corrosion
- Degree of Corrosion
- Impact on mechanical properties

Concrete Composition
- Aggregate types, sources, blends & proportions
- Cement type & proportion
- Ratio of water to cement
- Air content
- Admixtures
- Variability

Concrete Condition
- Distribution of mixtures
- Macro-cracking
- Microcracking
- Chemical changes
- Hydration
- Carbonation
- Chloride penetration
- Deleterious reaction

Transport Properties
- Absorption
- Permeability
- Diffusivity
- Resistivity



- Understand conditions at failure
- Develop statistical confidence
- Calibrate analytical models
- Evaluate hypotheses

All sources NIST

Structural Testing

Jack Moehle

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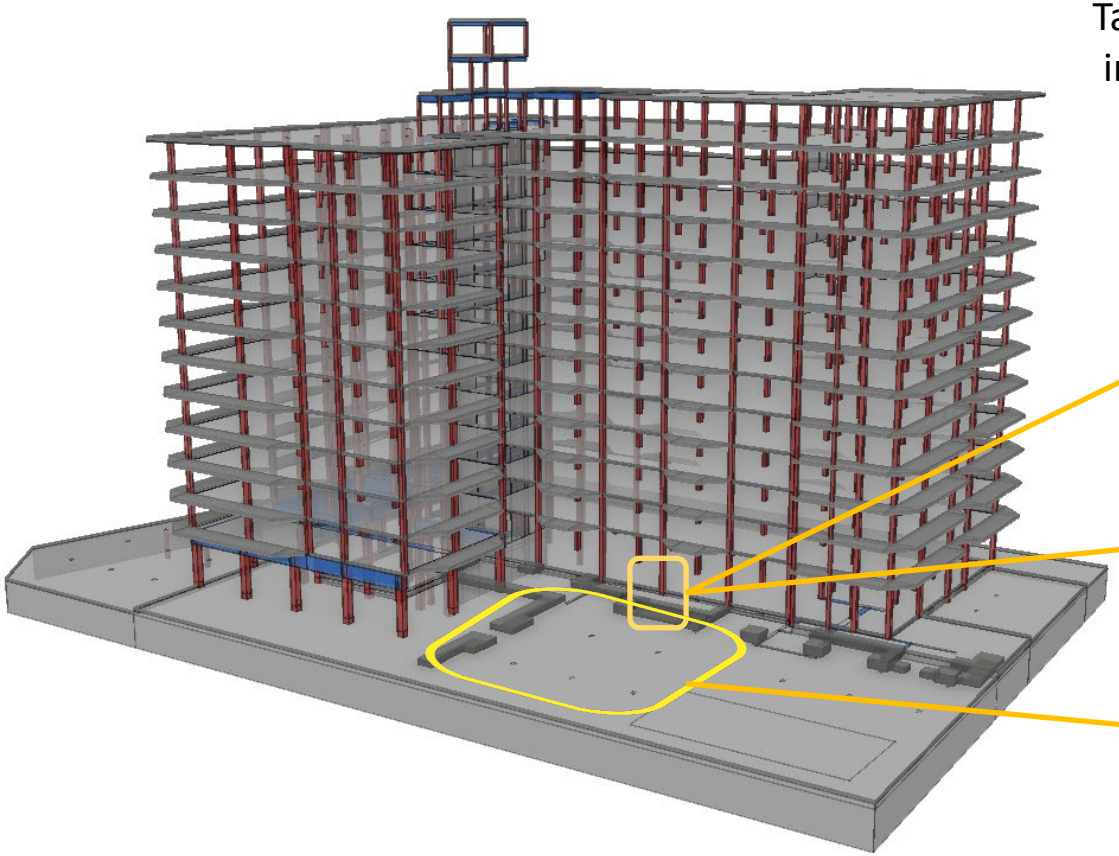
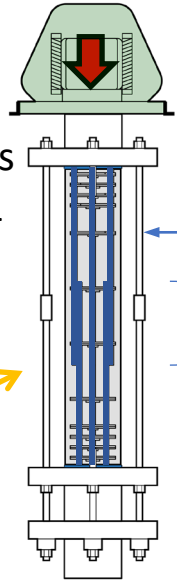
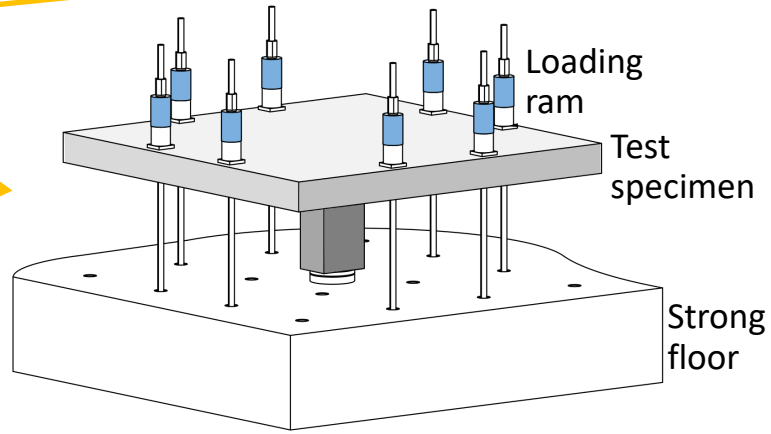
CTS Investigation: Structural Tests

