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AISC Live Webinars

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AISC Live Webinars

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AISC Live Webinars

Course Description

The Structural Stability Game Show!
September 25, 2020

This webinar will feature a panel of engineers and academics, who will present their views on the root cause of three structural collapse case studies. The audience will then be given an opportunity to vote on which cause was most likely. Finally, the moderator will reveal and explain the true nature of the collapse.



AISC Live Webinars

Learning Objectives

- Identify sources of instability for several structural configurations.
- Describe methods for how to approach stability analysis computationally and experimentally.
- Show how the structural factor of safety can be significantly impacted if one neglects considering stability.
- Explain the importance of communication during the design and construction of a project with case studies.



The Structural Stability Game Show!



Cliff D. Bishop
Exponent



Patricia Clayton
UT Austin



Larry Griffis
Walter P. Moore



John D. Hooper
Magnusson Klemencic



Ron Ziemian
Bucknell University

SteelDay
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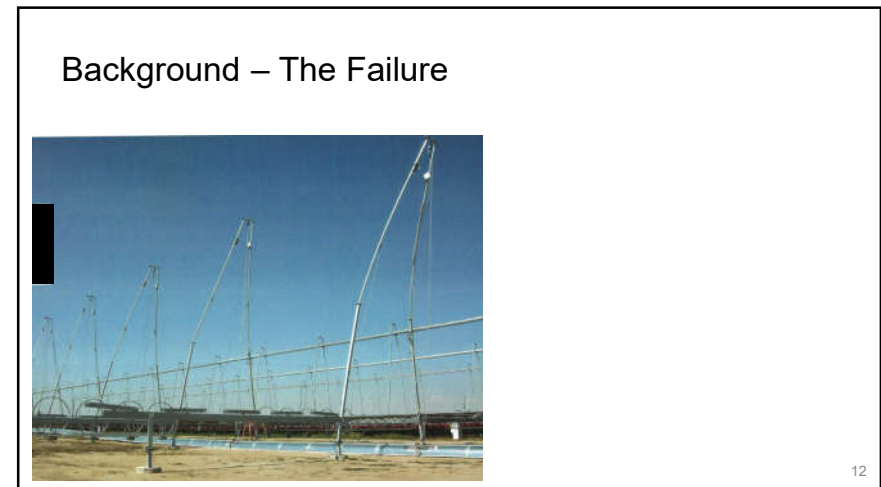
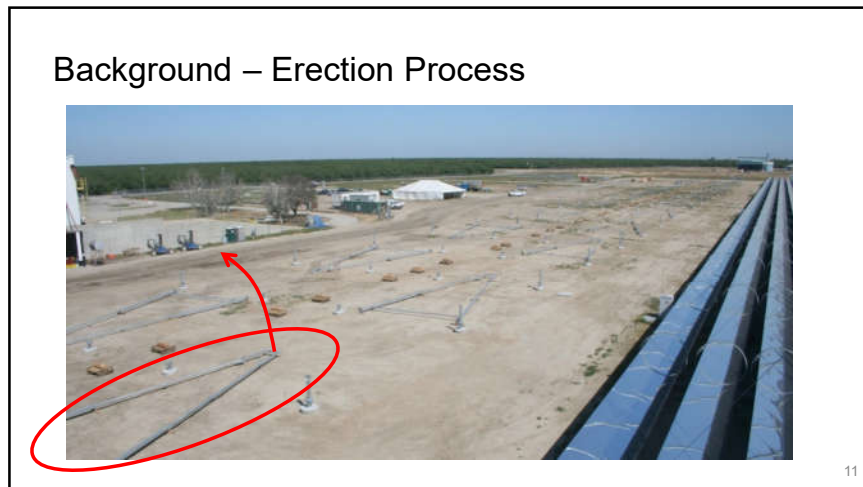
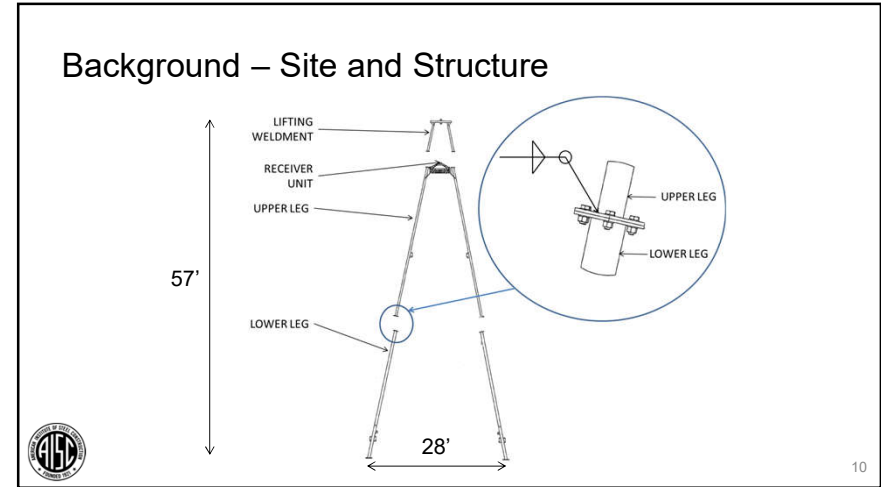
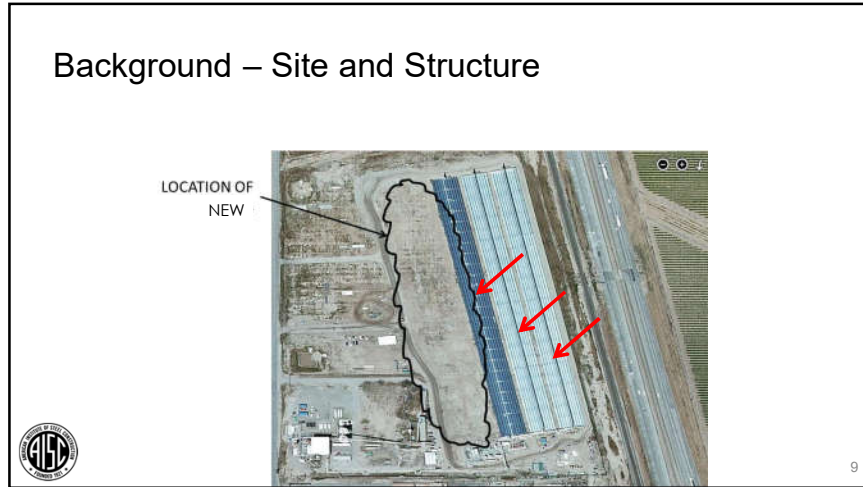
September 25, 2020
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Case 1: Solar power support structure

