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Course Description

Get Fired Up: What Structural Engineers Should Know About Fire Design

February 22, 2017

Typically, fire protection is the responsibility of the architect, but it is becoming more common today that the structural engineer is involved when the prescriptive approach is inadequate and fire engineering becomes desirable. The presentation begins with a background on the current state of fire design including governing standards and the impact of historical fires. Then, the behavior of steel structures in fire conditions is discussed including beams and columns, connections, tensile membrane action and web-buckling. This lecture will focus on what the structural engineer needs to know about fire protection and design and what benefits and advantages steel structures offer in fire resistance.



Learning Objectives

- Identify key differences between prescriptive fire protection and structural fire engineering.
- Identify codes and standards that address fire design
- Describe how historical fires have shaped current codes and practice
- Understand behavior of steel structures in fire conditions including beams and columns, connections, tensile membrane action and web-buckling



There's always a solution in steel.

Get Fired Up: What Structural Engineers Should Know About Fire Design



Maria E. Moreyra Garlock, PhD, PE
Associate Professor
Dept. Civil & Environmental Engineering
Princeton University
Princeton, NJ







① BACKGROUND / Fires That Transformed USA History /

Great
Chicago Fire
of 1871



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① BACKGROUND / Fires That Transformed USA History /

Great
Chicago Fire
of 1871



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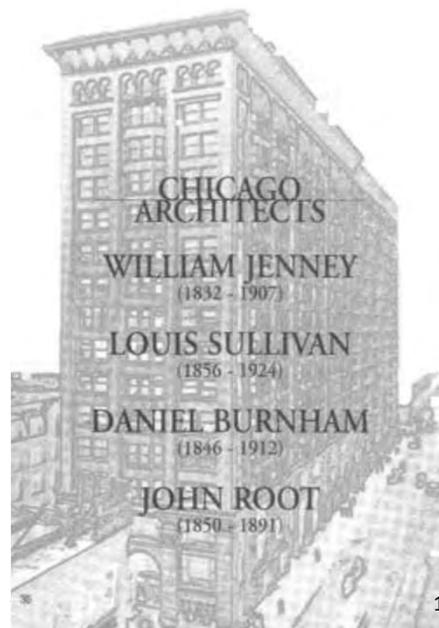


① BACKGROUND / Fires That Transformed USA History /

Great
Chicago Fire
of 1871

Transformation of:

- Building codes
- Architecture



① BACKGROUND / Fires That Transformed USA History /

NYC, 1911
Triangle
Shirtwaist Co.

Transformation of...

- politics & labor laws
- bldg. fire safety





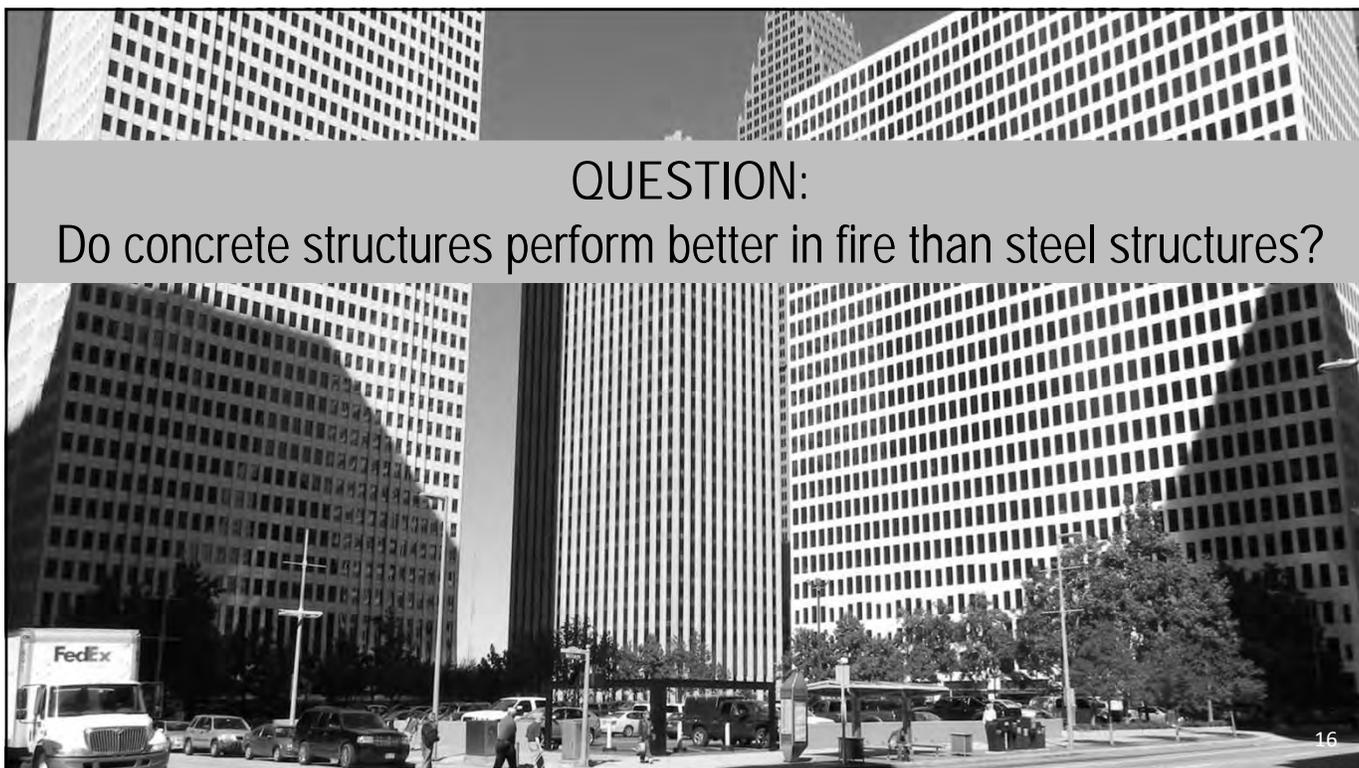
① BACKGROUND / Fires That Transformed USA History /

NYC: Sept. 11, 2001
(WTC 1, 2, 5, 7)

Transformation of...
the way we think
about fire design of
structures



Figure 2. Internal Collapse Area in WTC 5 (World Trade..., 2002).





QUESTION:

Do concrete structures perform better in fire than steel structures?

ANSWER:

ALL materials have some form of weakness in fire.



<https://www.youtube.com/watch?v=gwQfpMnSh90>





VIDEO



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OUTLINE

- ① BACKGROUND
 - Where did we come from?
 - Where are we now and where are we going with fire design?
- ② STRUCTURAL FIRE ENGINEERING (SFE)
 - *Real* structural response to *real* fire
- ③ WHY SFE?
 - efficiency, economy, elegance
- ④ CONCLUSIONS



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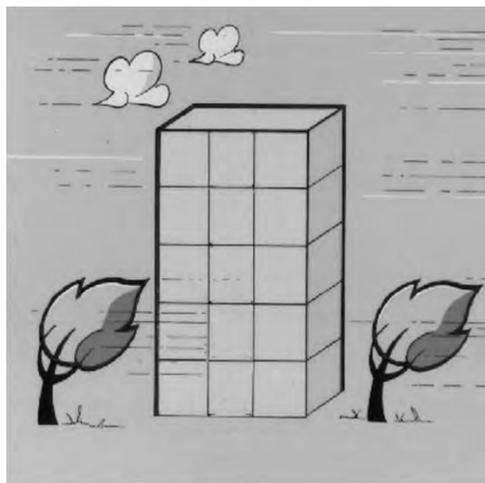
① BACKGROUND / Current Practice in USA /

How is fire resistance traditionally determined?



① BACKGROUND / Current Practice in USA /

How is fire resistance traditionally determined?



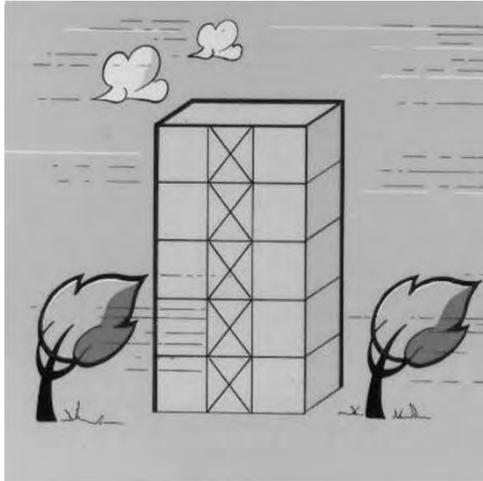
How does a building resist wind?





① BACKGROUND / Current Practice in USA /

How is fire resistance traditionally determined?



One solution is to design the building to resist wind using bracing.



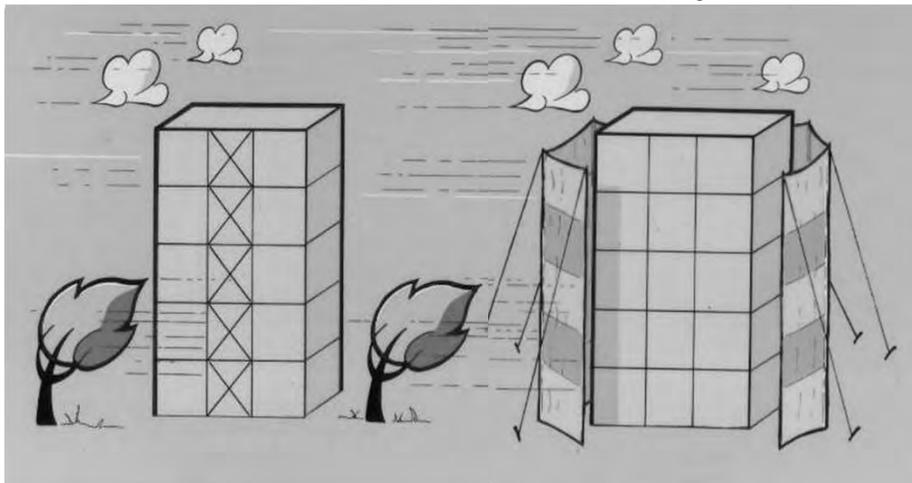
slide credit: Jeff Robison, British Steel

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① BACKGROUND / Current Practice in USA /

How is fire resistance traditionally determined?



One solution is to design the building to resist wind using bracing.

An alternative is to protect the building from wind.



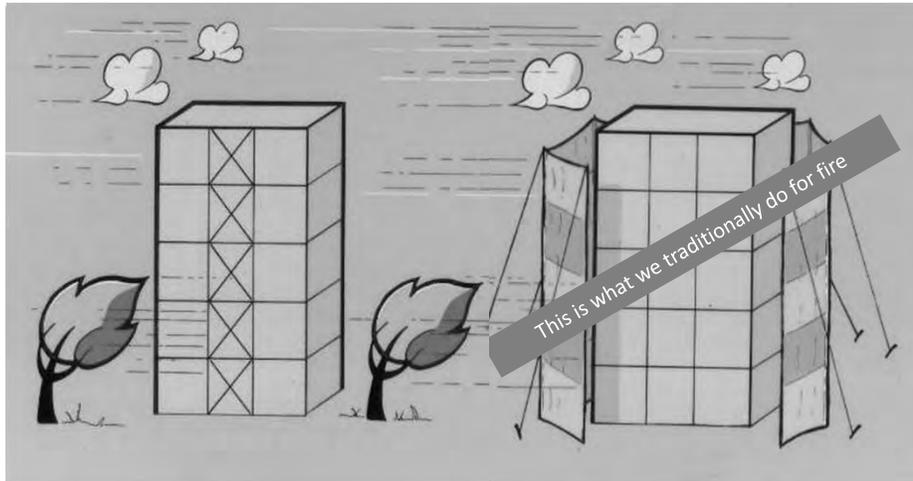
slide credit: Jeff Robison, British Steel

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① BACKGROUND / Current Practice in USA /

How is fire resistance traditionally determined?



One solution is to design the building to resist wind using bracing.

An alternative is to protect the building from wind.

slide credit: Jeff Robison, British Steel

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① BACKGROUND / Current Practice in USA / *Prescriptive*



Designers select materials and assemblies to meet fire resistance using “approved methods”:

- qualification testing (ASTM E119)
- computational methods that show ASTM E119 equivalence

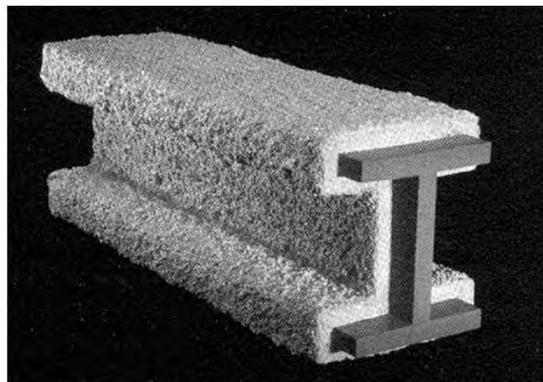
26





① BACKGROUND / Current Practice in USA / *Prescriptive*
Protection Systems for Steel

- Board Systems
- Spray on Systems
- Intumescent Paint
- Concrete Encasement
- Concrete Filling
- ... etc ...

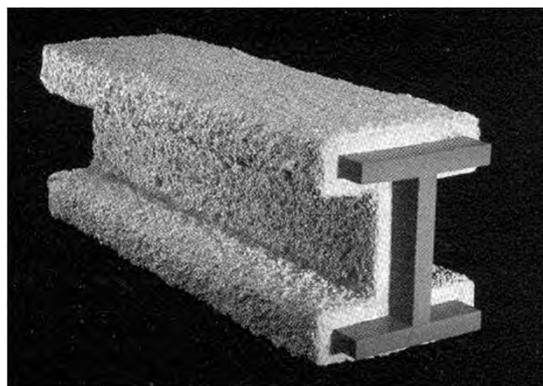


27



① BACKGROUND / Current Practice in USA / *Prescriptive*
Protection Systems for Steel

- Board Systems
- Spray on Systems
- Intumescent Paint
- Concrete Encasement
- Concrete Filling
- ... etc ...



Regardless of the system used, an engineered approach to fire safety will lead to more efficient, economical, and elegant solutions



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① BACKGROUND / Current Practice in USA / *Prescriptive*



QUESTION:
Does the fire resistive rating
imply the *time* that the
structural integrity is
maintained?

29



① BACKGROUND / Current Practice in USA / *Prescriptive*



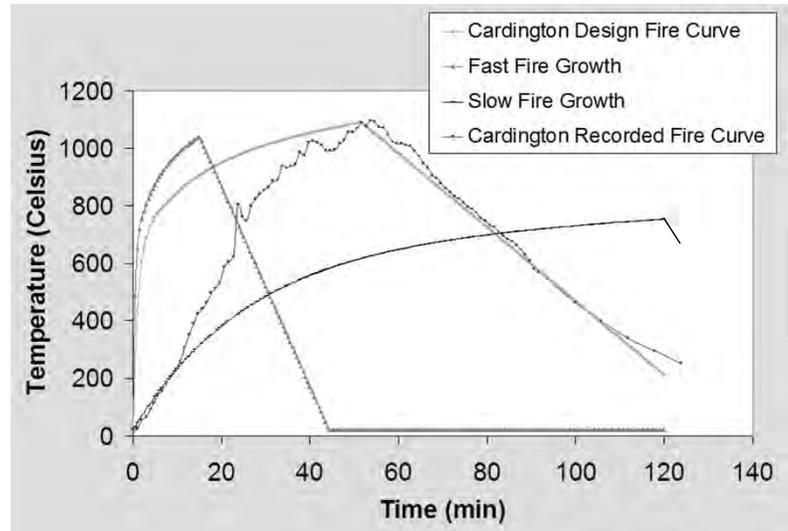
QUESTION:
Does the fire resistive rating
imply the *time* that the
structural integrity is
maintained?