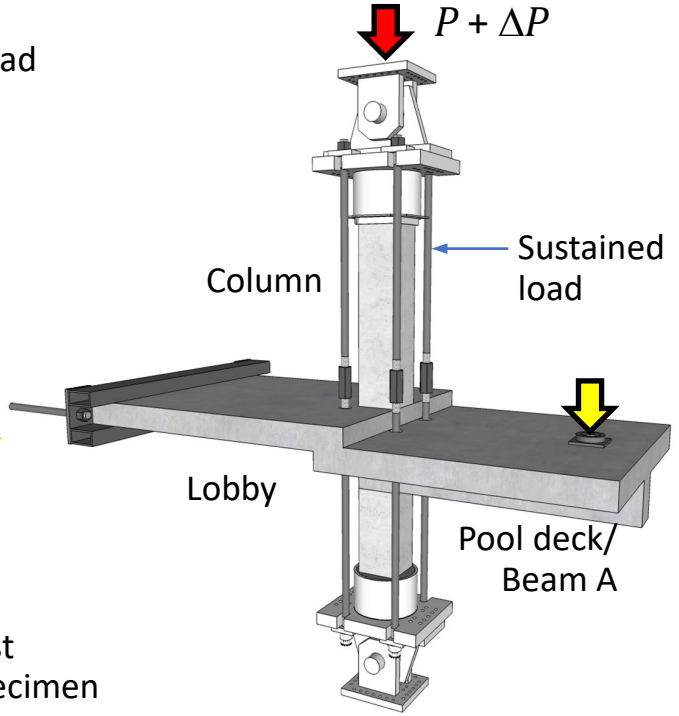


Task 3 – Lap splices in column at L-9.1



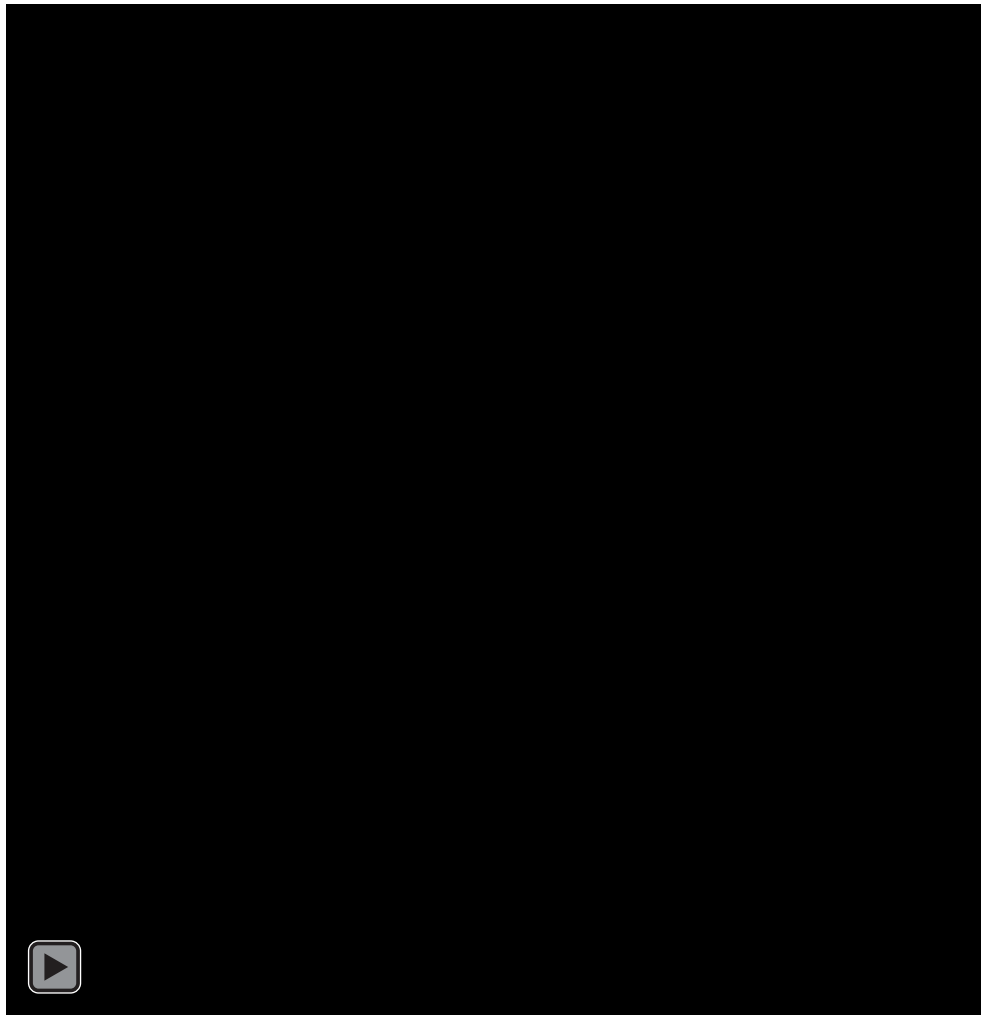


Task 1 – Slab-column connection in pool deck



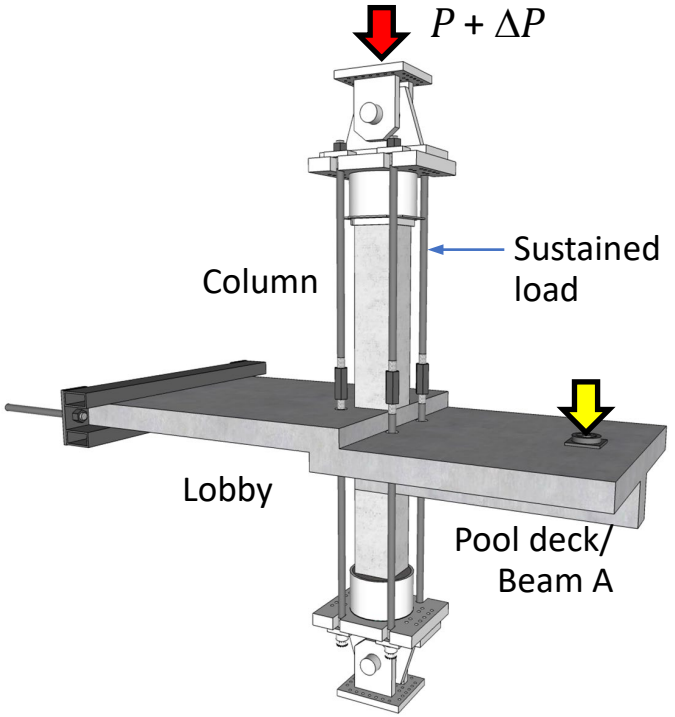
Task 2 – Connection at L-9.1

CTS Investigation: Structural Tests



Source: NIST using ATENA software

Computer Simulation of Task 2 Test



Task 2 – Connection at L-9.1

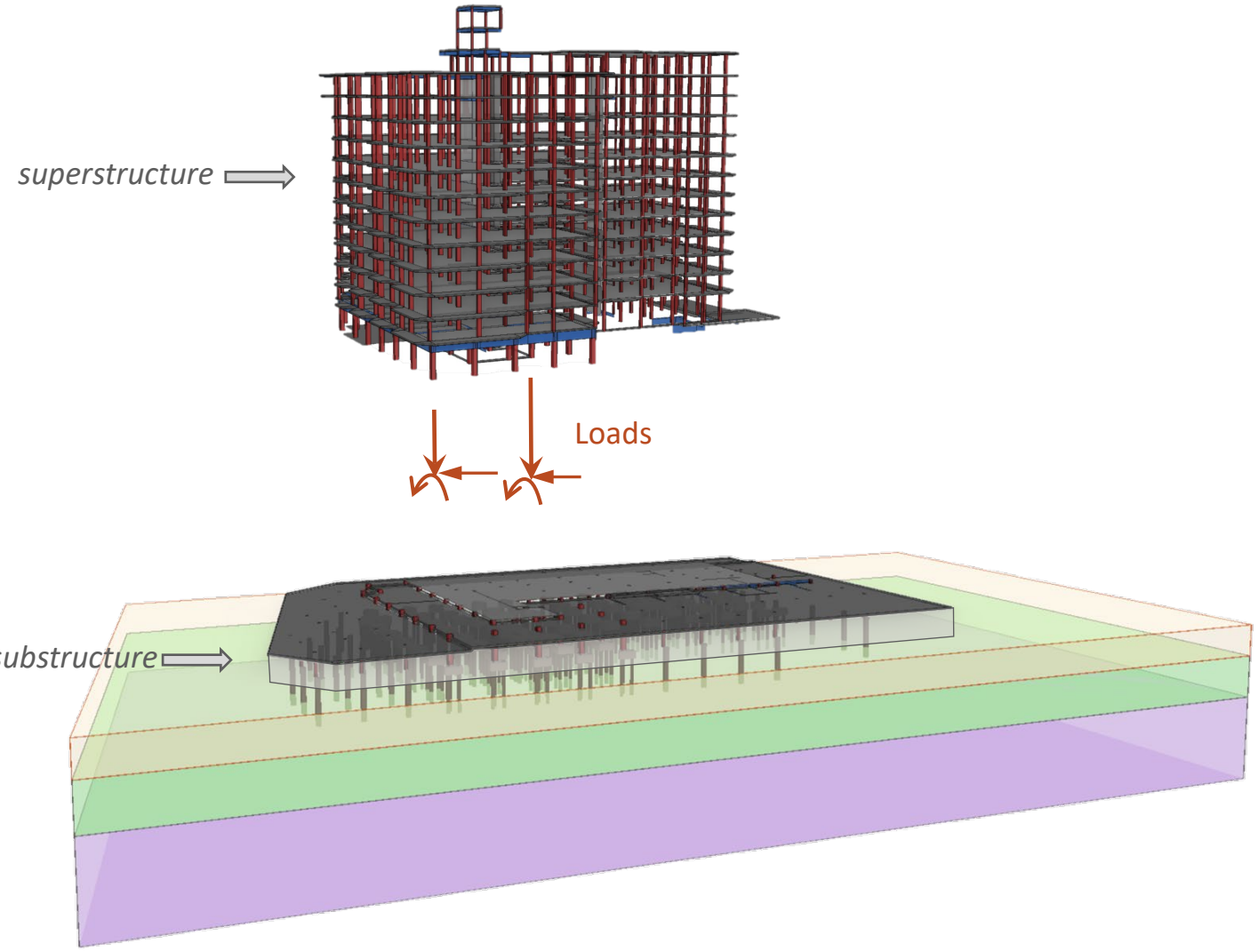
PRELIMINARY ANALYSIS RESULTS

Geotechnical Modeling and Testing

Sissy Nikolaou

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

CTS Investigation: Soil-Structure Interaction (SSI)