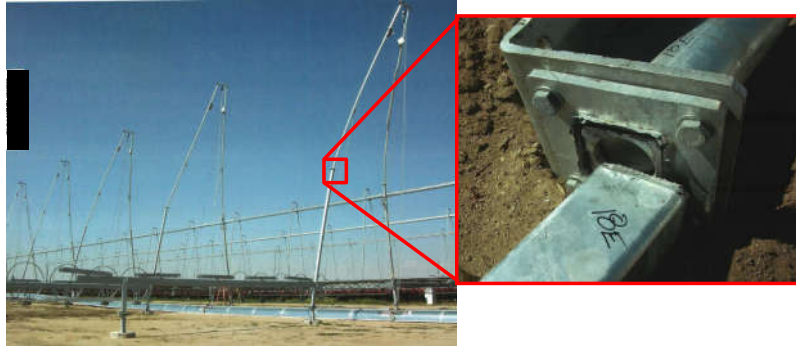


8





Background – The Failure



13

Contestants' discussion of root cause



14

Contestants' discussion of root cause

A. Weld failure



15

Contestants' discussion of root cause

A. Weld failure




B. Inadequate design





16




Contestants' discussion of root cause

A. Weld failure 


B. Inadequate design 


C. Poor construction sequencing 





17


Contestants' discussion of root cause

A. Weld failure 

B. Inadequate design 


C. Poor construction sequencing 


D. Extreme weather 





18

What was the root cause?


A. Weld failure 

B. Inadequate design 

C. Poor construction sequencing 


D. Extreme weather 


**Time
to
Vote!**





19

What was the root cause?


A. Weld failure 

B. Inadequate design 

C. Poor construction sequencing 

D. Extreme weather 

**Select
your
answer!**



20

What was the root cause?

A. Weld failure



B. Inadequate design



C. Poor construction sequencing



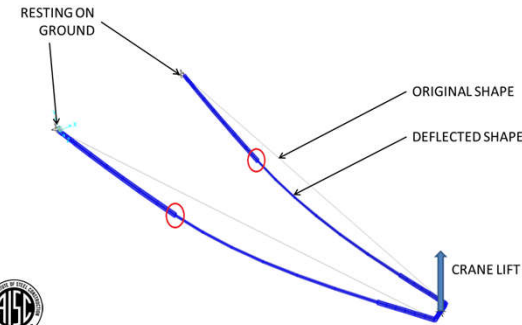
D. Extreme weather



21

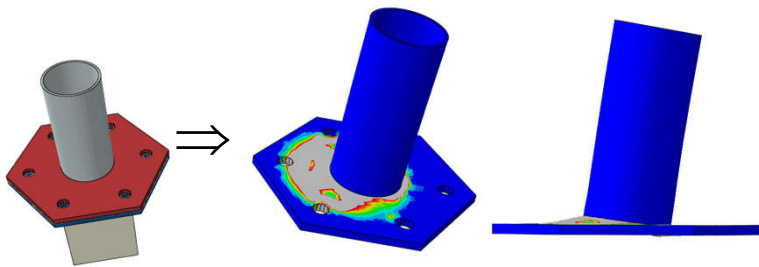
Sufficient weld

max. moment at welds
between upper and lower
weldment is
95 kip-in.