SHORT ANSWER:
no

30



① BACKGROUND / Current Practice in USA / Prescriptive



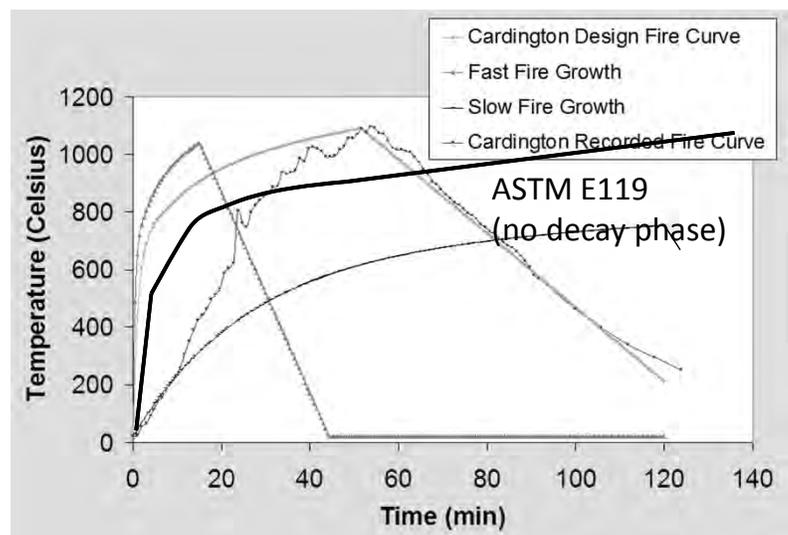
31



① BACKGROUND / Current Practice in USA / Prescriptive

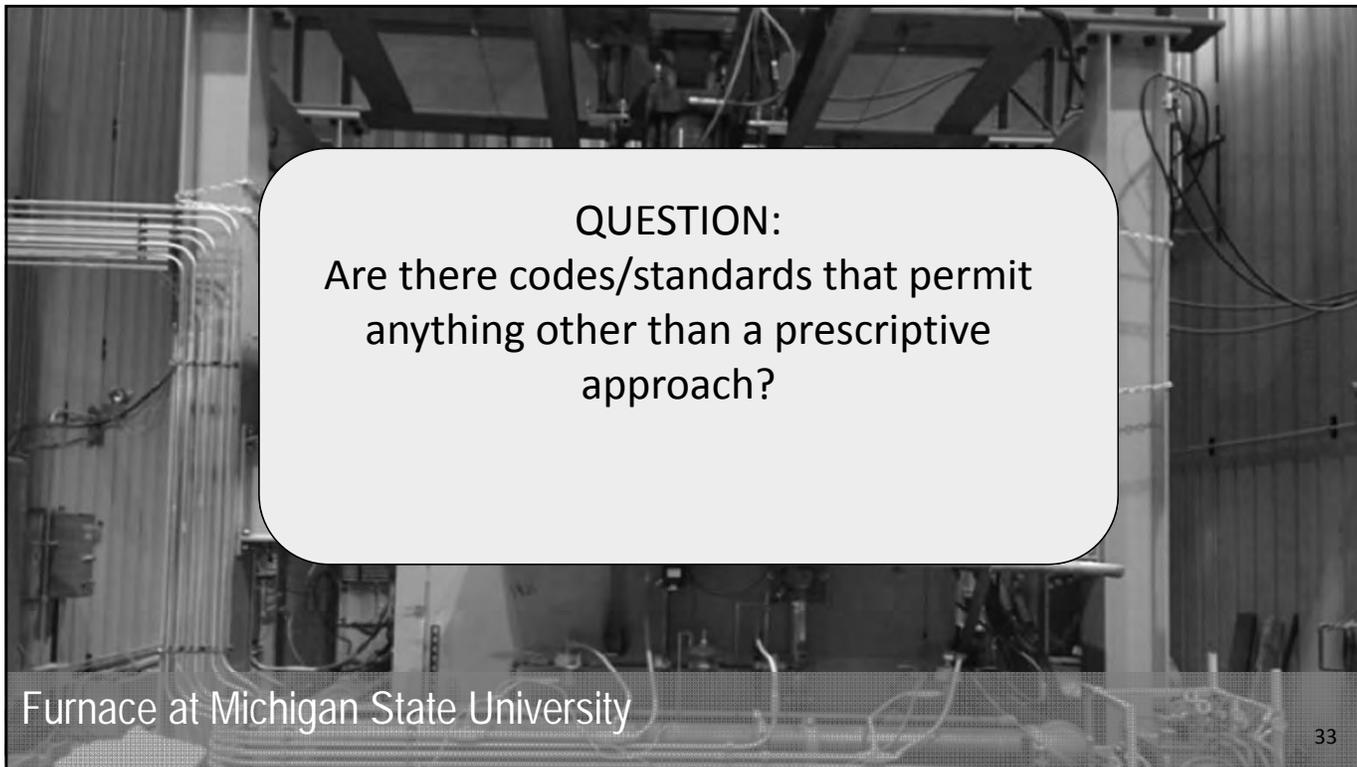
ASTM E119 Fire
Resistance

- Comparative test, not a predictive test
- Principally a thermal test, not a structural test



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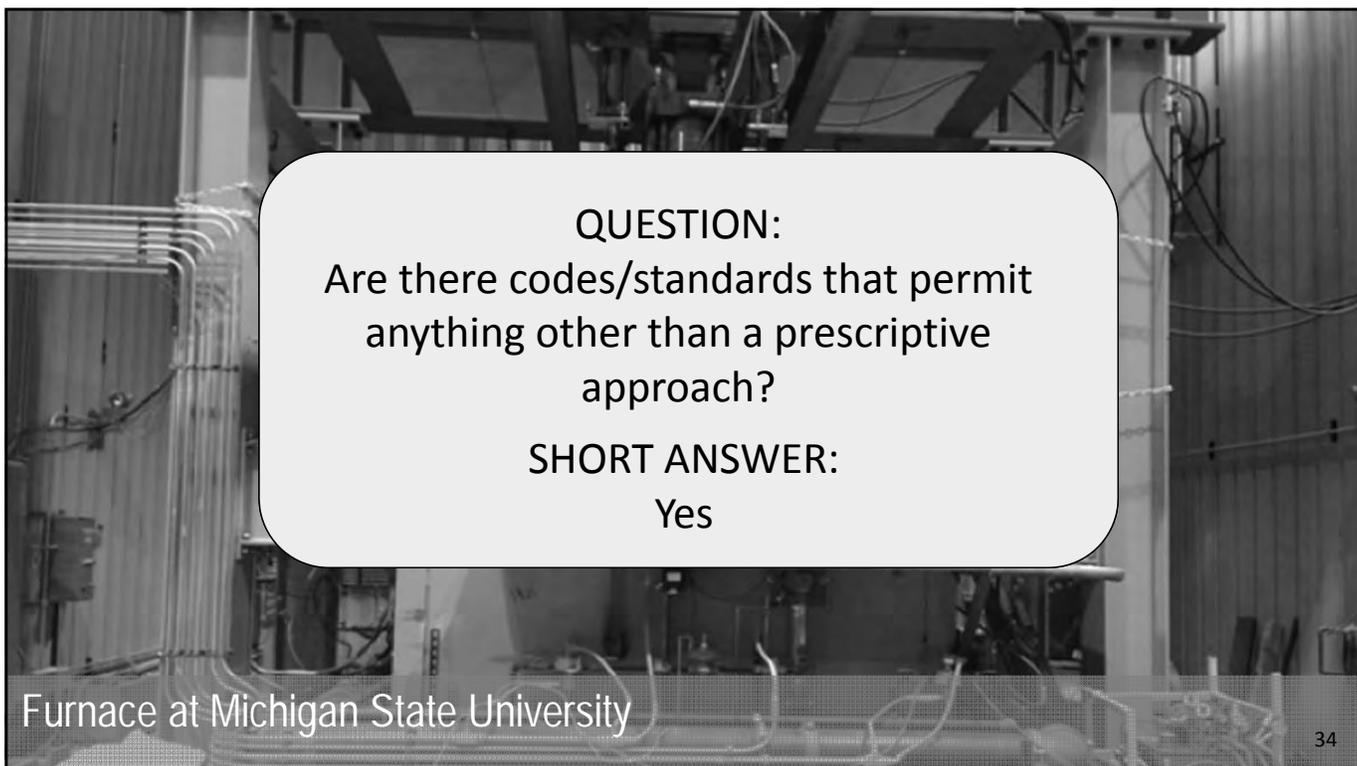


A black and white photograph of a large industrial furnace. The furnace is a large, rectangular structure with a complex network of pipes and cables on its exterior. The interior of the furnace is visible through a large opening, showing a dark, cavernous space with structural beams and various mechanical components. The lighting is dramatic, highlighting the metallic surfaces and the intricate piping.

QUESTION:
Are there codes/standards that permit anything other than a prescriptive approach?

Furnace at Michigan State University

33



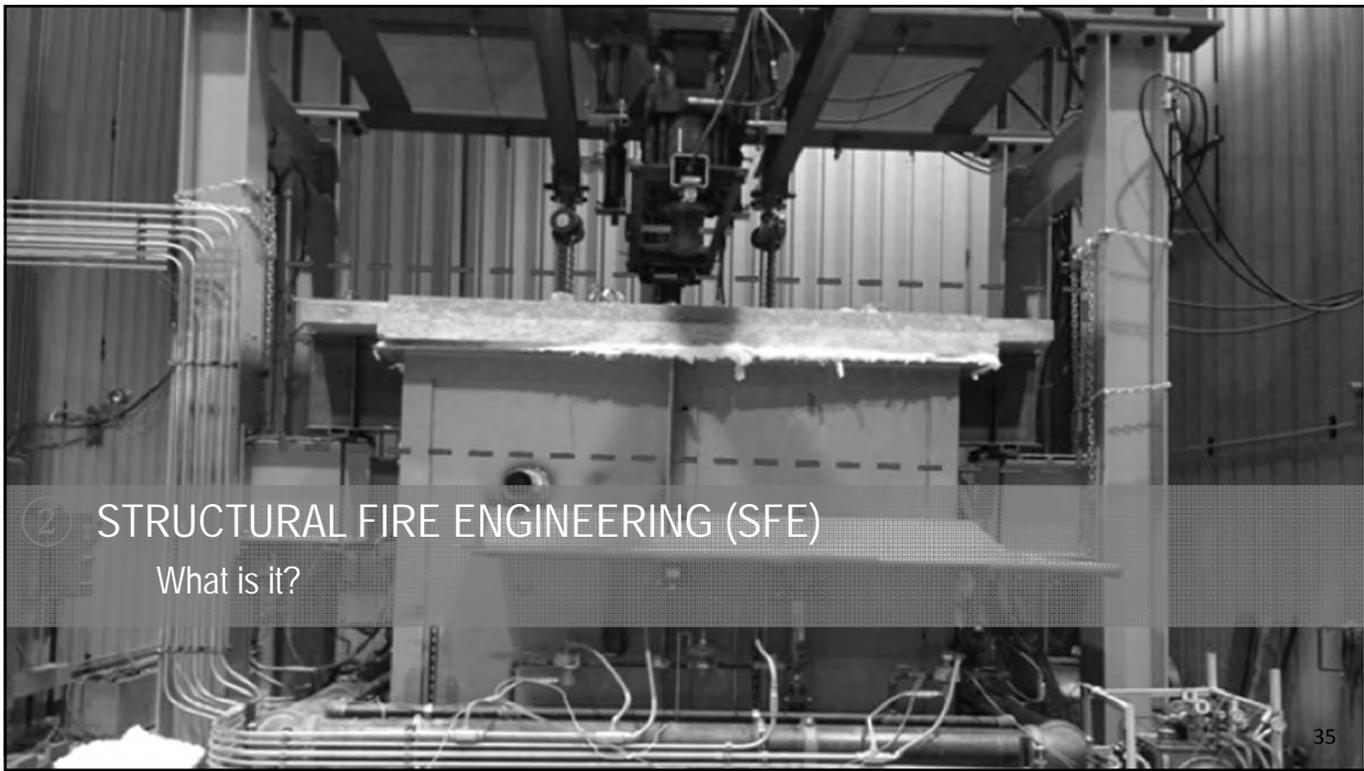
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QUESTION:
Are there codes/standards that permit anything other than a prescriptive approach?

SHORT ANSWER:
Yes

Furnace at Michigan State University

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② SFE / What is it? /

Structural Fire Engineering (SFE) → Performance based design for fire

Frames/systems behave much better than individual elements

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② SFE / What is it? /

Structural Fire Engineering (SFE) → Performance based design for fire

- Fire is treated as a “load” (like wind, earthquake, etc...)
- Can evaluate systems and components.
- *Where possible*, design the structure to withstand fire rather than protect against it.