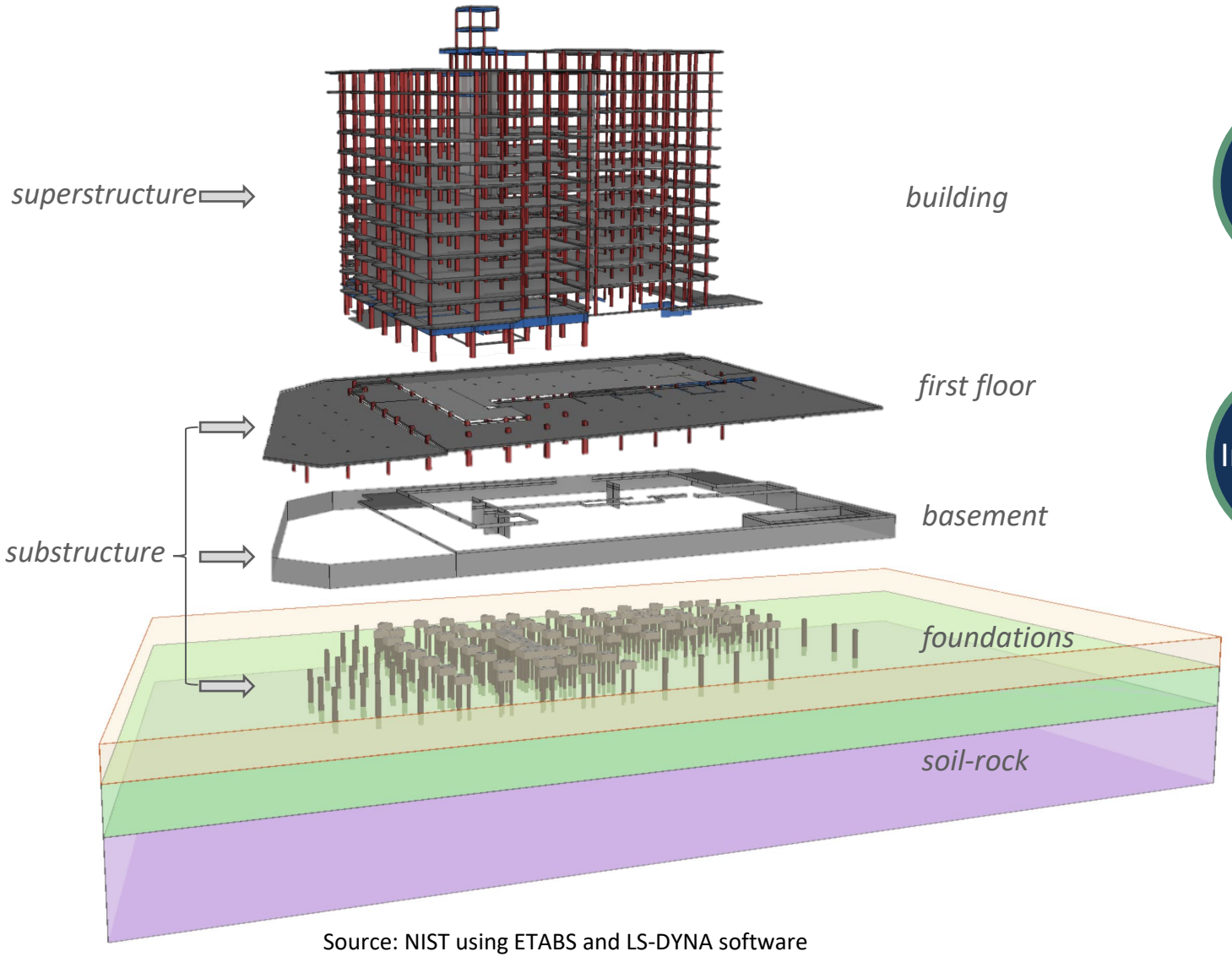


Loads

Substructure elements of soil, rock, foundation piles, and basement walls receive loads from the superstructure

Source: NIST using ETABS and LS-DYNA software

CTS Investigation: Soil-Structure Interaction (SSI)



Source: NIST using ETABS and LS-DYNA software

Loads

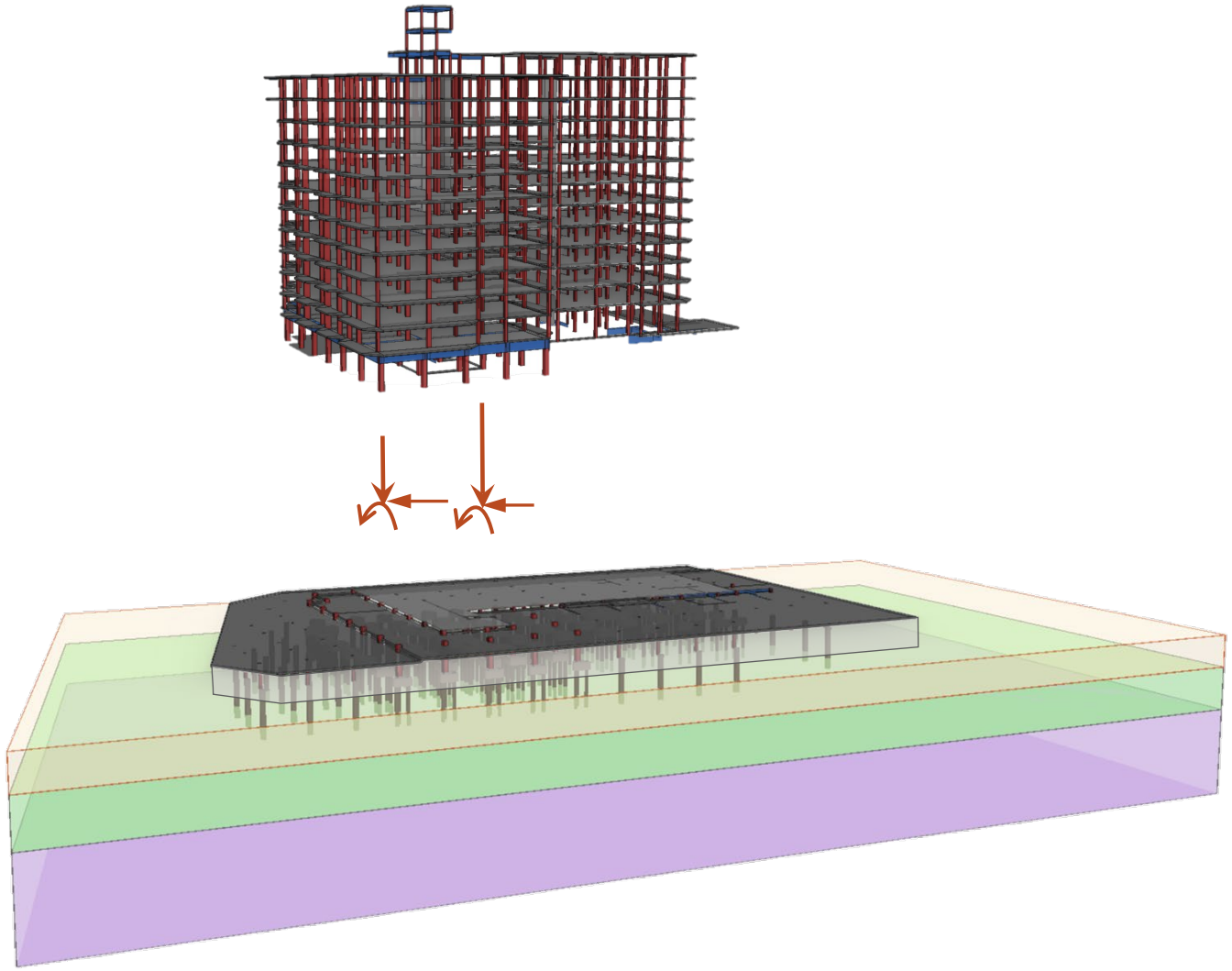
Substructure elements of soil, rock, foundation piles, and basement walls receive loads from the superstructure