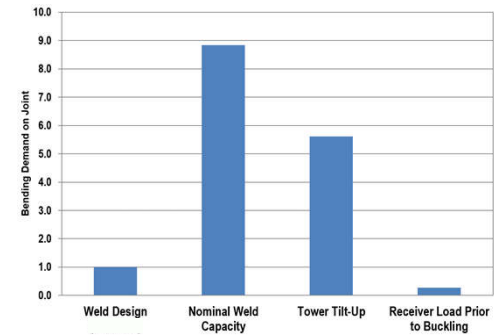
22

Sufficient weld



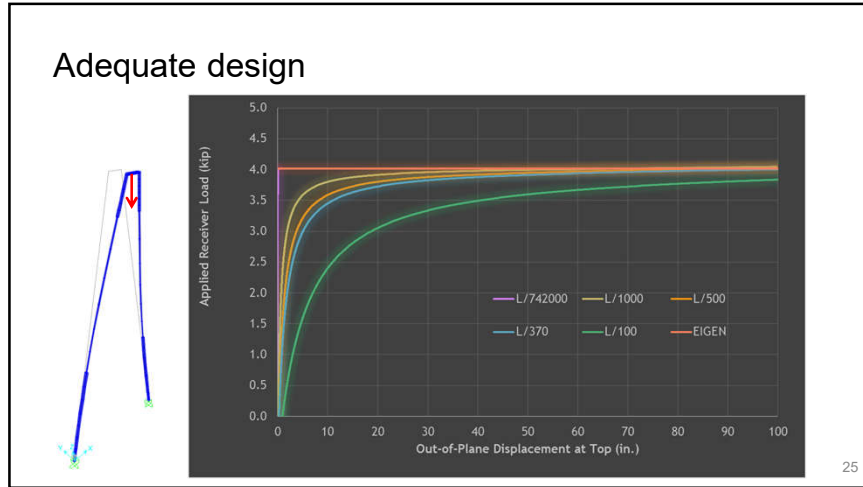
23

Sufficient weld



24



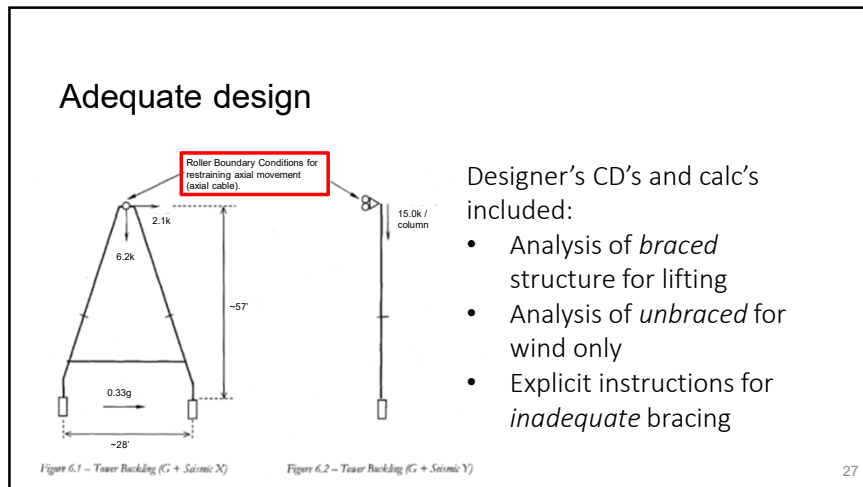


Adequate design

Model	Top Bracing?	Total Load (kips)	
		Eigen	L-D
Case 1: Self-weight only	Unbraced	17.8	-
Case 2: Receiver + self-weight	Unbraced	6.1	5.6
Case 3: Receiver + self-weight	Fully Braced	30	-

weight of tower + receiver
4.8 kips + 2.1 kips = 6.9 kips

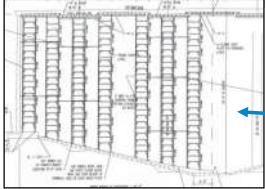
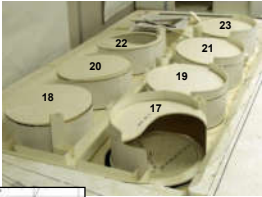
26