Frames/systems behave much better than individual elements

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② SFE / What is it? / *Difference with Prescriptive?*

| | Prescriptive | SFE |
|---------------------------------|--------------------|-------------|
| States how a building is to.... | ... be constructed | ... perform |
| | | |
| | | |

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② SFE / What is it? / *Difference with Prescriptive?*

| | Prescriptive | SFE |
|--|--------------------|-------------|
| States how a building is to.... | ... be constructed | ... perform |
| Knowledge of structural behavior needed? | NO | YES |
| | | |



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② SFE / What is it? / *Difference with Prescriptive?*

| | Prescriptive | SFE |
|--|-------------------------------|--------------------------|
| States how a building is to.... | ... be constructed | ... perform |
| Knowledge of structural behavior needed? | NO | YES |
| Primary role in domain of... | architect (non-engineered) | engineer (engineered) |



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② SFE / What is it? / *Analysis Steps*

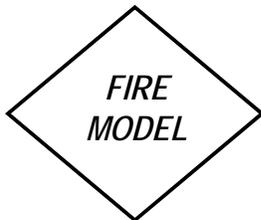
- FIRST STEP: Define Performance Objectives



② SFE / What is it? / *Analysis Steps*

- FIRST STEP: Define Performance Objectives

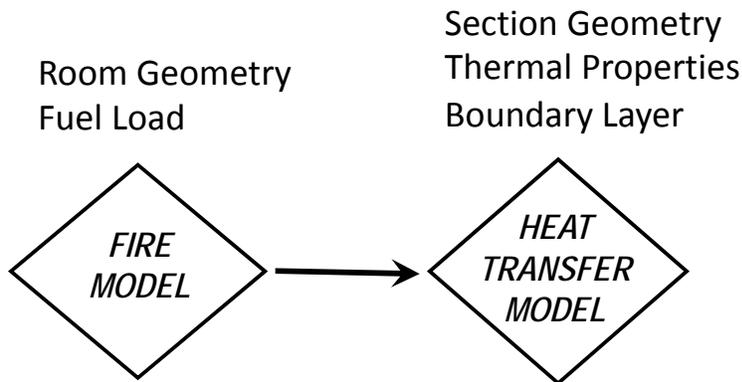
Room Geometry
Fuel Load





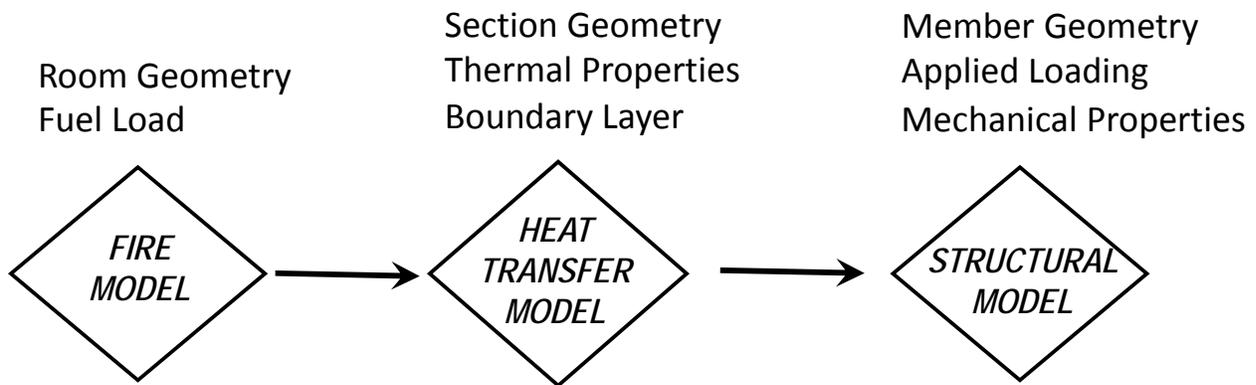
② SFE / What is it? / Analysis Steps

- FIRST STEP: Define Performance Objectives



② SFE / What is it? / Analysis Steps

- FIRST STEP: Define Performance Objectives





② SFE / What is it? / Codes and Standards

Natl. bldg. codes include SFE:

- NFPA 5000 (2012)
- IBC (2012)

2012 IBC Section 101.3 Intent: “To establish minimum requirements to safeguard public health, safety, and general welfare through structural strength, means of egress facilities, stability, sanitation, adequate light and ventilation, energy conservation, and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations.”



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② SFE / What is it? / Codes and Standards

Natl. bldg. codes include SFE:

- NFPA 5000 (2012)
- IBC (2012)

Advances in Building
Standards in USA since 9/11

- AISC 360 (two types of analyses)

User Note: Design by qualification testing is the prescriptive method specified in most building codes. Traditionally, on most projects where the architect is the prime professional, the architect has been the responsible party to specify and coordinate fire protection requirements. Design by analysis is a new engineering approach to fire protection. Designation of the person(s) responsible for design for fire conditions is a contractual matter to be addressed on each project.



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② SFE / What is it? / Codes and Standards

Natl. bldg. codes with SFE:

- NFPA 5000 (2012)
- IBC (2012)

Advances in Building
Standards in USA since 9/11

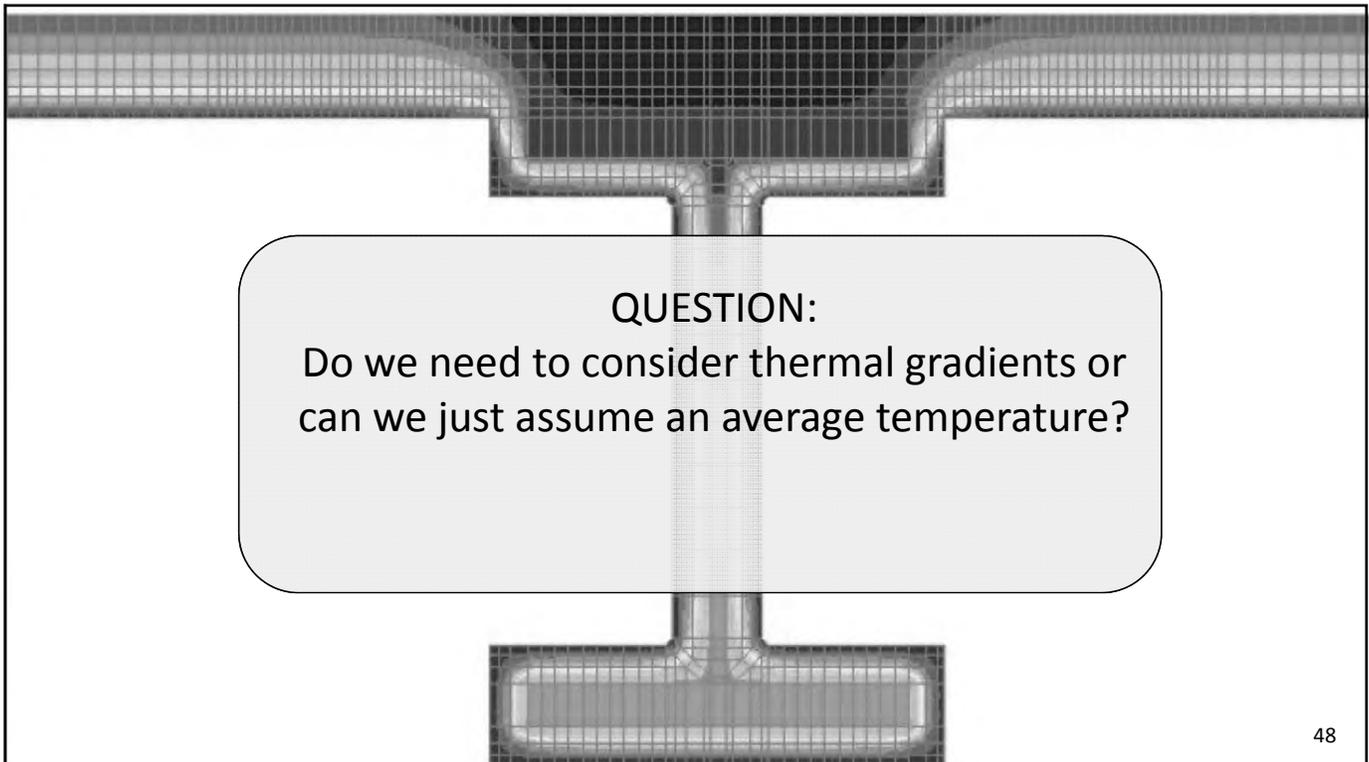
- AISC 360
- ASCE DOCUMENTS

WHAT

*ASCE 7-16: Performance-based Design
Procedures for Fire Effects on Structures*

HOW

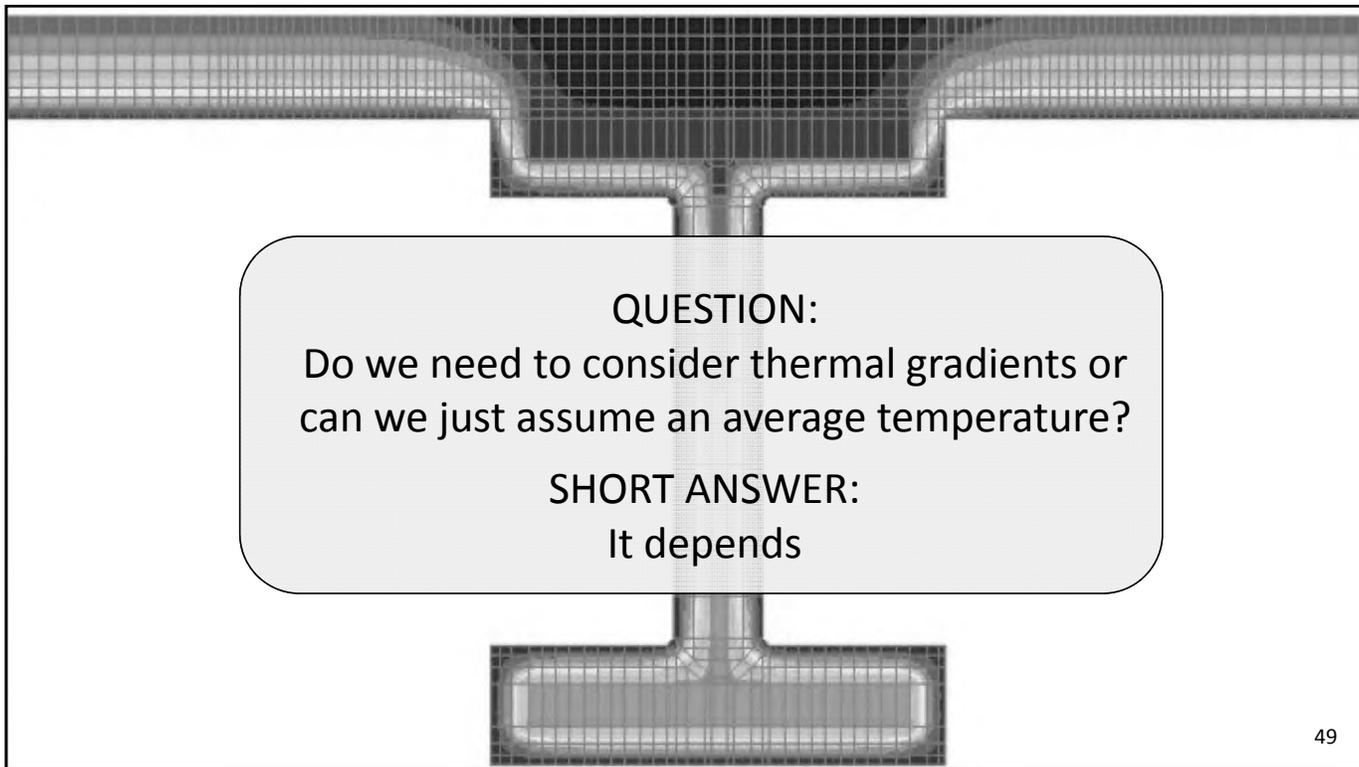
*ASCE/SEI Guideline:
Structural Fire Engineering (in progress)*



QUESTION:

Do we need to consider thermal gradients or
can we just assume an average temperature?





QUESTION:
Do we need to consider thermal gradients or
can we just assume an average temperature?