and

Interaction

interact with each other and with the superstructure, depending on their relative stiffness

CTS Investigation: Soil-Structure Interaction (SSI)



Source: NIST using ETABS and LS-DYNA software

Loads

Substructure elements of soil, rock, foundation piles and basement walls receive loads from the superstructure

and

Interaction

interact with each other and with the superstructure, depending on their relative stiffness

SSI analyses require

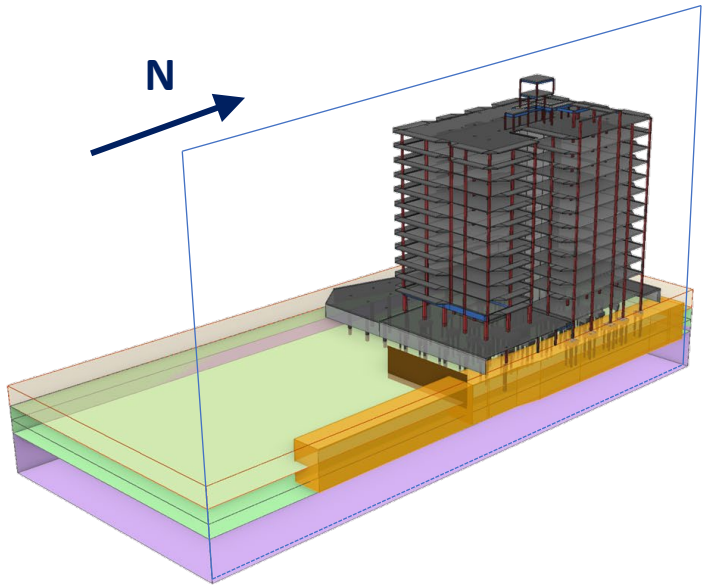
Analysis

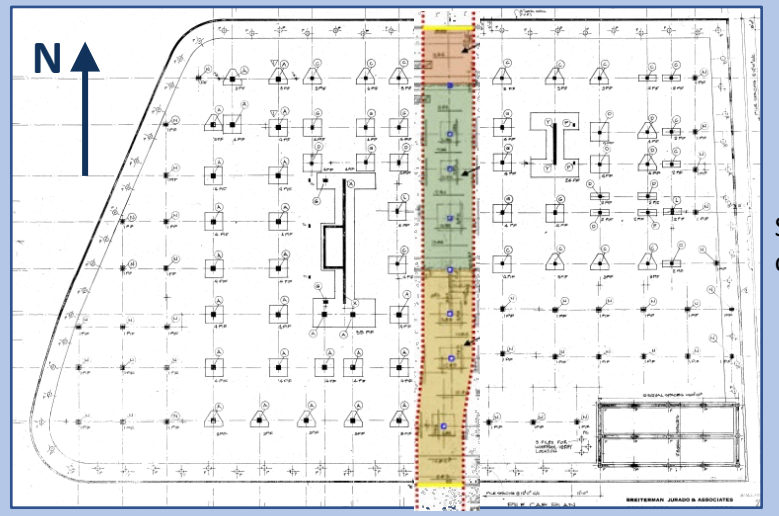
material properties of strength, stiffness, and behavior changes for various levels of loading to evaluate potential impacts of:

- differential settlement
- tidal action
- column-pile eccentricity
- construction vibrations

and more…..

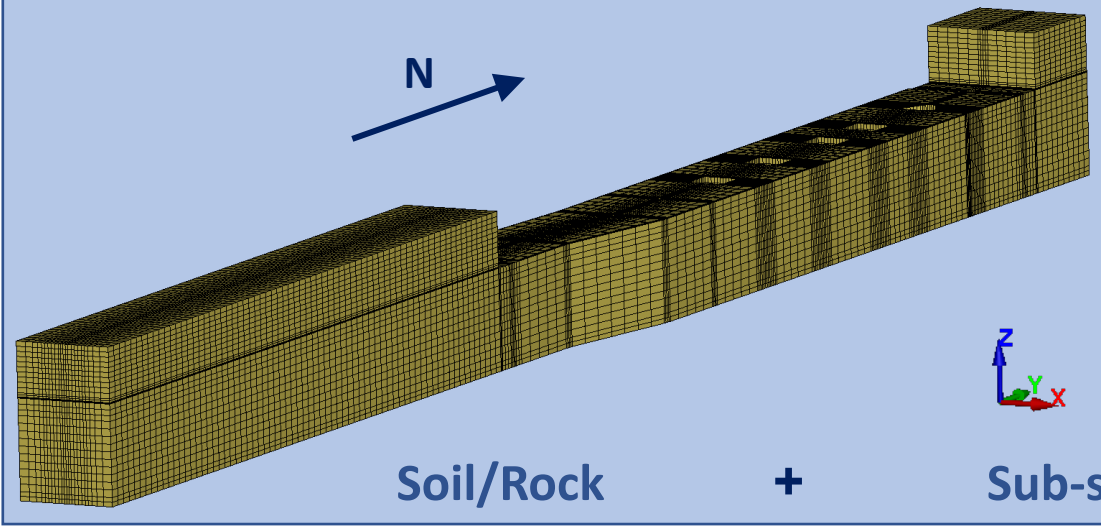
CTS Investigation: 3D Slice SSI Simulations