Case 2: Dome scaffolding collapse

28


Background



- Project required construction of 7 digester tanks
- Tanks were numbered from 17 to 23
- Dimensions
 - 125-ft diameter concrete tank
 - 50-ft tall
 - 1-ft thick wall and slab
- Base of tanks slopes down towards center
- Aluminum falsework used to support formwork and deck pour

29

Background




At the Time of the Accident:

- Tanks 17 and 18 had already been constructed; roof decks poured without incident
- Tank 19 was ready for concrete deck pour
- Tanks 20 and 21 had the falsework almost fully installed

30

Background



At the Time of the Accident:

- Concrete roof was being placed in Tank 19, moving south to north
- A little over half of the concrete had been placed


31

The failure



32


The Failure



- Falsework supporting the plywood in Tank 19 collapsed
- 29 persons on the roof deck
- 14 workers injured; 4 serious; **none** fatally injured
- Tanks 19, 20, and 21 were immediately put under Cal OSHA Order to Preserve, pending investigation

33

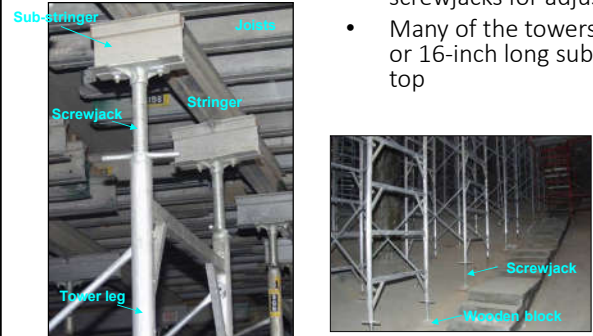
Scaffold Layout



- Plywood formwork for concrete deck was supported on aluminum beams
- Layers of aluminum beams supported on aluminum shoring towers

34


Scaffold Layout



- Top and bottom of the towers had screwjacks for adjustable extension
- Many of the towers also had 12-inch or 16-inch long sub-stringers at the top

35

Scaffold Layout



36

Observations – Tank 19



So... What caused the failure?

37

Contestants' discussion of root cause



38

Contestants' discussion of root cause

A. Stringer web buckling



39

Contestants' discussion of root cause

A. Stringer web buckling






B. Screwjack extensions




40







Contestants' discussion of root cause


- A. Stringer web buckling 
- B. Screwjack extensions 
- C. Inadequate bracing 



41





Contestants' discussion of root cause

- A. Stringer web buckling 
- B. Screwjack extensions 
- C. Inadequate bracing 
- D. Too much concrete 



42

What was the root cause?





- A. Stringer web buckling 
- B. Screwjack extensions 
- C. Inadequate bracing 
- D. Too much concrete 

**Time
to
Vote!**




43

What was the root cause?





- A. Stringer web buckling 
- B. Screwjack extensions 
- C. Inadequate bracing 
- D. Too much concrete 

**Select
your
answer!**



44

What was the root cause?

- A. Stringer web buckling 
- B. Screwjack extensions 
- C. Inadequate bracing 
- D. Too much concrete 



Failure Modes and Contributors Considered

- Longer screwjacks
- Missing cross-braces
- Slip at base due to missing/failed wood shims at base
- Different joist layout
- No outer frame bracing
- Bracing not tied to the wall
- Weld failure in frame
- Failure of couplers between frames
- Sub-stringer buckling
- 12-inch sub-stringers
- Eccentric installation of sub-stringers
- Overloading of tower legs
- Uneven load distribution
- Unequal screwjack extensions
- Swivel vs. fixed screwjack ends



Shoring System Design

TABLE 4 - THREE DIMENSIONAL WITH JACKS ONLY ON SCREWJACKS

For 1 to 3 Frame Leg to 20'7" High Towers, with 12" minimum screwjack extension

See and Section on Jacks Section 10.4.1. At one end of the tower, the tower, supported but not over 10'12" using 3 and 4 Foot High Frames. Note: For towers using only 4' high frames on 10' foot frames high, note in this table can be increased by 15%.

WEIGHT OF TOWER	MINIMUM SCREWJACK EXTENSION (MINIMUM EXTENSION)	MINIMUM SCREWJACK EXTENSION (MINIMUM EXTENSION)
One tier	9,000 lb (4130 kg)	8,800 lb (4000 kg)
Two tiers	11,000 lb (5000 kg)	10,800 lb (4900 kg)
Three tiers	13,000 lb (5900 kg)	12,800 lb (5800 kg)

TABLE 5 - THREE DIMENSIONAL WITH JACKS AND EXTENSION TOWER AS INDICATED

For 1 and 3 Frame High Towers using 4' and 4' high frames completely interconnected with extension tower and jacks attached at one end extended 12" with tower extended 12" at extension tower extended 10'12" in the other and replacing the jacks. One machine extension tower.