SHORT ANSWER:
It depends

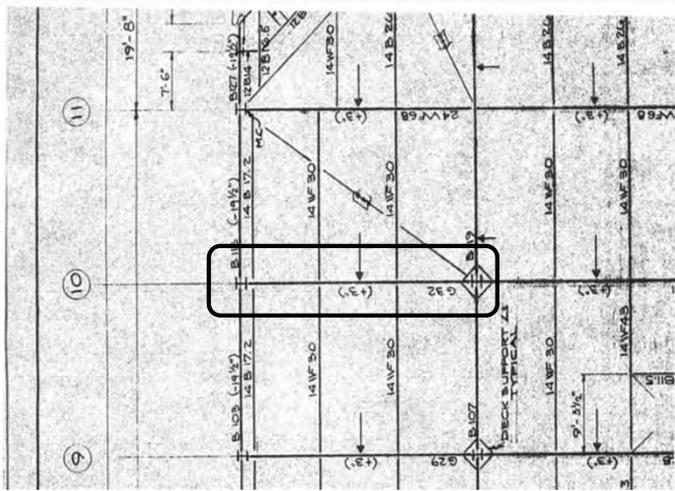
49



② STRUCTURAL FIRE ENGINEERING (SFE)
Beam-Columns

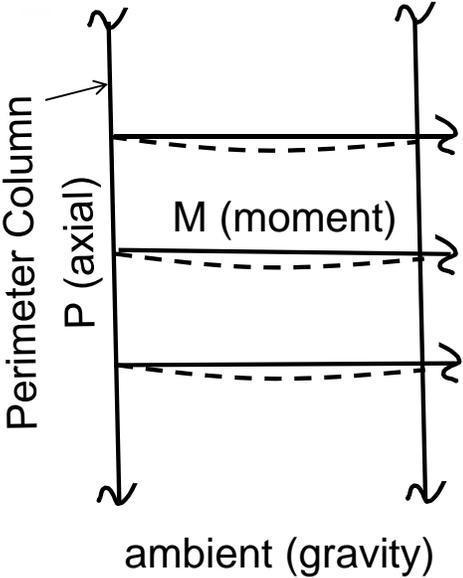
50

② SFE / Beam-Columns/



51

② SFE / Beam-Columns/



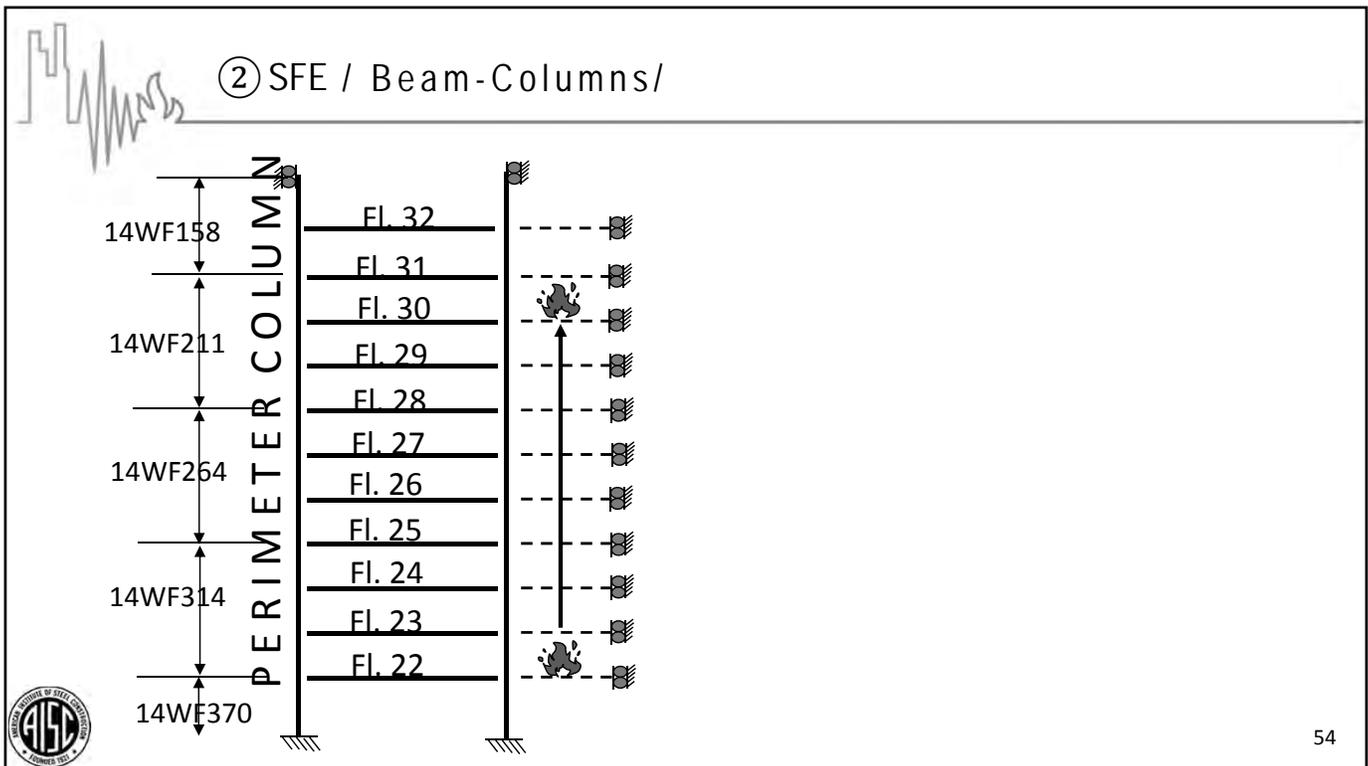
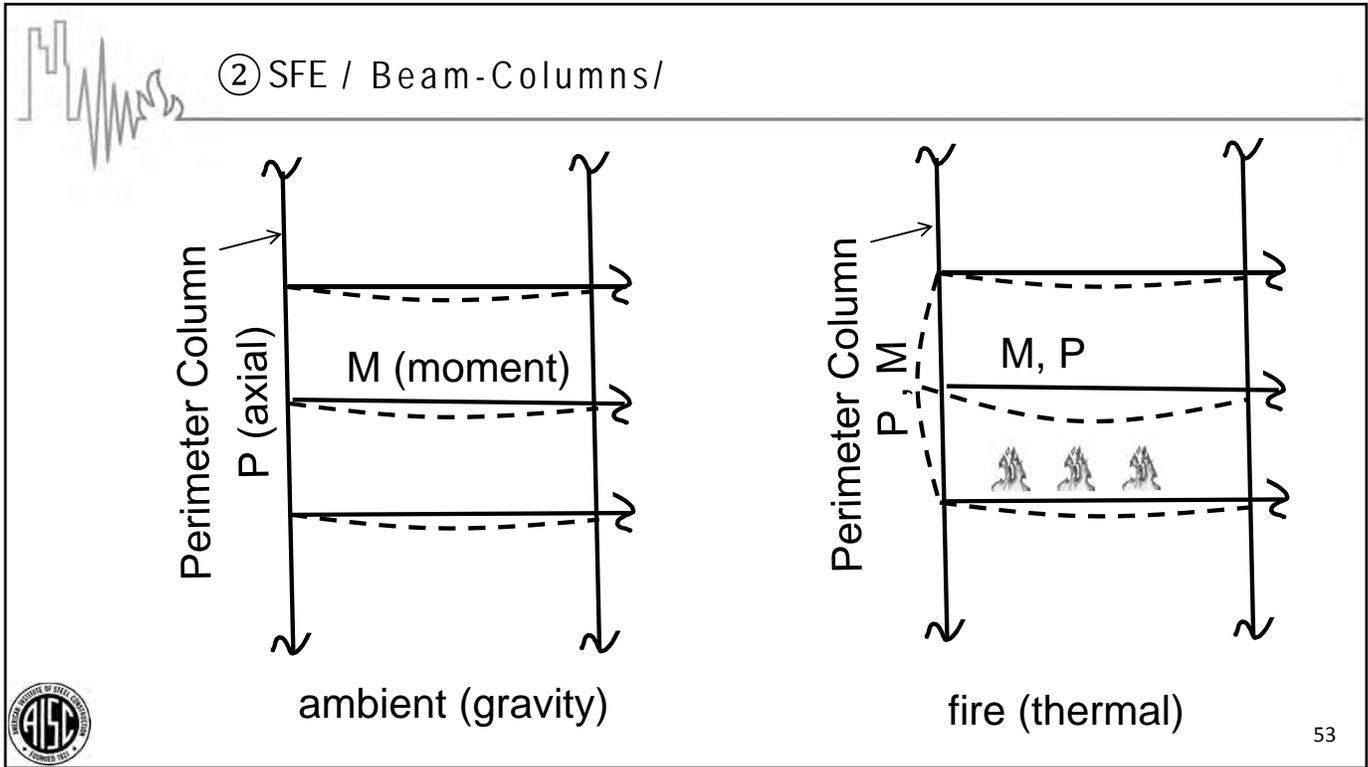
Perimeter Column

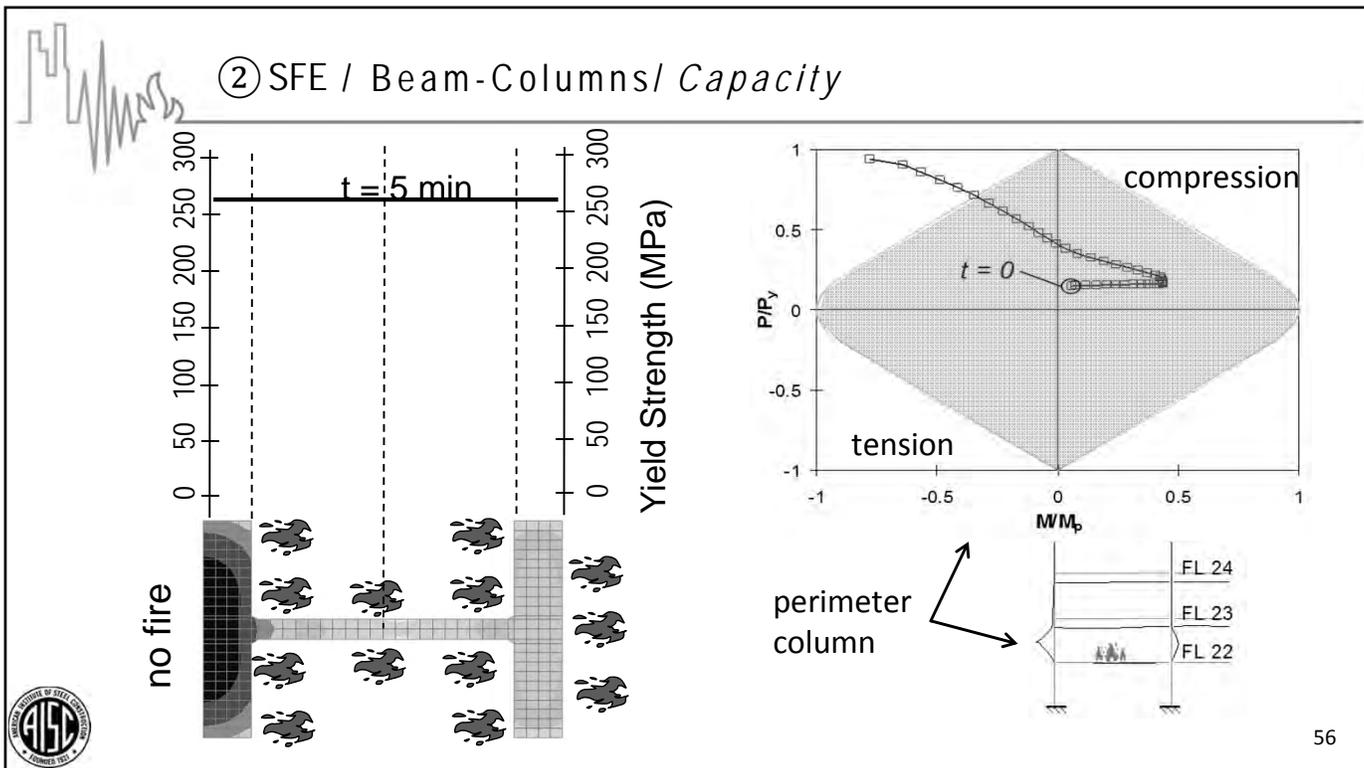
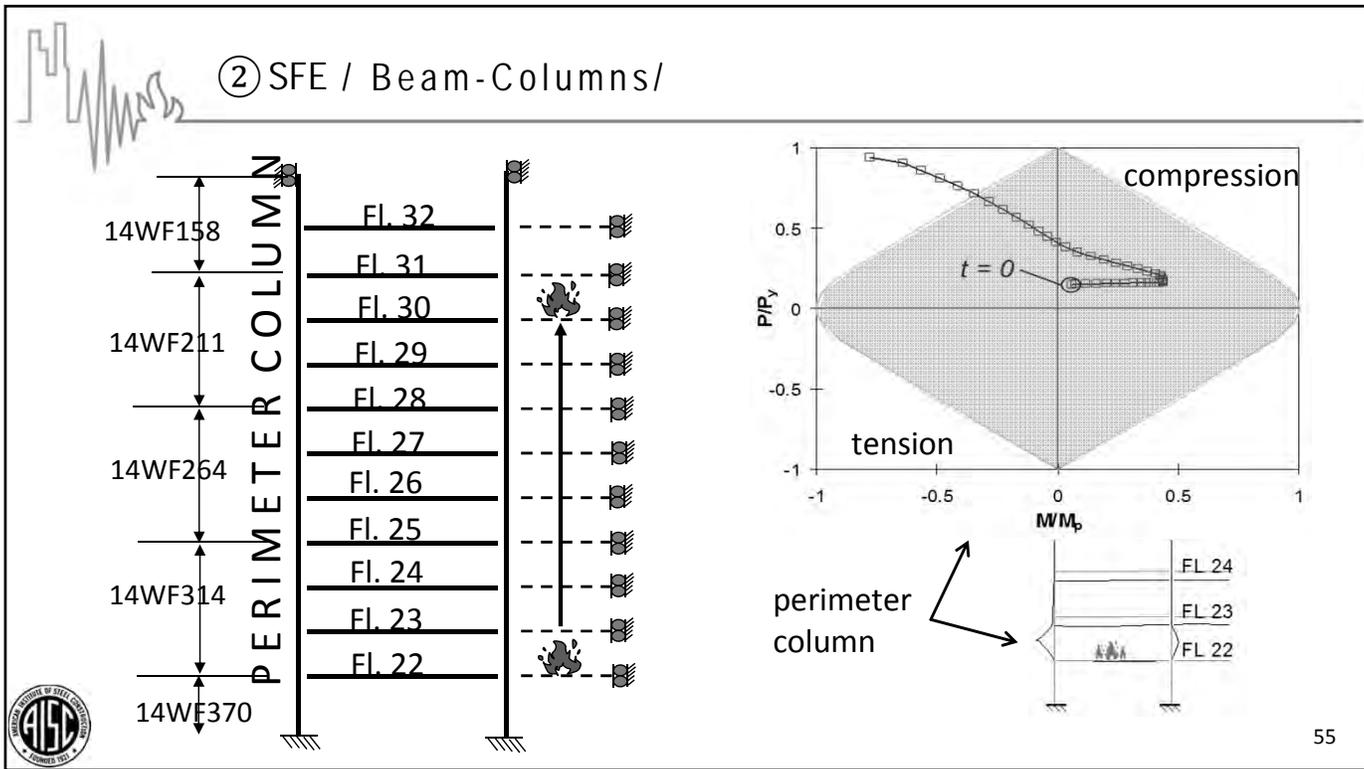
P (axial)

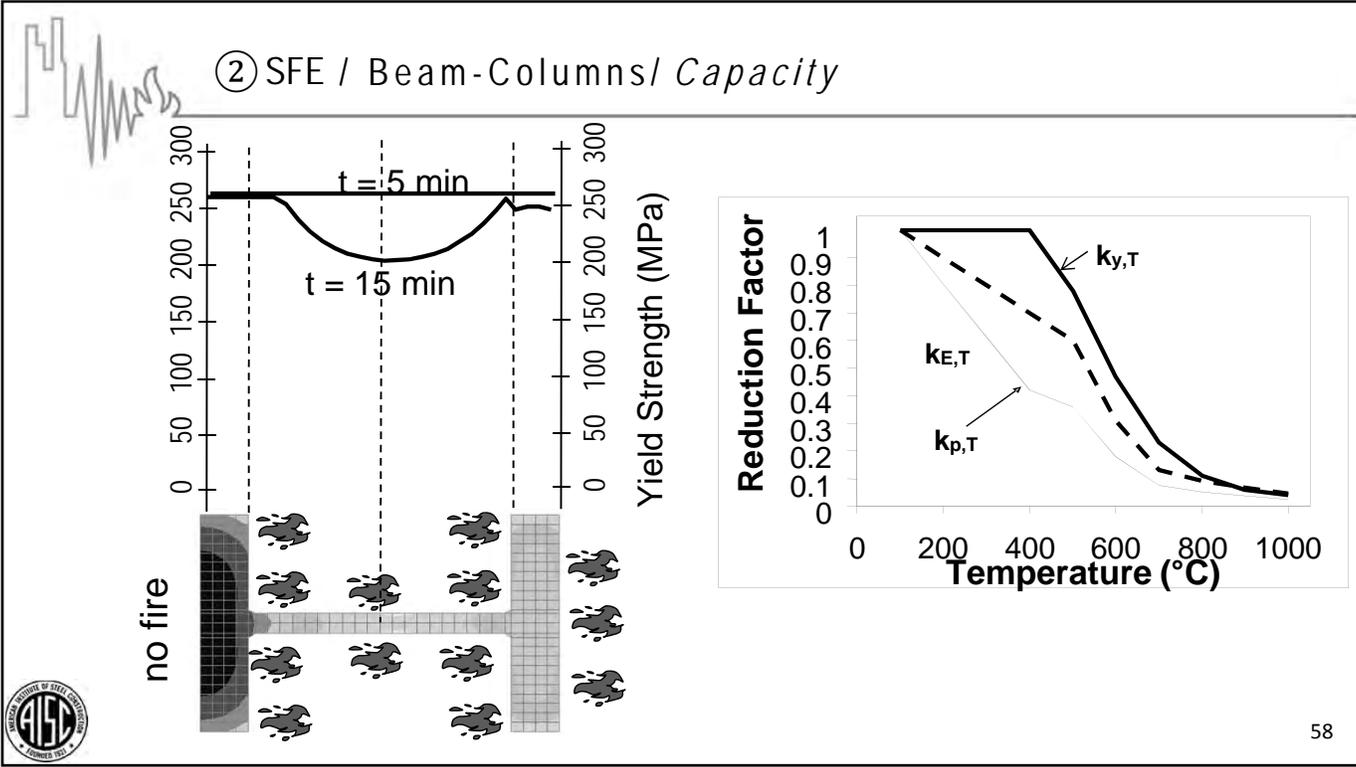
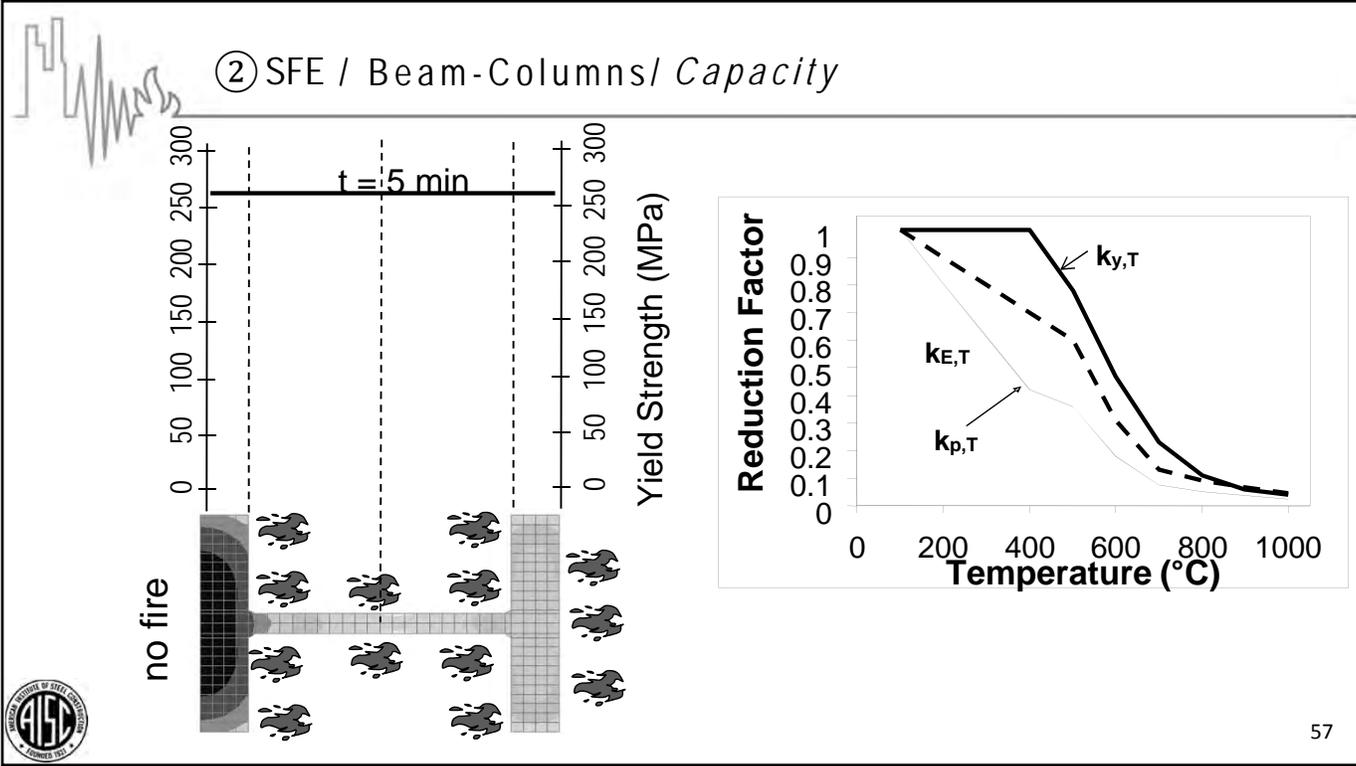
M (moment)