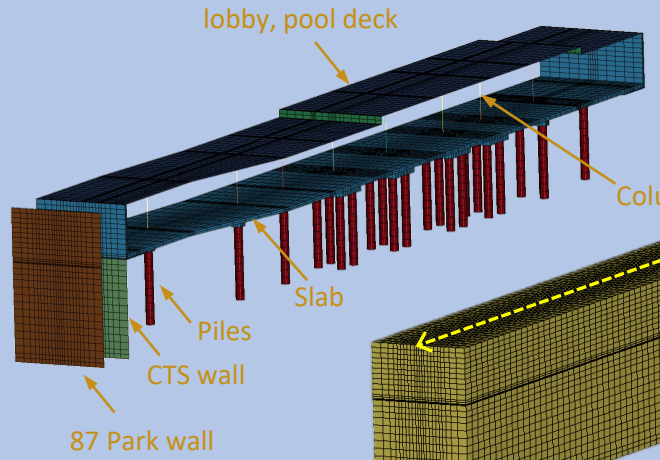


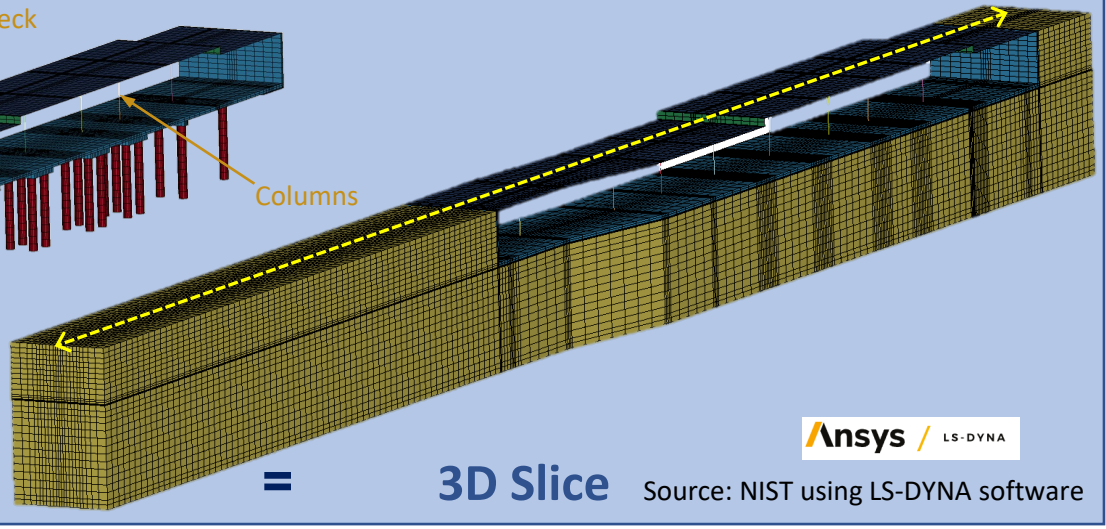
Source: Town of Surfside

Design Drawings



Soil/Rock + **Sub-structural**



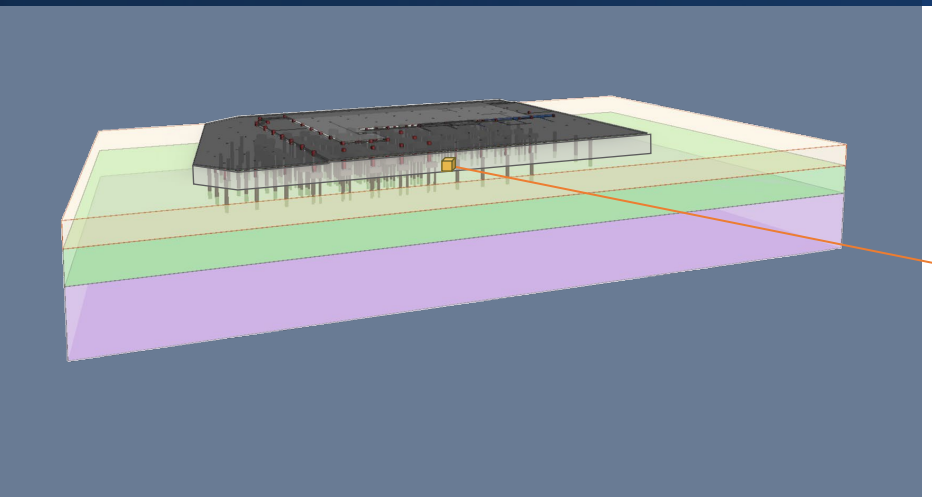


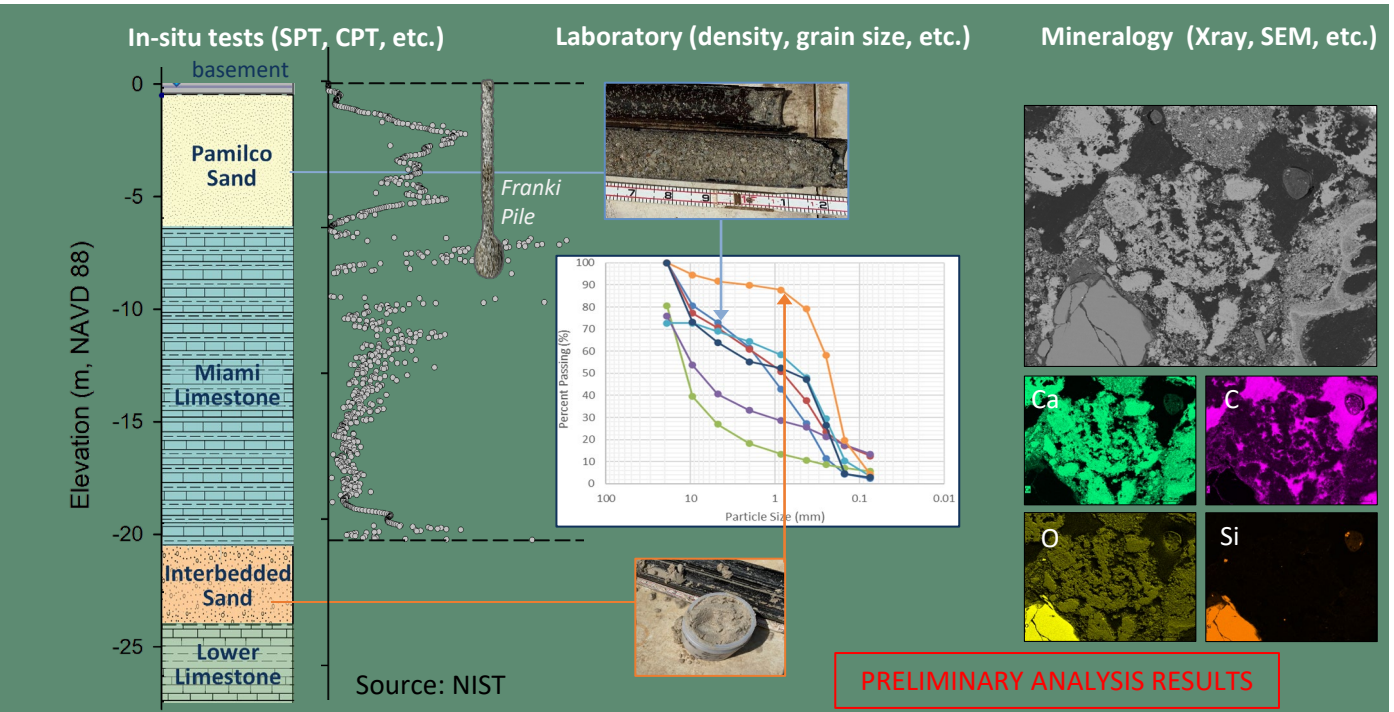
= **3D Slice**

Ansys / LS-DYNA

Source: NIST using LS-DYNA software

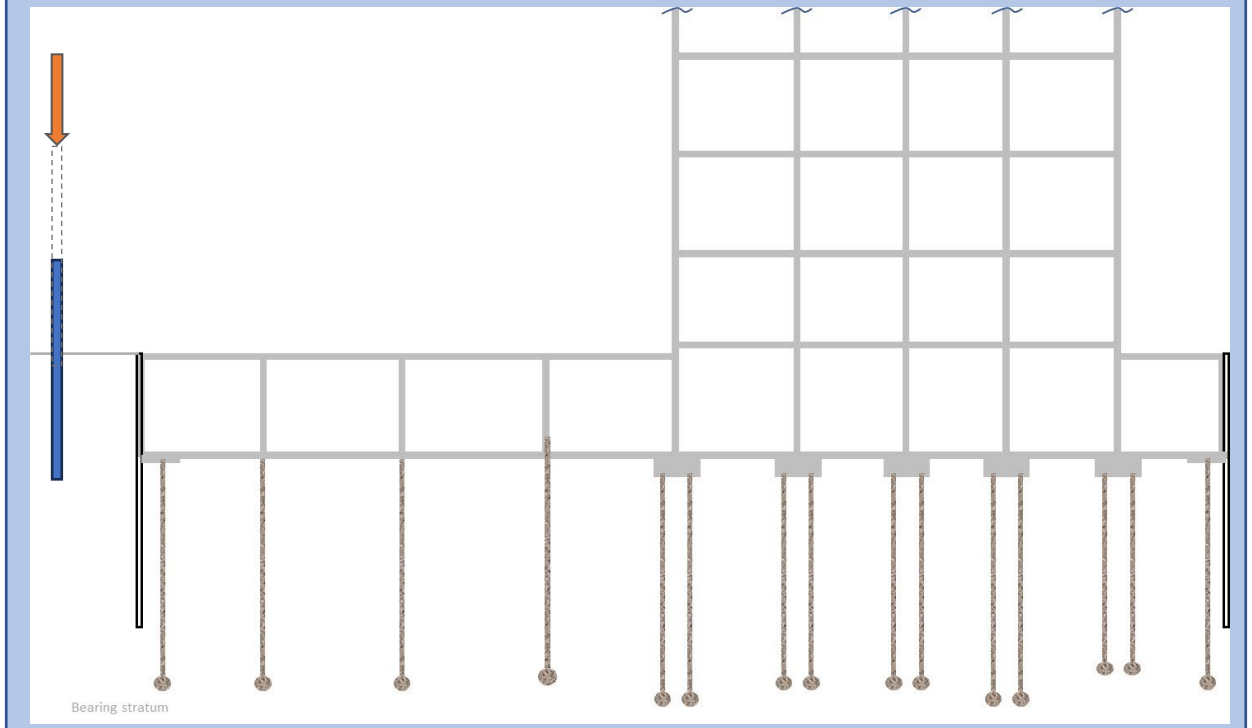
CTS Investigation: Testing and Properties for SSI



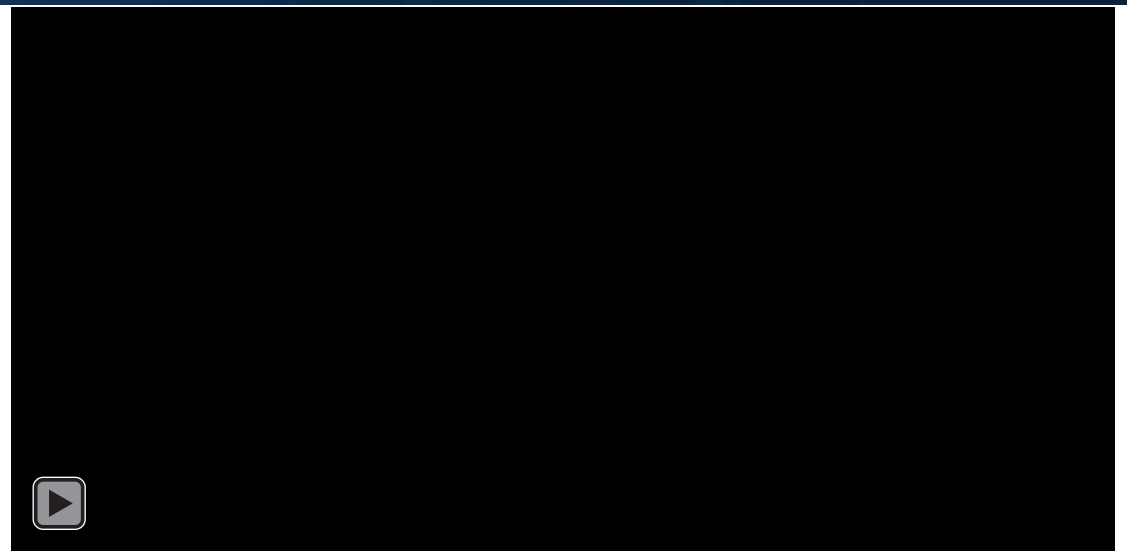


CTS Investigation: An SSI Application -- Vibrations Impacts