If tower are not completely interconnected, reduce all capacities by 15%. For towers using 12" high high with extension tower and jacks at indicated height. Note: The capacity for 10' and 4' frame should be interpolated. For towers using only 4' high frames 2, 3, and 4 frame high completely interconnected capacity can be increased by 15%.

LEAST EXTENSION TOWER EXTENDED	MAX. ALLOWABLE LOAD PER LEG (MIN. TOWER EXTENSION)	MAX. ALLOWABLE LOAD PER LEG (MIN. TOWER EXTENSION)
12"	9,000 lb (4130 kg)	8,800 lb (4000 kg)
18"	11,000 lb (5000 kg)	10,800 lb (4900 kg)
24"	13,000 lb (5900 kg)	12,800 lb (5800 kg)

NOTE: 12" EXTENSION TOWER MUST NOT BE EXTENDED MORE THAN 20'-12". 48" EXTENSION TOWER MUST NOT BE EXTENDED MORE THAN 30'-12".

- Maximum applied load per leg = 9,000 lb
- Allowable load per leg = 8,800 lb
- From Table 4 in Appendix G
 - 3 tier tower
 - Maximum 12-inch screwjack extension
- Factor of safety = 2.5
- Minimum ultimate capacity per leg = 22,000 lb

Shoring System Design



ALLOWABLE LOAD PER LEG

1 Frame High	2 Frame High	3 Frame High
8,800	10,800	12,800

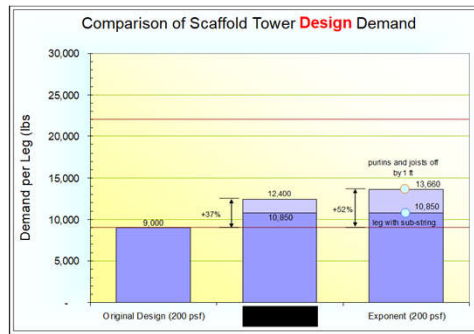
GENERAL NOTES, SPECIFICATIONS AND TYPICAL DETAILS FOR ELPER HAZLE HEAVY DUTY ALUMINUM SHORING SYSTEM

PERFORM CONSULTANTS SYSTEMS

RESISTANCE RATED AND CERTIFIED SS-600

- Design drawings specified
 - up to 9 tier towers with no outer frame bracing
 - 16-inch long sub-stringers on top of tower legs
- The effect of the sub-stringers on load capacity of the towers was not calculated.

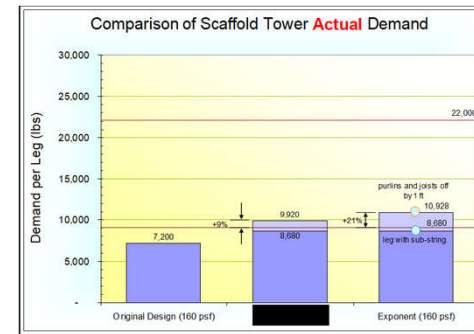
Design Loads (200 psf)



Design load included a 40 psf live load in addition to concrete and equipment weight

49

Actual Loads (160 psf)



Actual loads still considerably higher than original design load of 9,000 lbs

50

Full-Scale Field Testing



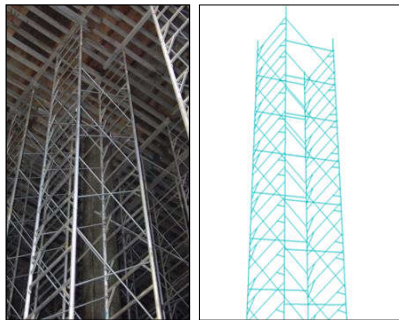
- Conducted full-scale field testing of exemplar shoring
- Towers were incrementally loaded to failure
- Failure due to sub-stringer web buckling leading to global buckling of scaffold towers
- The peak applied loads on legs with sub-stringers were
 - 14,850 lbs (Tower 1)
 - 13,750 lbs (Tower 2)
- Failure loads significantly below design ultimate of 22,000 lbs

51



52

Finite-Element Analysis

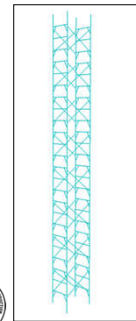


A finite element model of shoring tower was prepared in ABAQUS

The model was used to study the effect of various factors on the strength and stability of the shoring towers