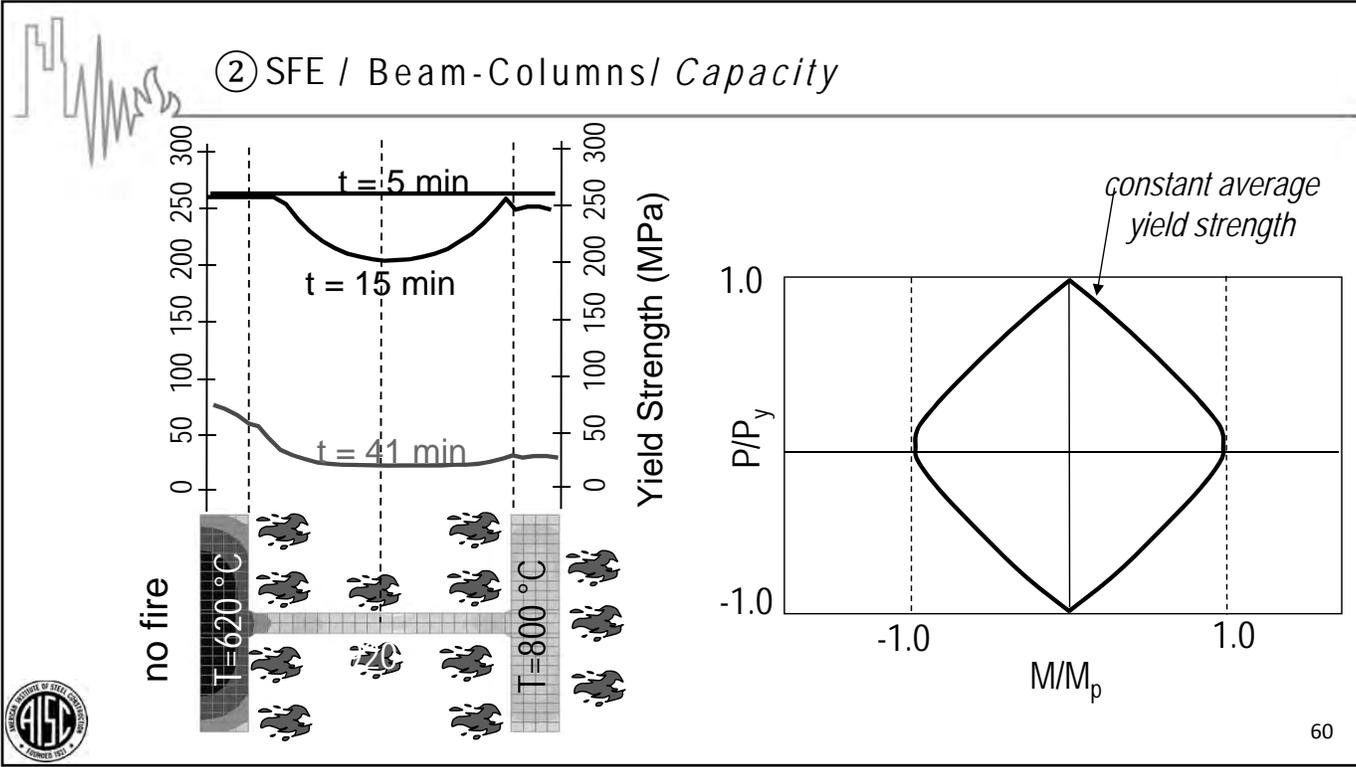
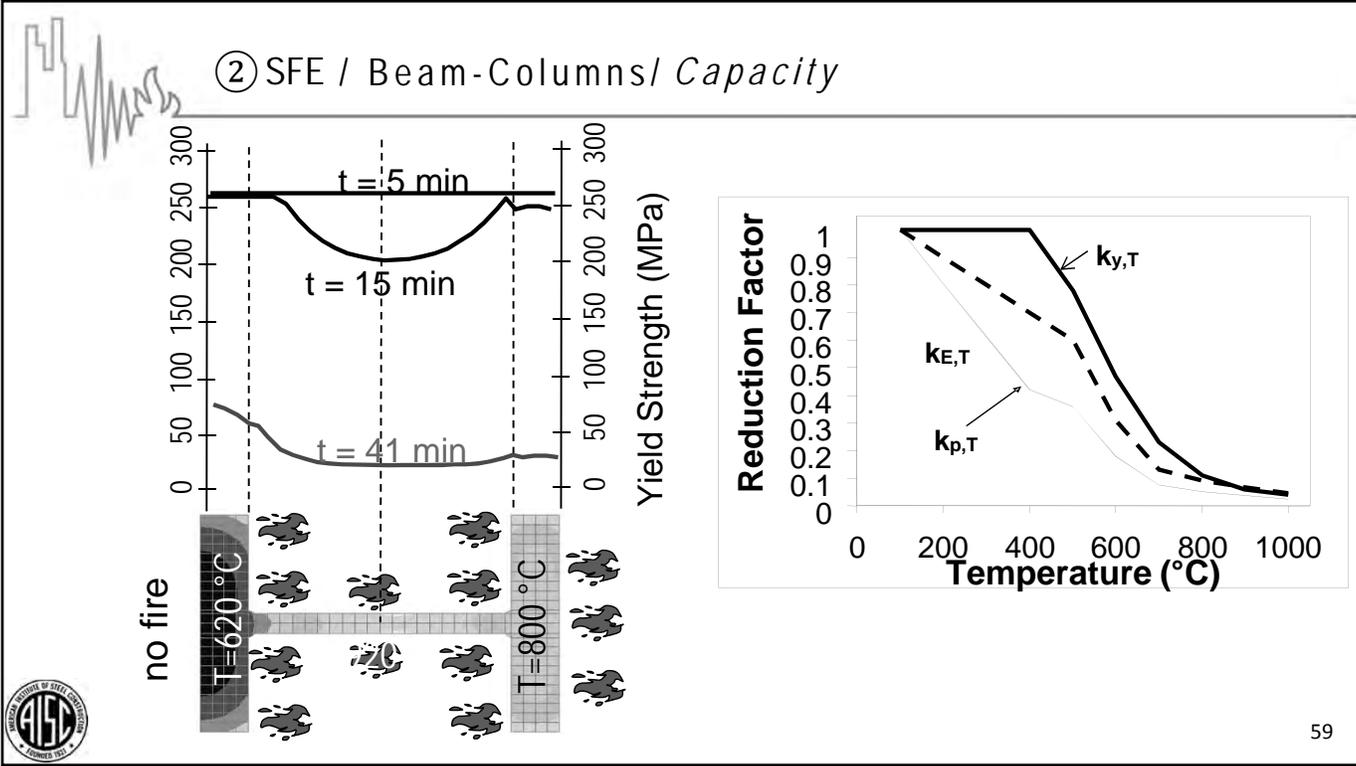
ambient (gravity)