Construction-induced vibrations



Source: NIST



Structural Collapse Modeling

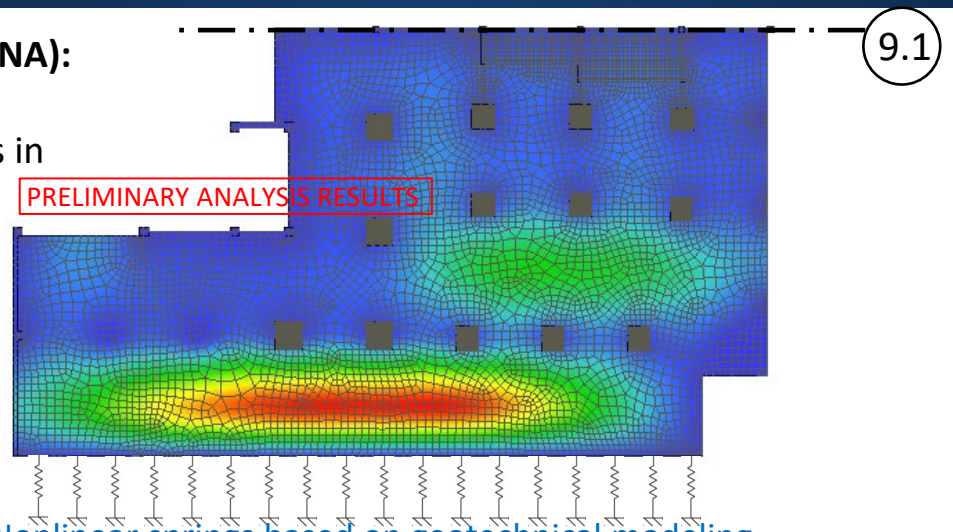
Fahim Sadek

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

CTS Investigation: Structural Collapse Modeling

(1) Pool deck slab model (ATENA):

- Evaluate multiple potential failure initiation mechanisms in pool deck slab
- Model addresses several behaviors and failure modes including flexure, shear, punching, shrinkage, creep, corrosion, and degradation.