53

Finite-Element Analysis



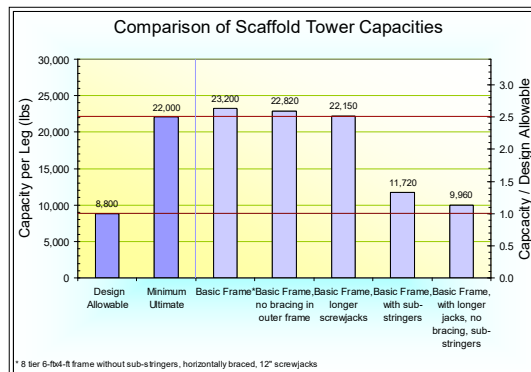
Factors investigated using F-E model

- Longer screwjacks
- No outer frame bracing
- Sub-stringer buckling
- Uneven load distribution
- Missing cross-brace
- Unequal screwjack extensions
- Missing/failed wood shims at base
- Weld failure in frame
- Failure of frame couplers



54

Finite-Element Analysis



Sub-stringers are the primary contributor to reduction in scaffold capacity

55

Case 3: Building roof collapse



56



Background



57

The Failure



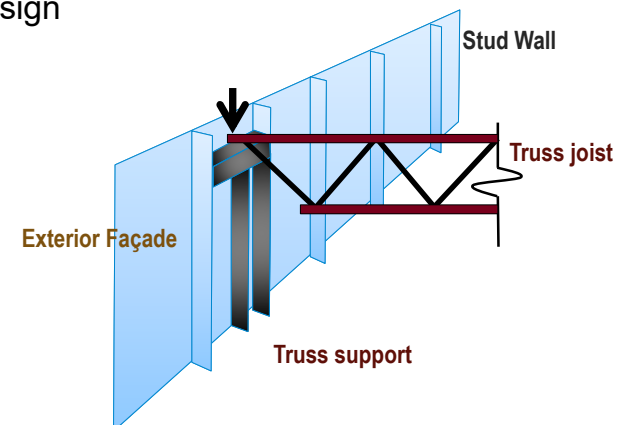
58

The Failure



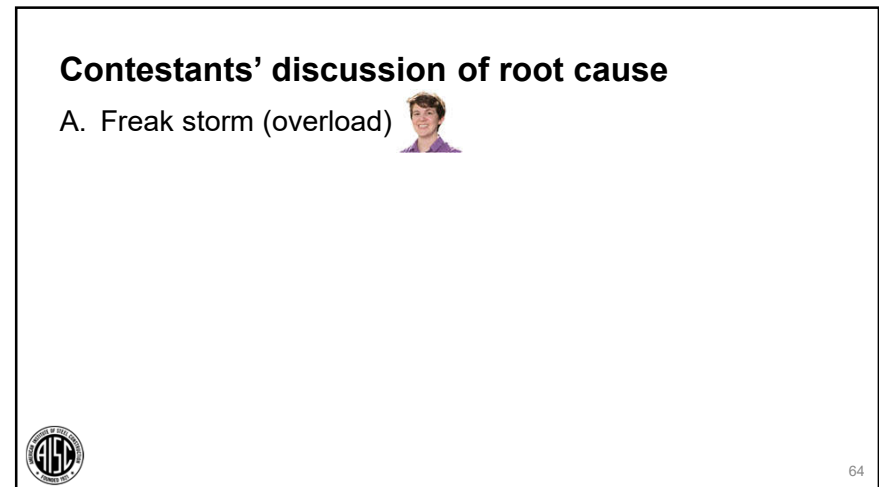
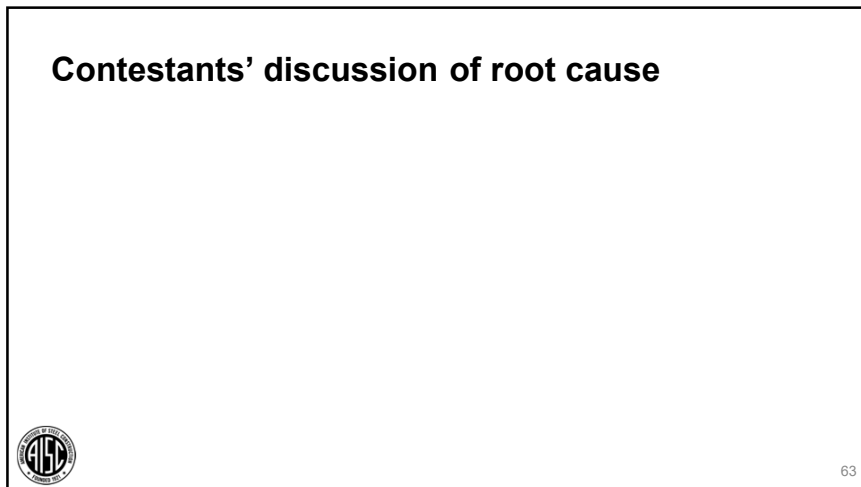
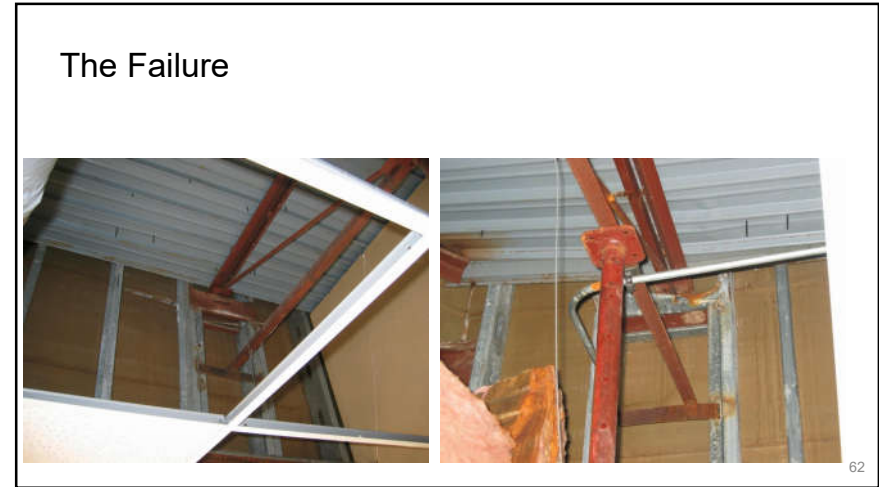
59