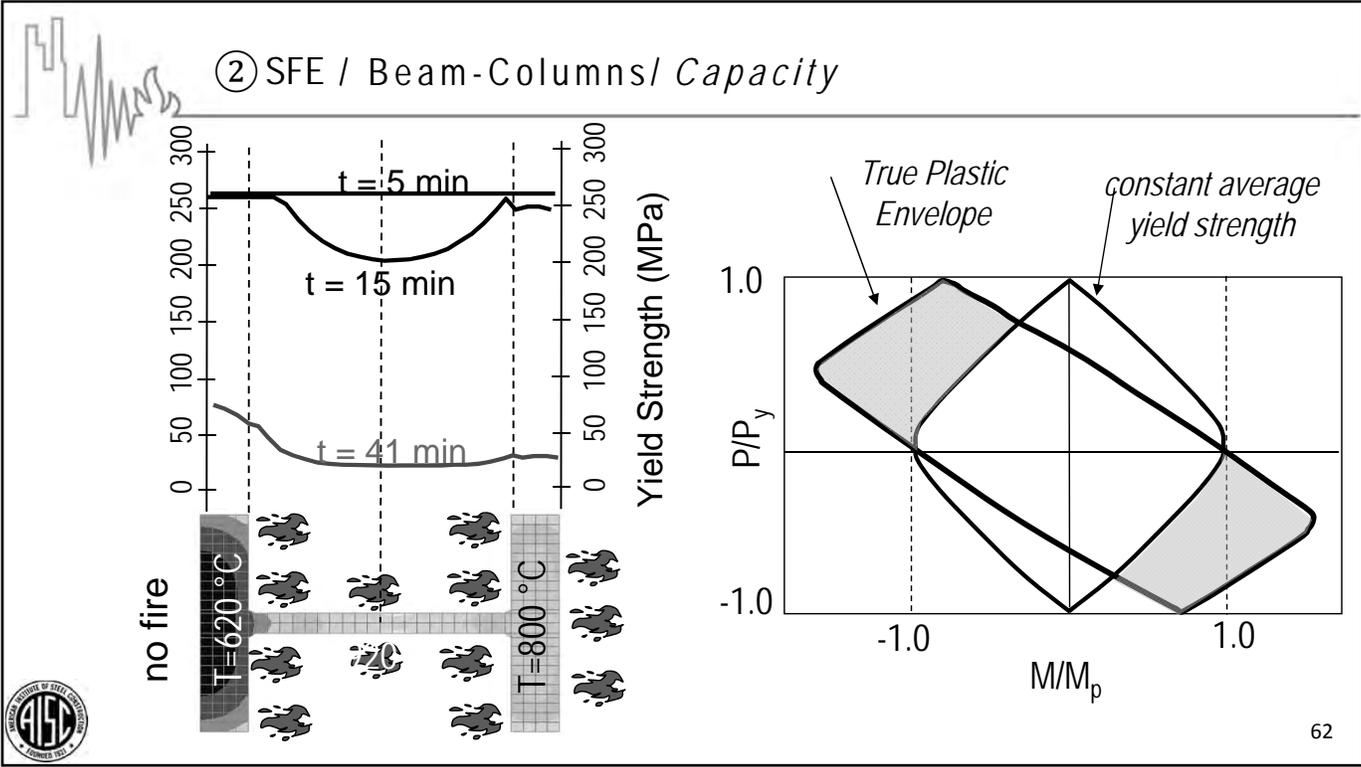
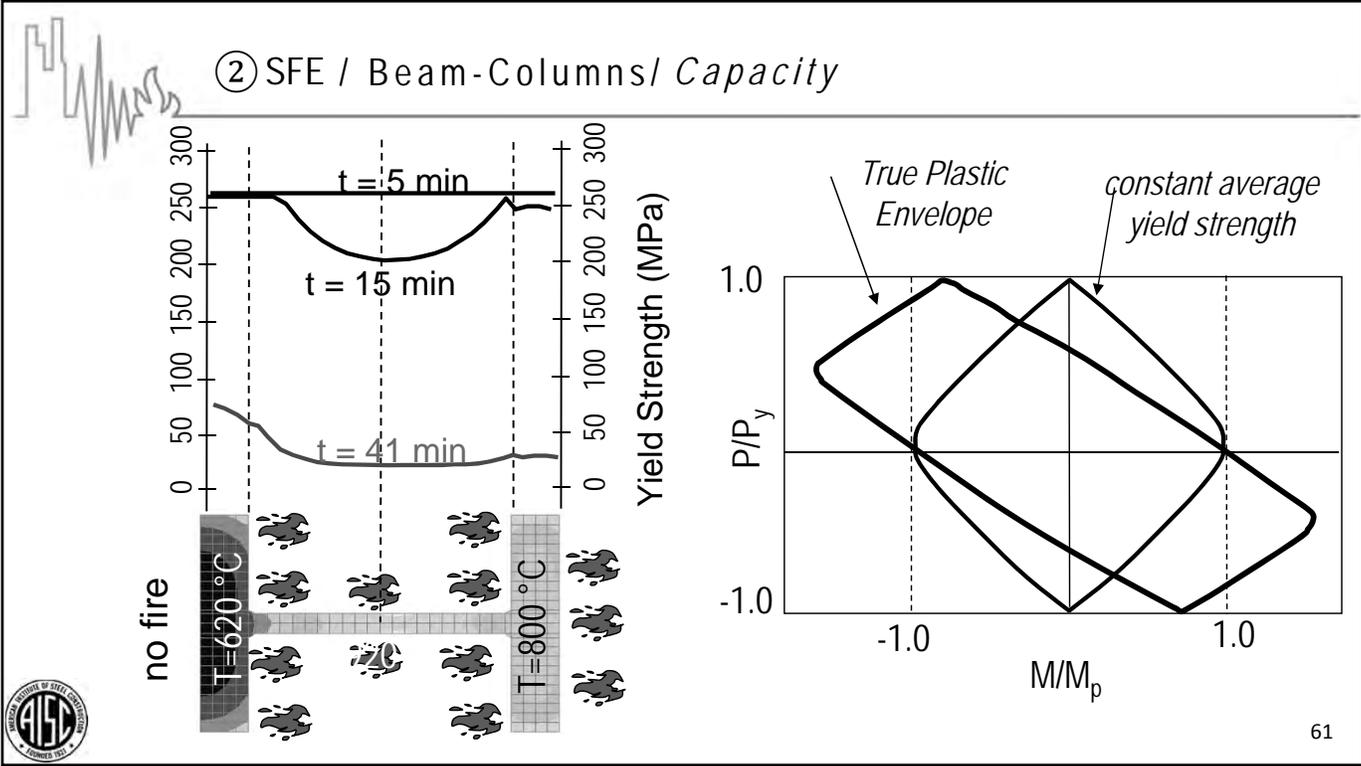
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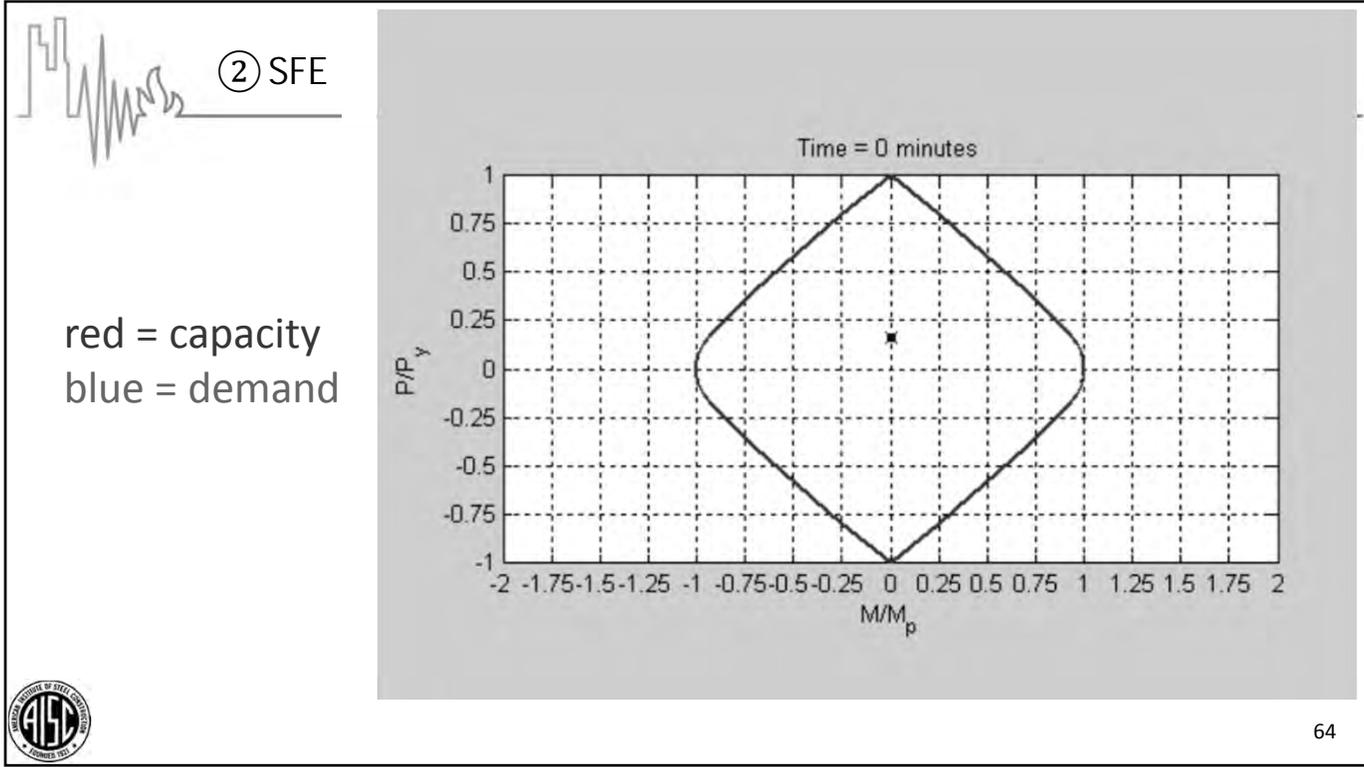
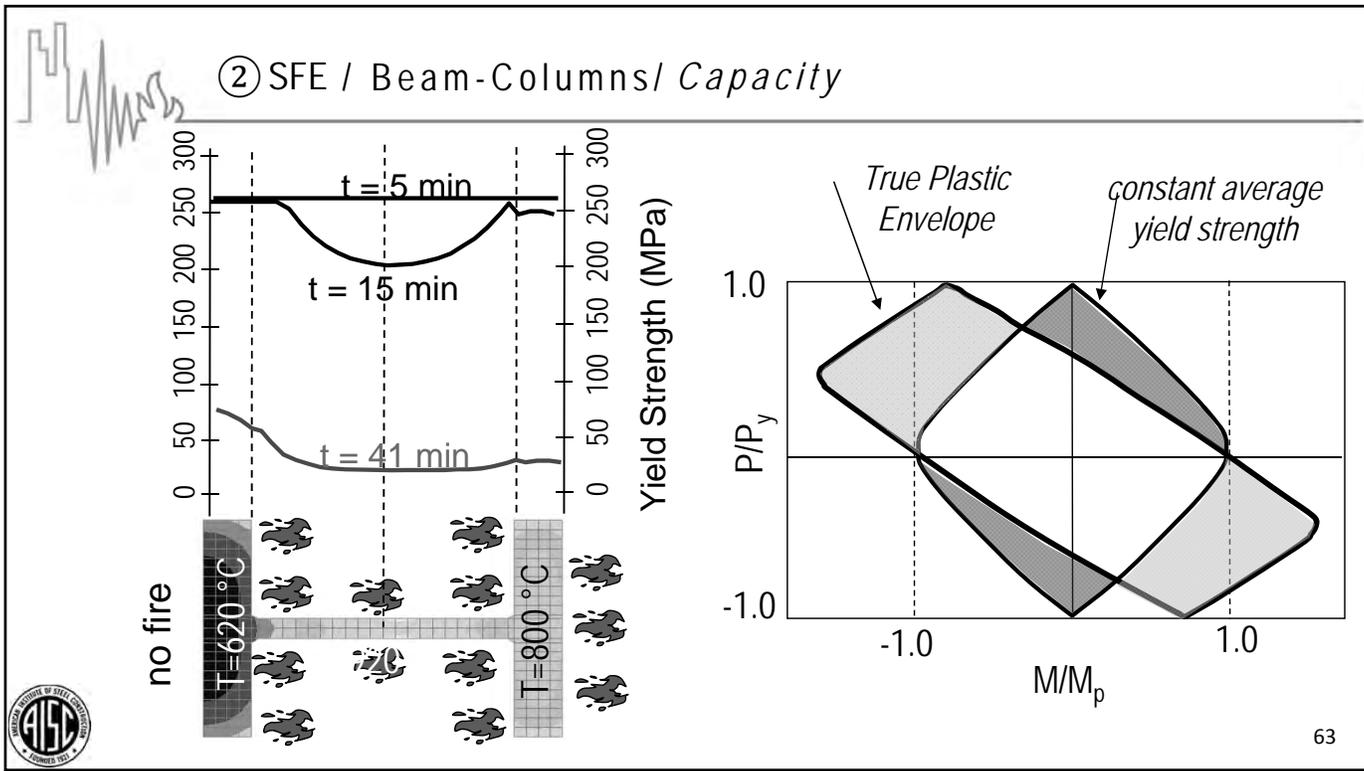














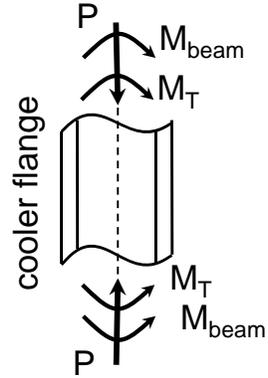
VIDEO



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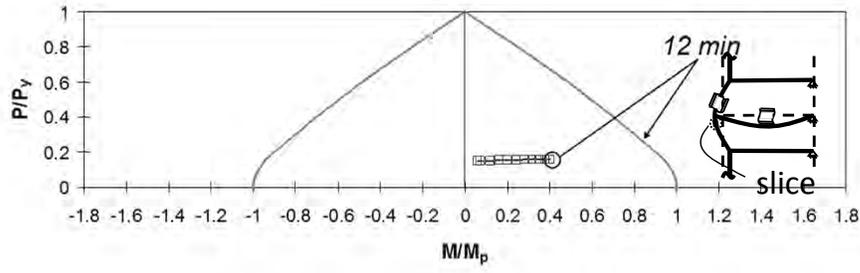
② SFE / Beam-Columns / Demand



cooler flange

P , M_{beam} , M_T

M_T , M_{beam} , P



P/P_y

M/M_p

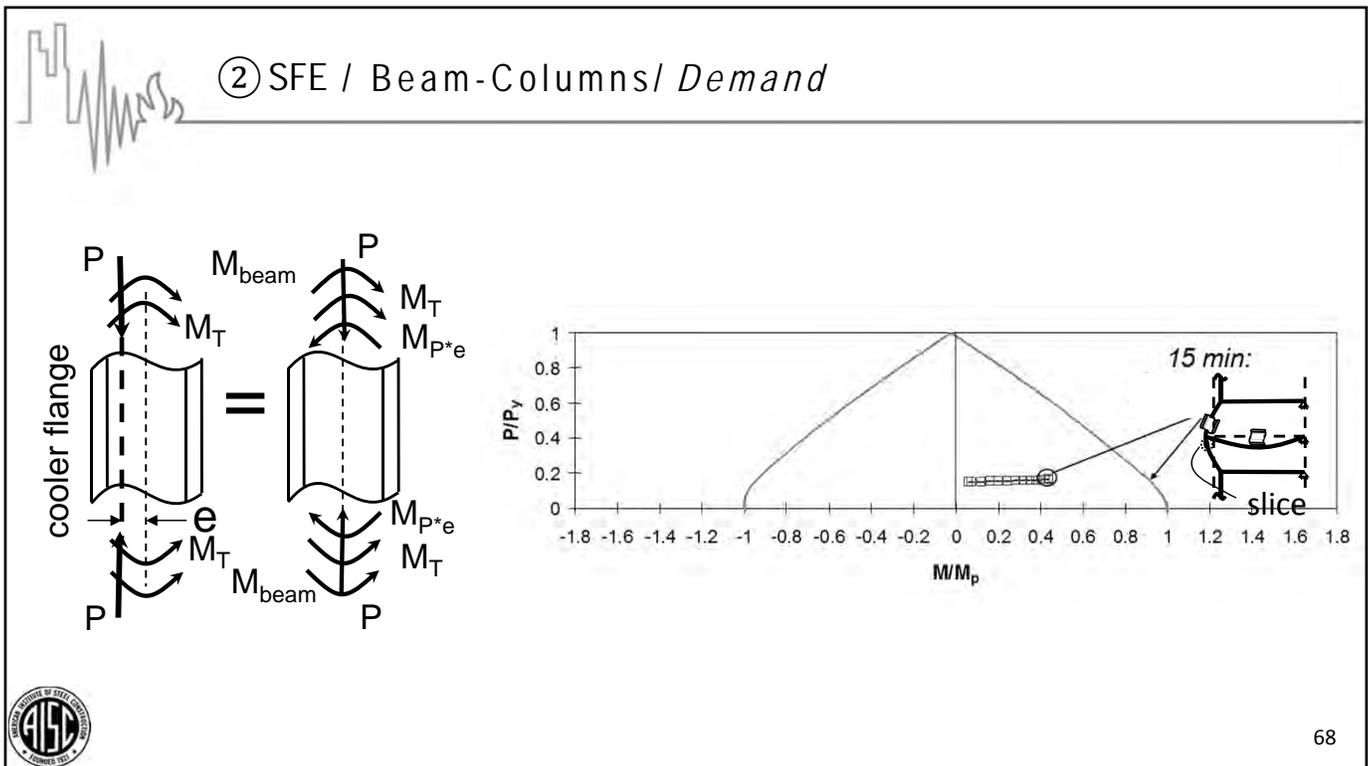
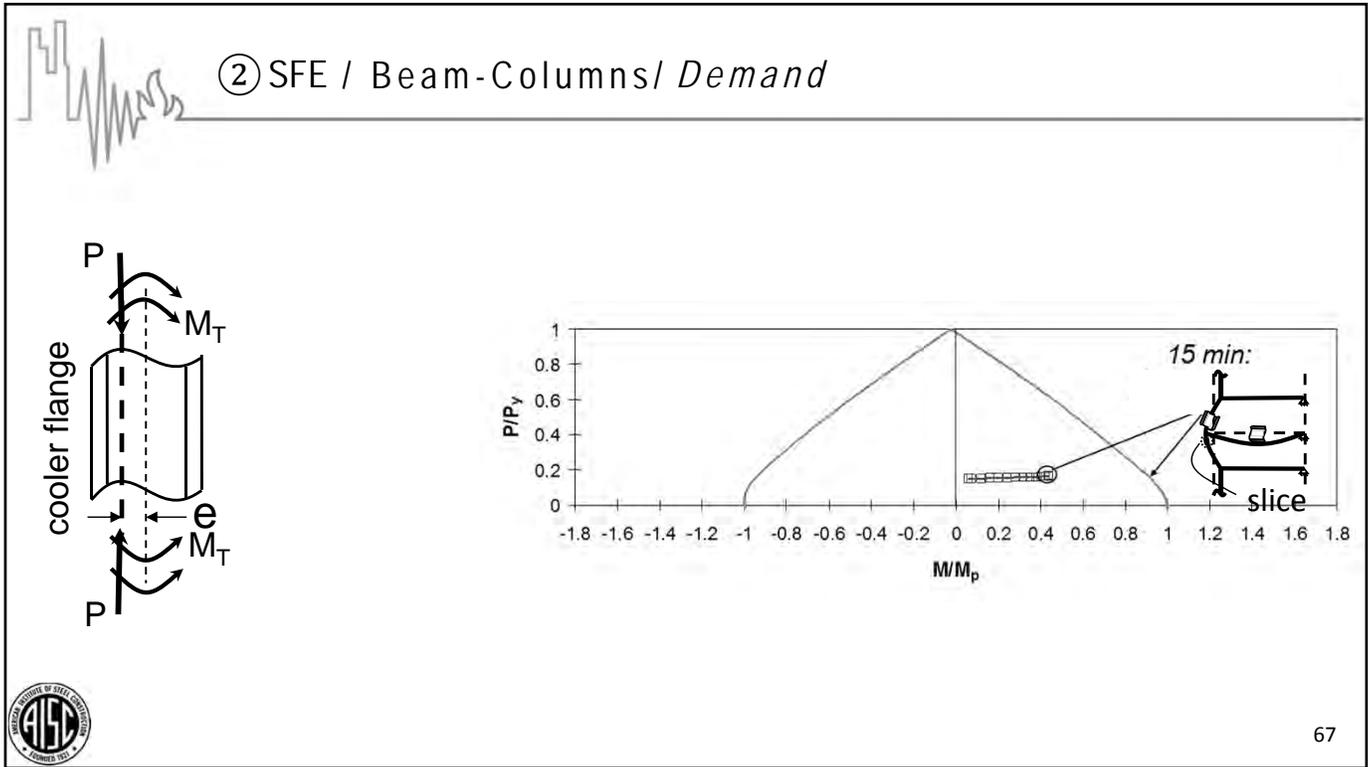
12 mfg