Nonlinear springs based on geotechnical modeling

Sources: NIST using ATENA and LS-DYNA software

CTS Investigation: Structural Collapse Modeling

(1) Pool deck slab model (ATENA):

- Evaluate multiple potential failure initiation mechanisms in pool deck slab
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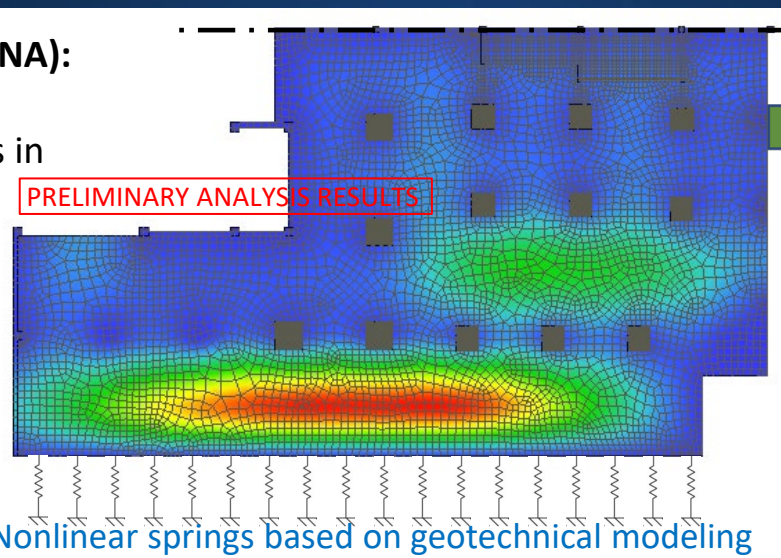
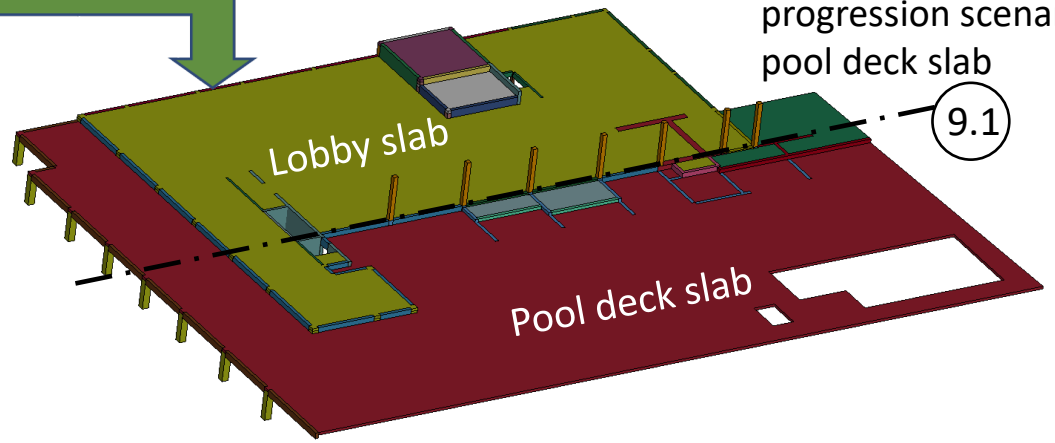


(2) First floor slab (LS-DYNA):

- Evaluate potential failure progression scenarios in pool deck slab



Sources: NIST using ATENA and LS-DYNA software

CTS Investigation: Structural Collapse Modeling

(1) Pool deck slab model (ATENA):

- Evaluate multiple potential failure initiation mechanisms in pool deck slab
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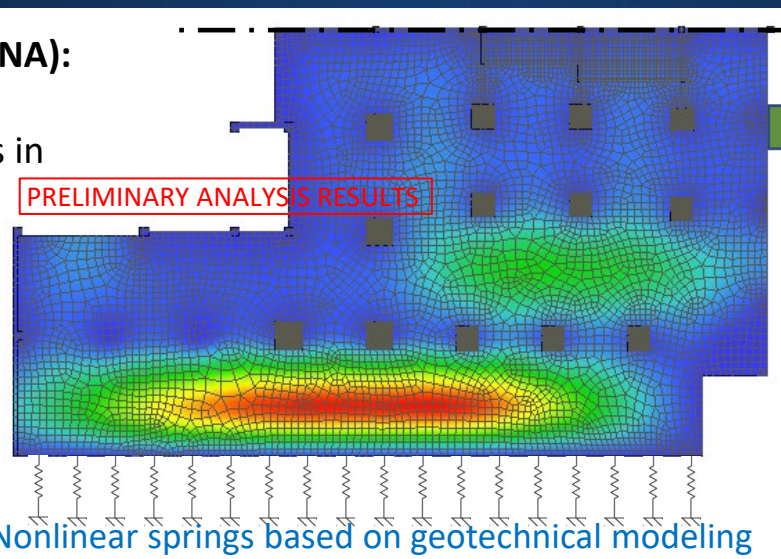

(2) First floor slab (LS-DYNA):

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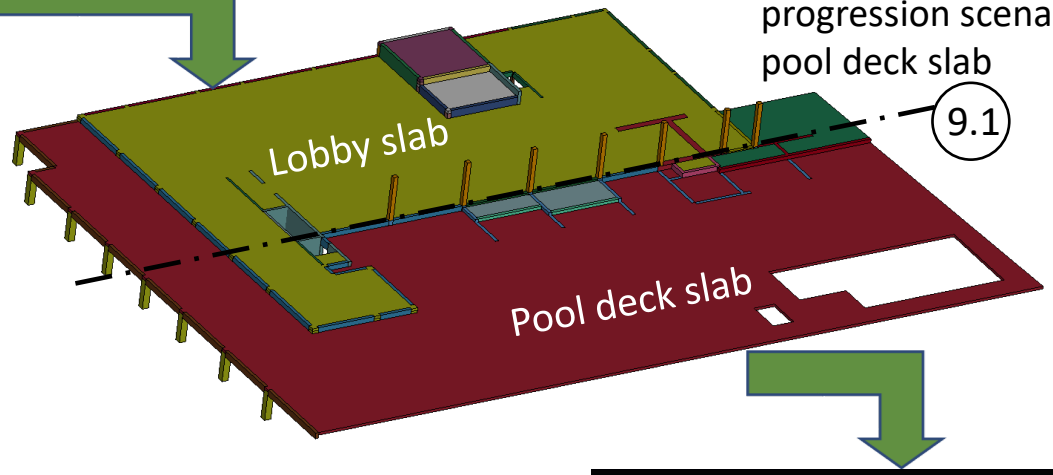
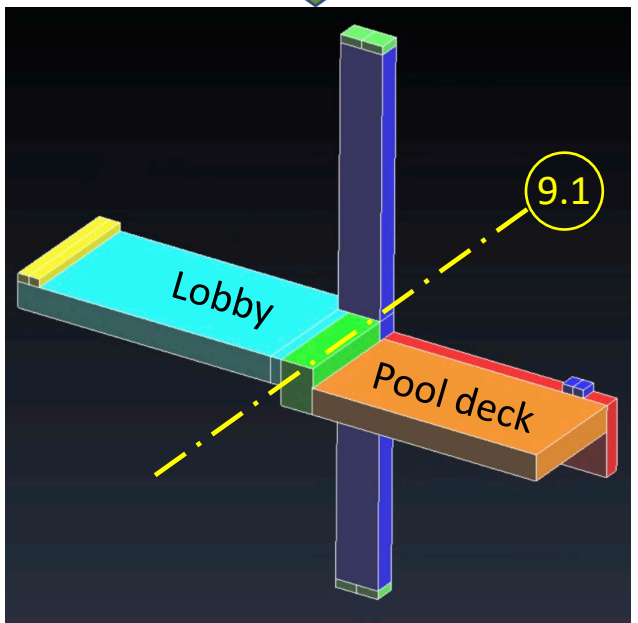


(3) Slab-beam-column connection (ATENA):

- Evaluate potential failure progression mechanisms at pool deck slab-tower interface
- Validate against experimental data