Design





60






Contestants' discussion of root cause


A. Freak storm (overload) 


B. Missing support (improper construction) 





65

Contestants' discussion of root cause

A. Freak storm (overload) 


B. Missing support (improper construction) 


C. Local member effects 





66


Contestants' discussion of root cause

A. Freak storm (overload) 

B. Missing support (improper construction) 


C. Local member effects 


D. Improper design 





67

What was the root cause?


A. Freak storm (overload) 

B. Missing support (improper construction) 

C. Local member effects 

D. Improper design 





**Time
to
Vote!**




68



What was the root cause?





- A. Freak storm (overload) 
- B. Missing support (improper construction) 
- C. Local member effects 
- D. Improper design 


Select
your
answer!



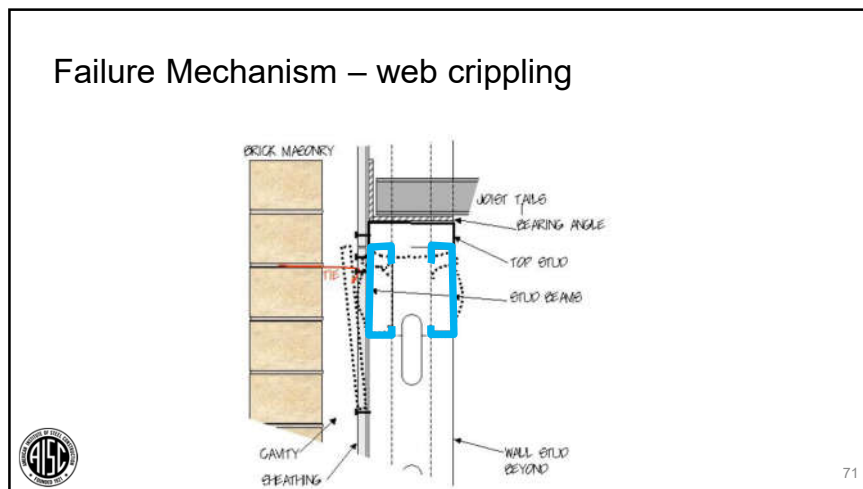
69

What was the root cause?

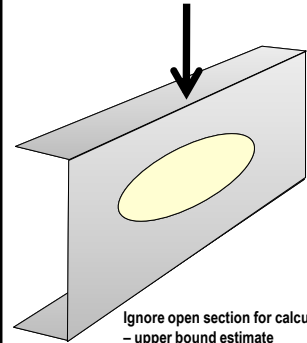
- A. Freak storm (overload) 
- B. Missing support (improper construction) 
- C. Local member effects 
- D. Improper design 



70




Failure Mechanism – web crippling



Ignore open section for calculations
– upper bound estimate


Description	P (kip)
Allowable Load (ASD)	1.9
Exponent Calculated Capacity	3.5
Non-Factored Loads (service loads)	4.0
BOCA Requirements ¹	6.4
“Expert” Report	7.4 (??)