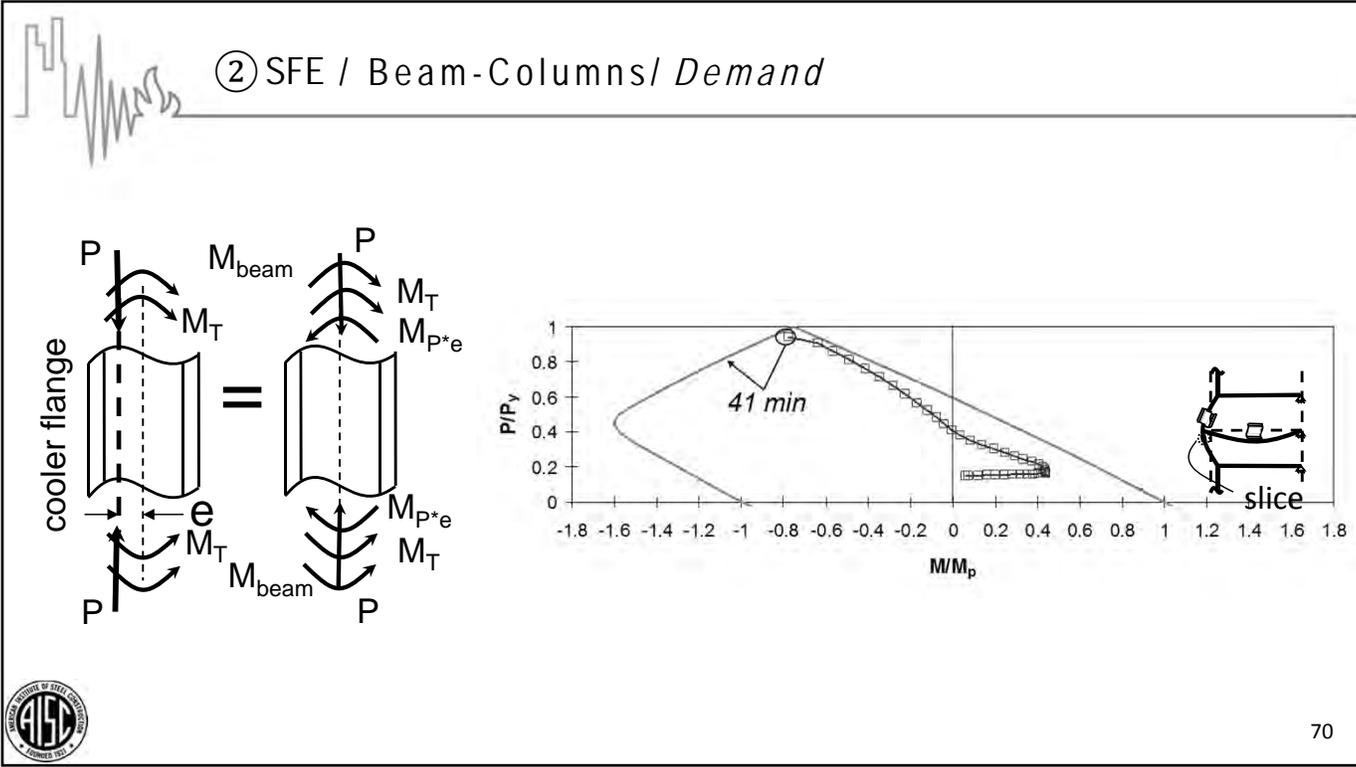
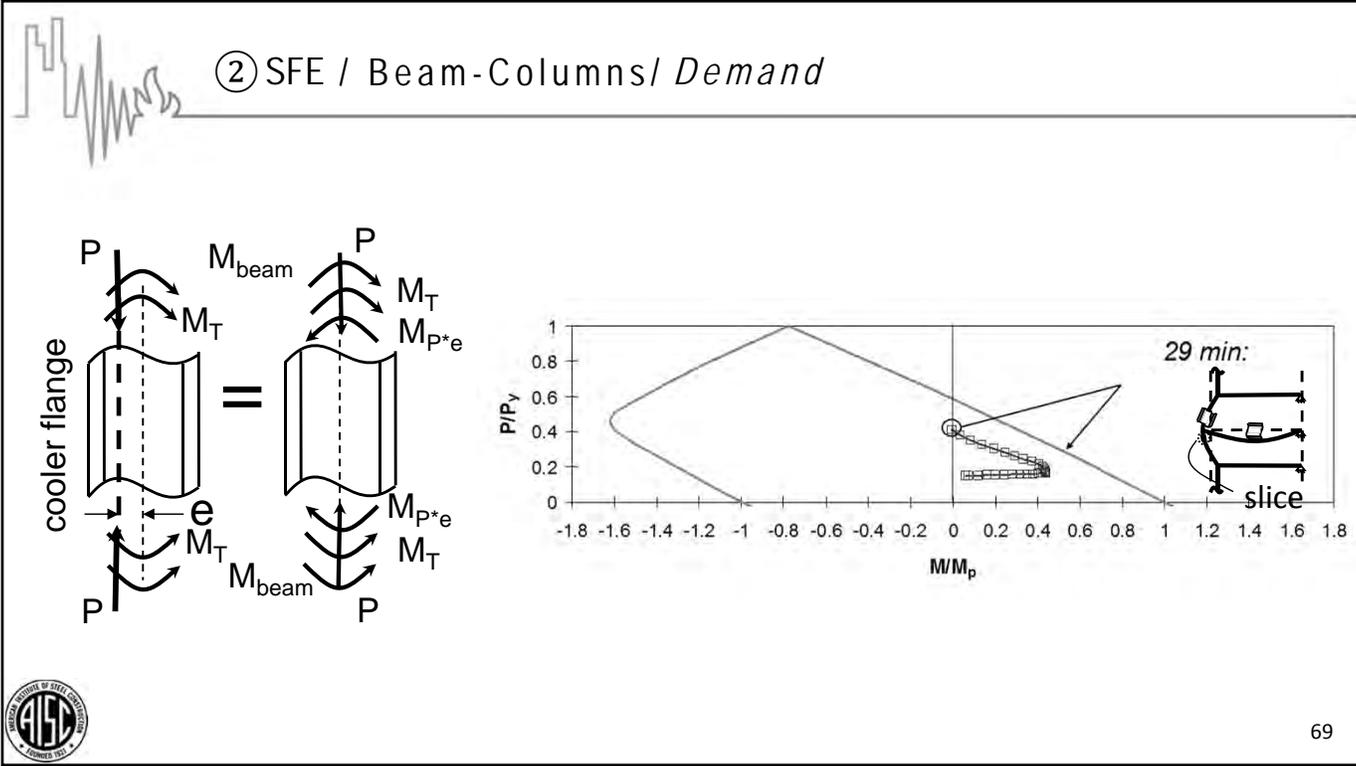
slice



66





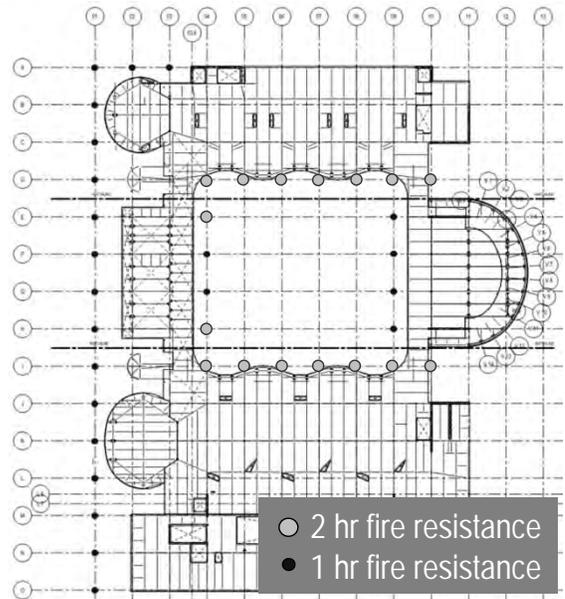




② SFE / Beam-Columns / case study

University Building (SFE: BuroHappold)

- Estimated cost of fire protection per column: \$20,000 (2 hours)
- SFE: assuming average temperature was NOT conservative
- Did not need to fire protect columns



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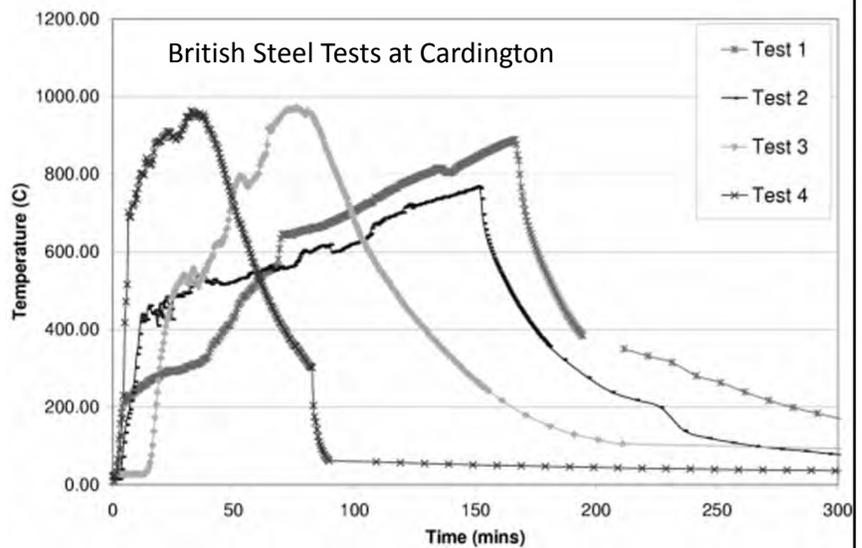


slide credit: F. Block, BuroHappold



② SFE

QUESTION:
Do structural failures *always* happen during the heating phase?



72

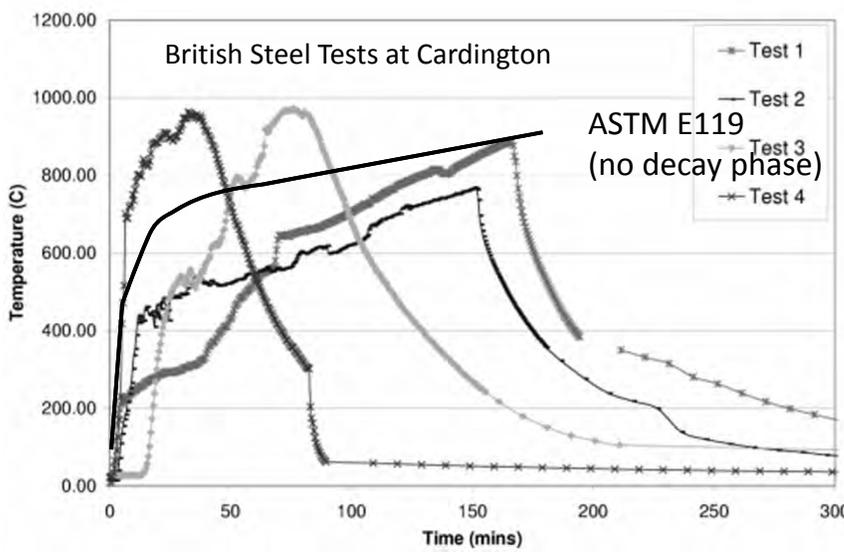




② SFE

QUESTION:
Do structural failures *always* happen during the heating phase?

SHORT ANSWER:
no

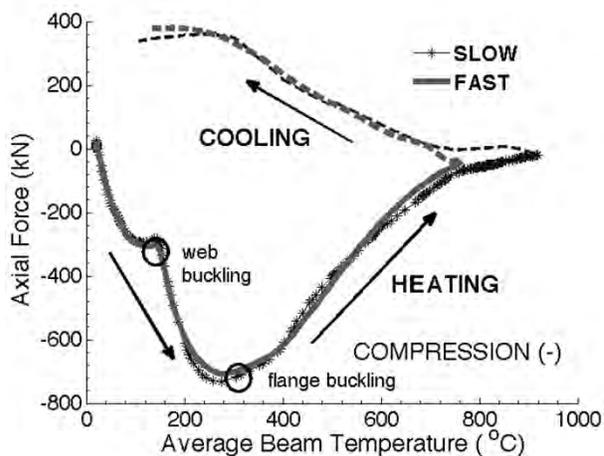


② STRUCTURAL FIRE ENGINEERING (SFE)
Connections

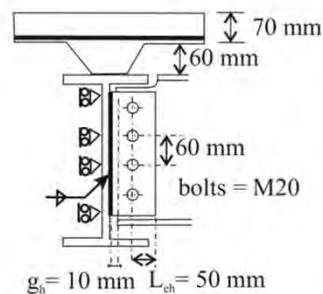
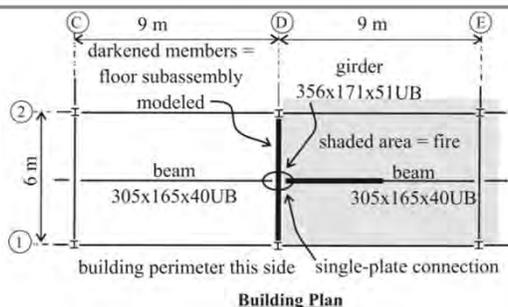




② SFE / connections /



② SFE / connections /



② SFE / connections /

The diagram shows a 3D perspective of a girder-beam connection. The girder is labeled 'GIRDER' and the beam is labeled 'BEAM'. Below it is a detailed view of the connection showing bolts and gusset plates.

The building plan shows a grid with columns C, D, and E, and beams 1 and 2. The distance between columns C and D is 9 m, and between D and E is 9 m. The height of the beams is 6 m. A shaded area between columns D and E and between beams 1 and 2 is labeled 'shaded area = fire'. The girder is labeled '356x171x51UB' and the beams are labeled '305x165x40UB'. A 'single-plate connection' is shown between the girder and the beam. The building perimeter is on the left side.

The connection detail shows a top view of the girder and beam. The girder has a depth of 70 mm. The beam has a depth of 60 mm. The connection is shown with bolts and gusset plates. The bolts are labeled 'bolts = M20'. The gap between the girder and beam is labeled $g_h = 10 \text{ mm}$ and the length of the connection is labeled $L_{ch} = 50 \text{ mm}$.