Sources: NIST using ATENA and LS-DYNA software

CTS Investigation: Structural Collapse Modeling

(1) Pool deck slab model (ATENA):
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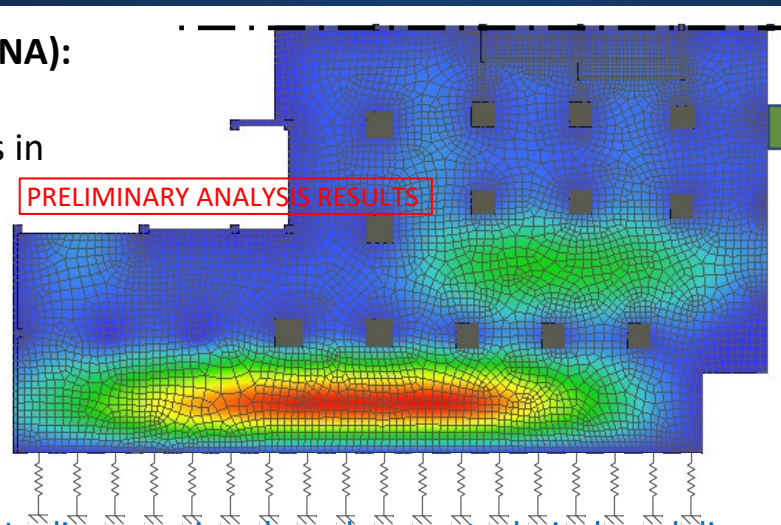
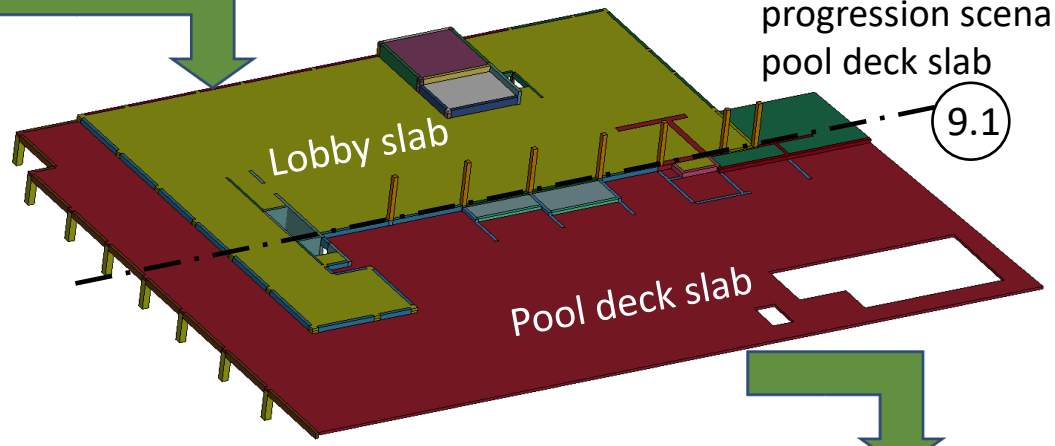
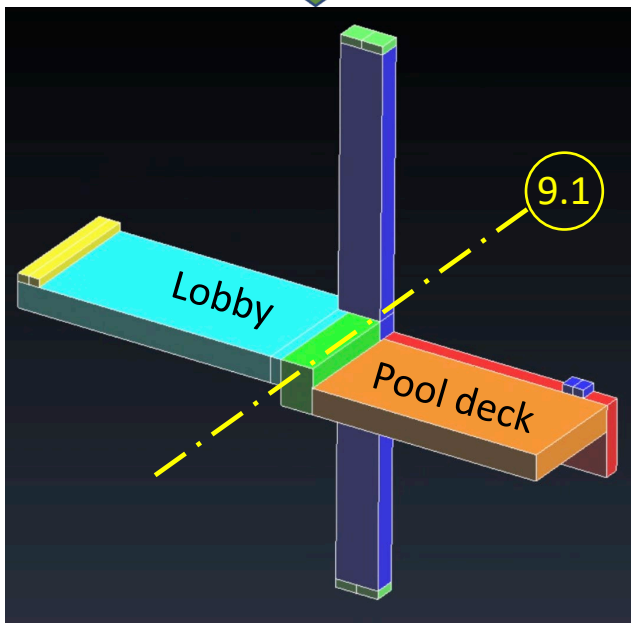


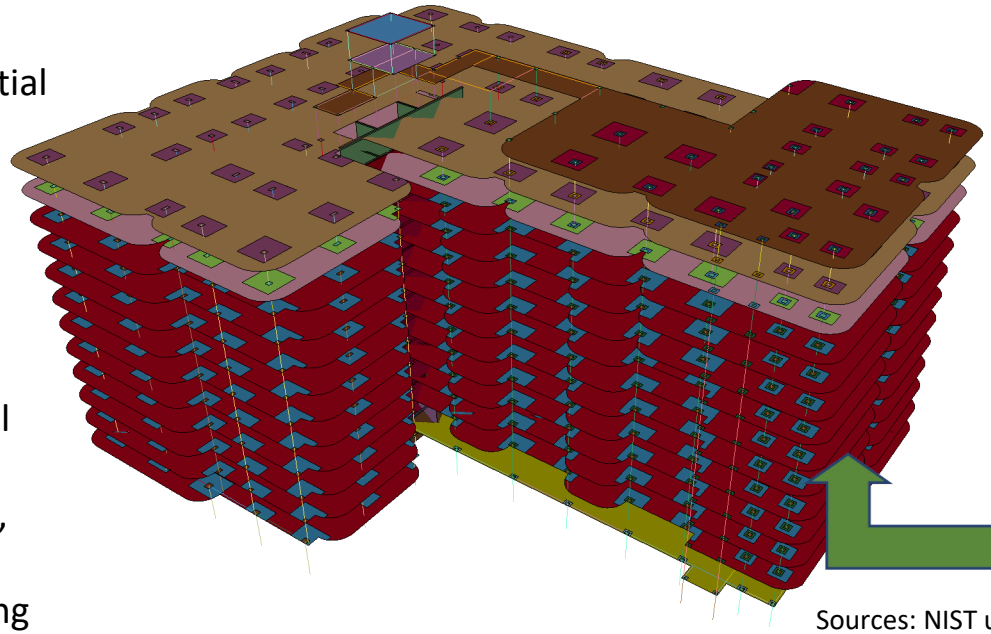
(2) First floor slab (LS-DYNA):
- Evaluate potential failure progression scenarios in pool deck slab



(3) Slab-beam-column connection (ATENA):
- Evaluate potential failure progression mechanisms at pool deck slab-tower interface
- Validate against experimental data



(4) Global tower model (LS-DYNA):
- Evaluate multiple potential failure progression mechanisms within the tower
- Explore possible failure initiation mechanisms within the tower
- Model addresses several behaviors and failure modes including flexure, shear, punching, and column buckling/crushing



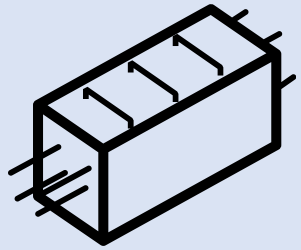
Sources: NIST using ATENA and LS-DYNA software

Questions?

Theme 1:
Timeline and Evidence Collection

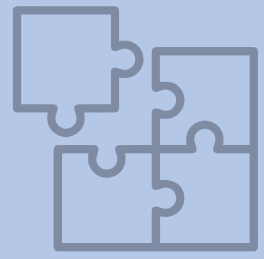
Judith Mitrani-Reiser, N. Emel Ganapati, David Goodwin, Christopher Segura, Jonathan Weigand, Kam Saidi, Jack Moehle

Theme 2:
Analysis and Testing Updates



Fahim Sadek, James Harris, Christopher Segura, Kenneth Hover, Jack Moehle, Sissy Nikolaou

Theme 3:
Analysis of Failure Hypotheses



Glenn Bell, Fahim Sadek, Georgette Hlepas, Scott Jones, James Harris, Youssef Hashash

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