¹Building Officials and Code Administrators requires assemblies to withstand 2.5 times live load for testing



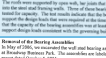
72


Opposing Expert report






 The roofs were supported by open web, bar joists that were in turn supported by bearing assemblies built into the steel stud framing walls. Three of these bearing assemblies were removed from the buildings and tested for capacity. The test results indicate that the bearing assemblies as constructed were sufficient to support the design loads that were required at the time of construction of the building. The tests indicate that the capacity of the bearing assemblies was at least 7,429 lbs, which is in my opinion sufficient to support design loads consistent with the governing building code.







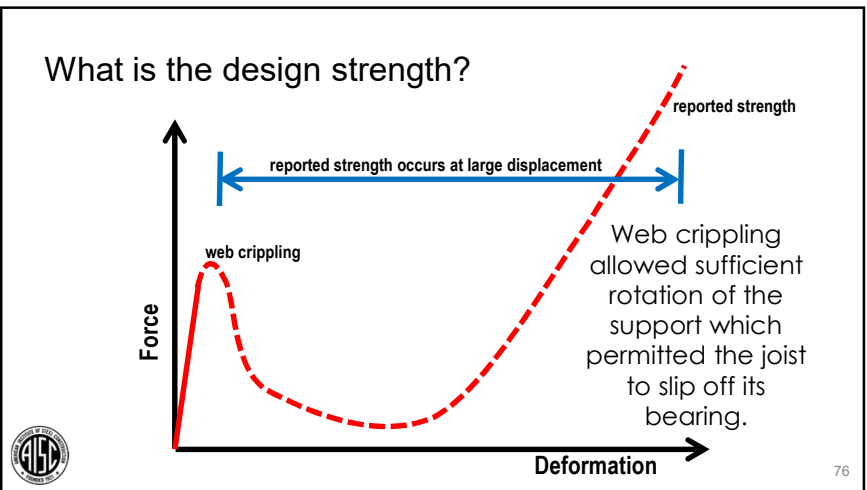
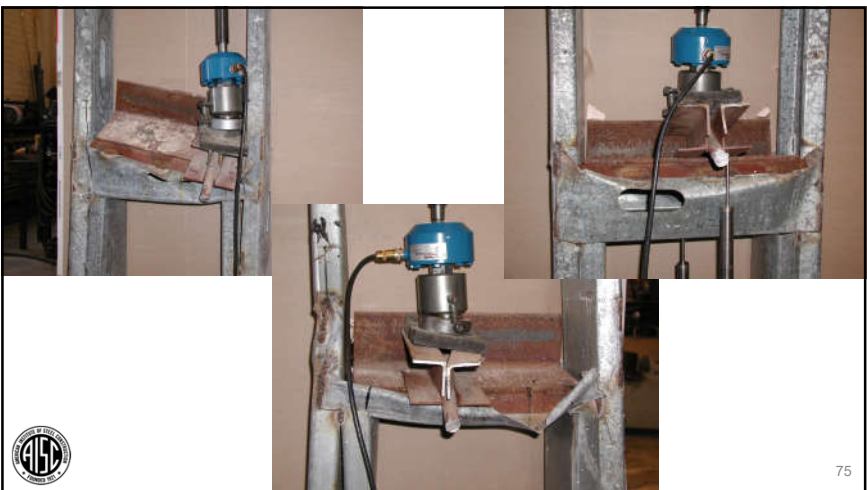
73

Opposing Expert Report

Table 1. Results of Capacity Tests on Bearing Assemblies

Design Criteria				Test Results		
Design Dead Load (DL) (psf)	Design Live Load (LL) (psf)	Total Design Load (DL + LL) (psf)	Boca 1981 Test Load (psf)	Bearing Assembly	Test Load (lbs)	Equivalent Total Load per Square Foot (psf)
12	20.8	32.8	52	N 13	7429	61
12	20.8	32.8	52	N 24	5167	??
12	20.8	32.8	52	S 13	3942	?



74








“For since the fabric of the universe is most perfect, and is the work of a most wise Creator, nothing whatsoever takes place in the universe in which some relation of maximum and minimum does not appear.”

Leonhard Euler in *Lineas Curvas (Elastic Curves)*, 1744

Thank you for your participation!


The Structural Stability Game Show!

				
Cliff D. Bishop <i>Exponent</i>	Patricia Clayton <i>UT Austin</i>	Larry Griffis <i>Walter P. Moore</i>	John D. Hooper <i>Magnusson Klemencic</i>	Ron Ziemian <i>Bucknell University</i>

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