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② SFE / connections /

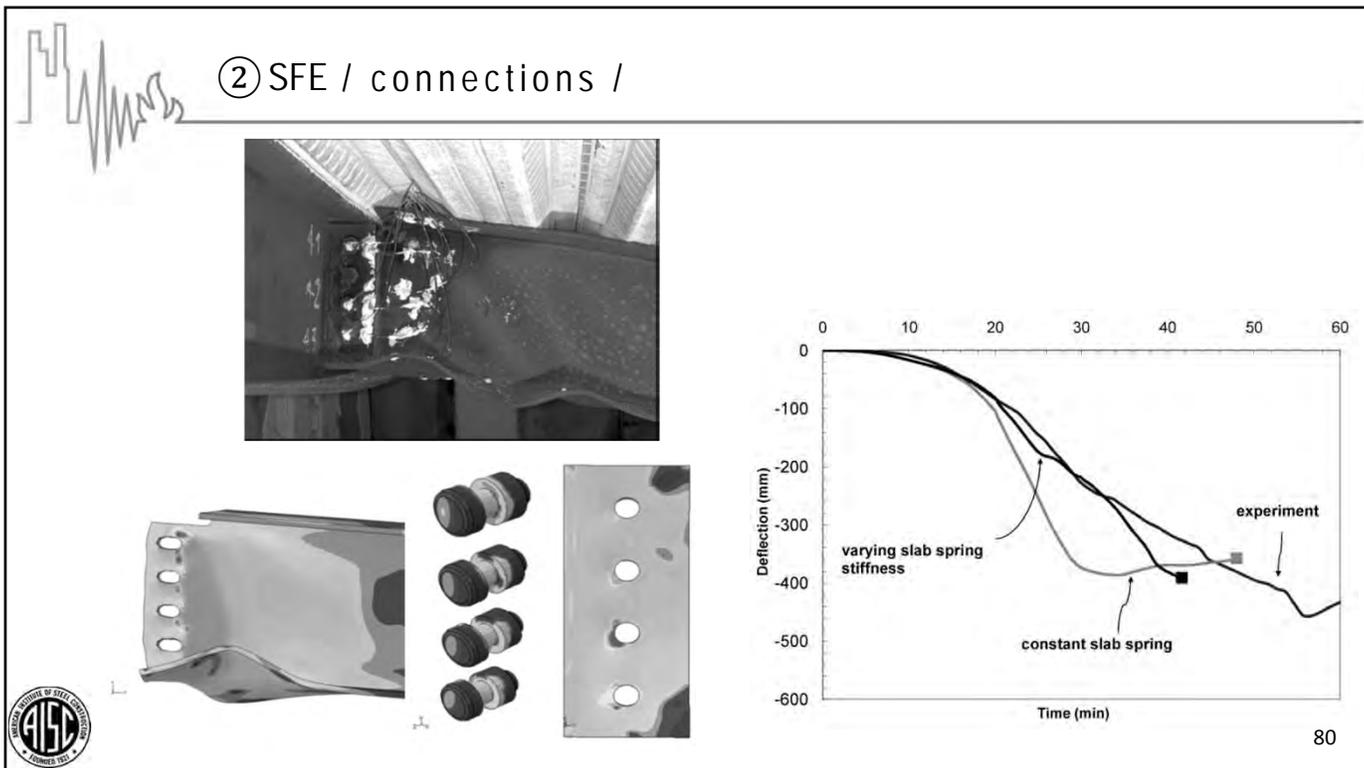
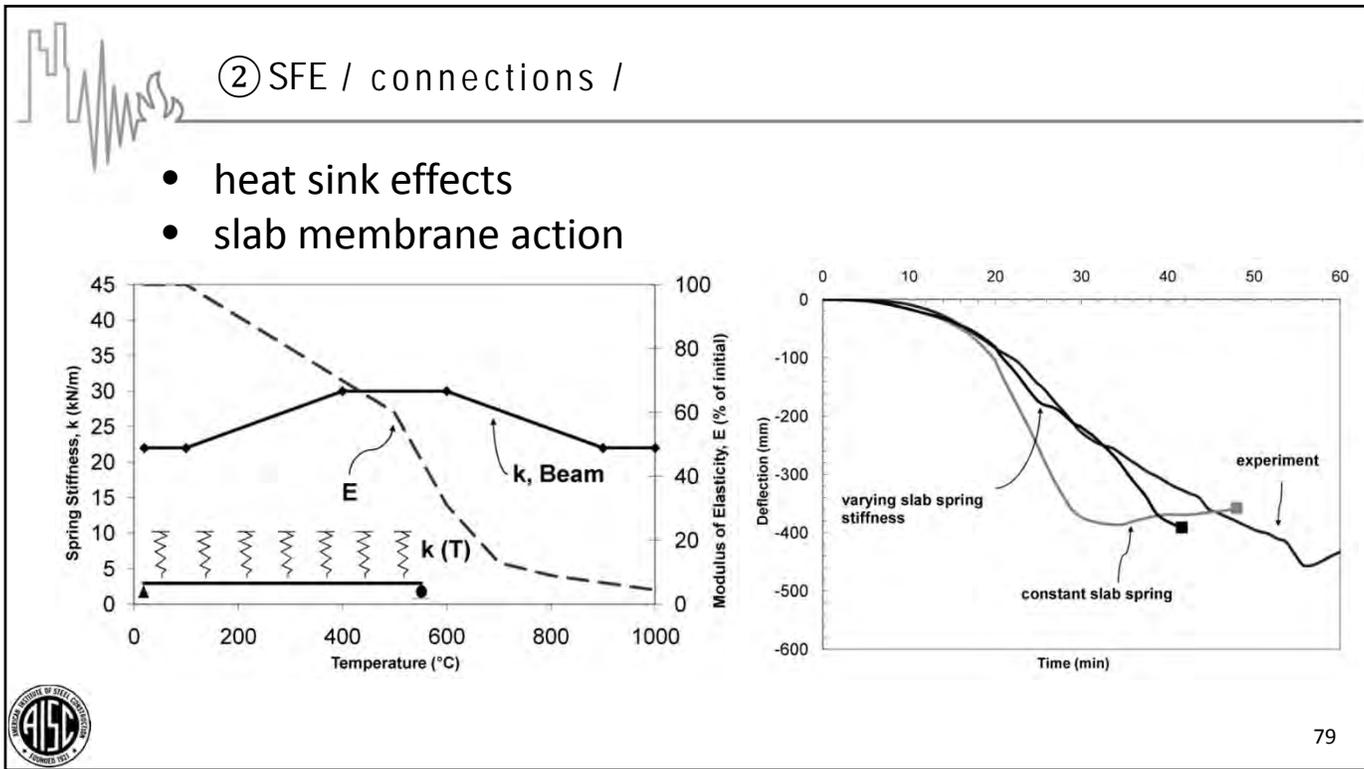
- heat sink effects
- slab membrane action

The graph plots Spring Stiffness, k (kN/m) on the left y-axis (0 to 45) and Modulus of Elasticity, E (% of initial) on the right y-axis (0 to 100) against Temperature ($^{\circ}\text{C}$) on the x-axis (0 to 1000). The solid line represents k , and the dashed line represents E . The k curve starts at approximately 22 kN/m at 0°C, peaks at 30 kN/m at 400°C, and then decreases to about 22 kN/m at 1000°C. The E curve starts at 100% at 0°C and decreases to about 5% at 1000°C. A horizontal line at the bottom of the graph is labeled $k(T)$.

The building plan is identical to the one on slide 77, showing a grid with columns C, D, and E, and beams 1 and 2. The distance between columns C and D is 9 m, and between D and E is 9 m. The height of the beams is 6 m. A shaded area between columns D and E and between beams 1 and 2 is labeled 'shaded area = fire'. The girder is labeled '356x171x51UB' and the beams are labeled '305x165x40UB'. A 'single-plate connection' is shown between the girder and the beam. The building perimeter is on the left side.

The connection detail is identical to the one on slide 77, showing a top view of the girder and beam. The girder has a depth of 70 mm. The beam has a depth of 60 mm. The connection is shown with bolts and gusset plates. The bolts are labeled 'bolts = M20'. The gap between the girder and beam is labeled $g_h = 10 \text{ mm}$ and the length of the connection is labeled $L_{ch} = 50 \text{ mm}$.

78



② SFE / connections /



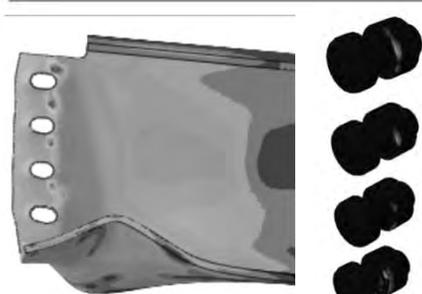
- Bolt grade
- Web reinforcing plate
- Shear tab thickness
- g_h



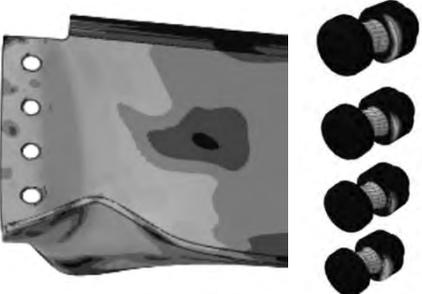
81

② SFE / connections /

Grade 8.8
(Cardington)



Grade 5.6



- Bolt grade
- Web reinforcing plate
- Shear tab thickness
- g_h

Cardington:

- End time: 123 min
- Max Tension: 359 KN

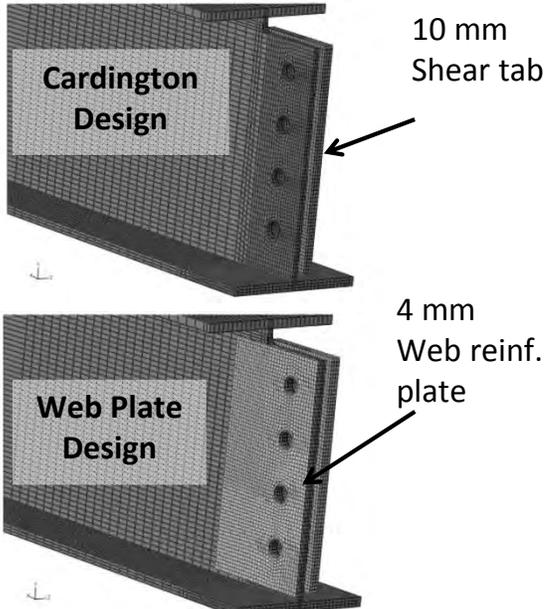
Modification:

- End time: 101 min
- Max Tension: 192 KN



82

② SFE / connections /



- Bolt grade
- Web reinforcing plate
- Shear tab thickness
- g_h

Cardington:

- End time: 123 min
- Max Tension: 359 KN

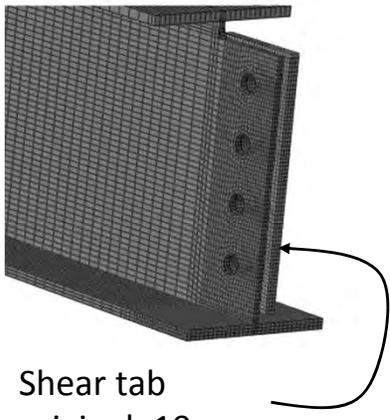
Modification:

- End time: 202 min **
- Max Tension: 622 KN

** = no failure

83

② SFE / connections /



Web thickness = 6 mm

Shear tab
original: 10 mm
modified: 6 mm

- Bolt grade
- Web reinforcing plate
- Shear tab thickness
- g_h

Cardington:

- End time: 123 min
- Max Tension: 359 KN

Modification:

- End time: 178 min
- Max Tension: 348 KN

84

② SFE / connections /

- Bolt grade
- Web reinforcing plate
- Shear tab thickness
- g_h

Cardington:

- End time: 123 min
- Max Tension: 359 KN

Modification:

- End time: 178 min
- Max Tension: 348 KN

85

② SFE / connections /

- Bolt grade
- Web reinforcing plate
- Shear tab thickness
- g_h

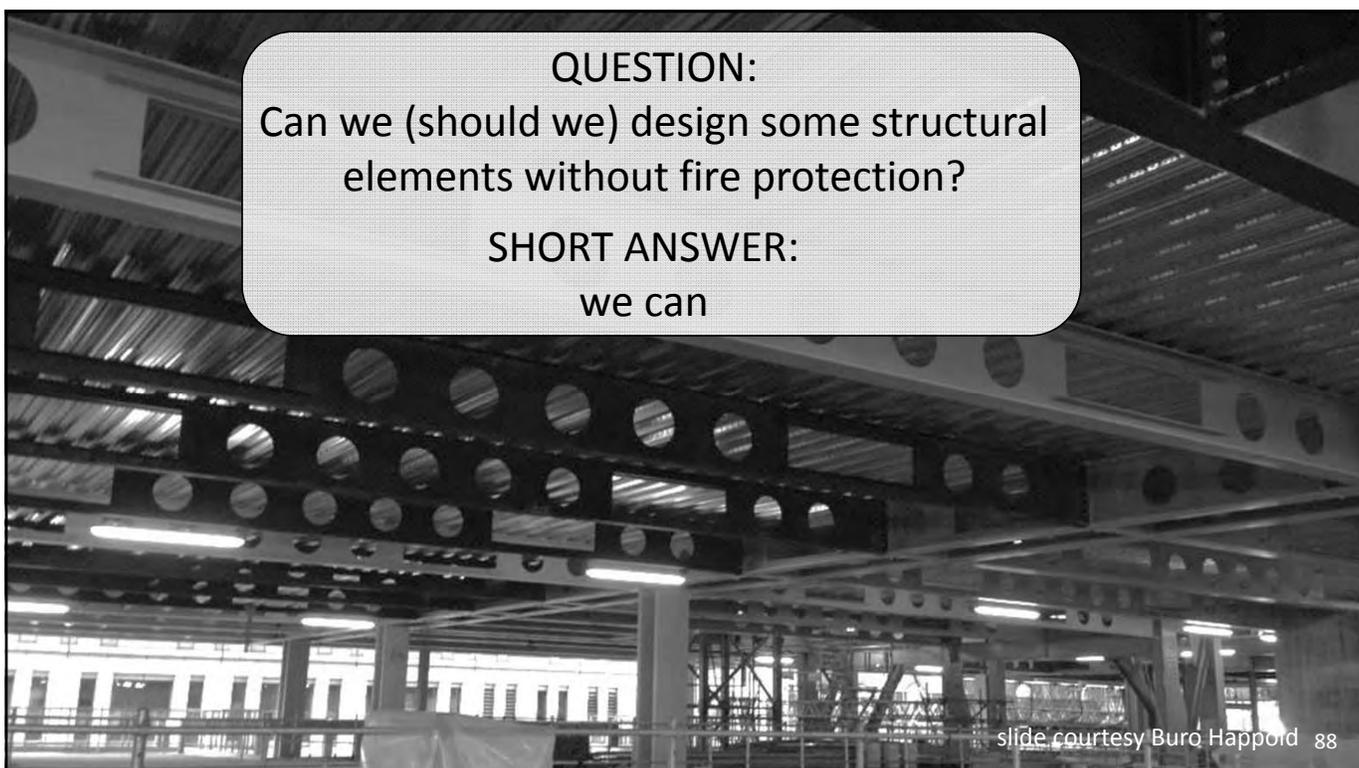
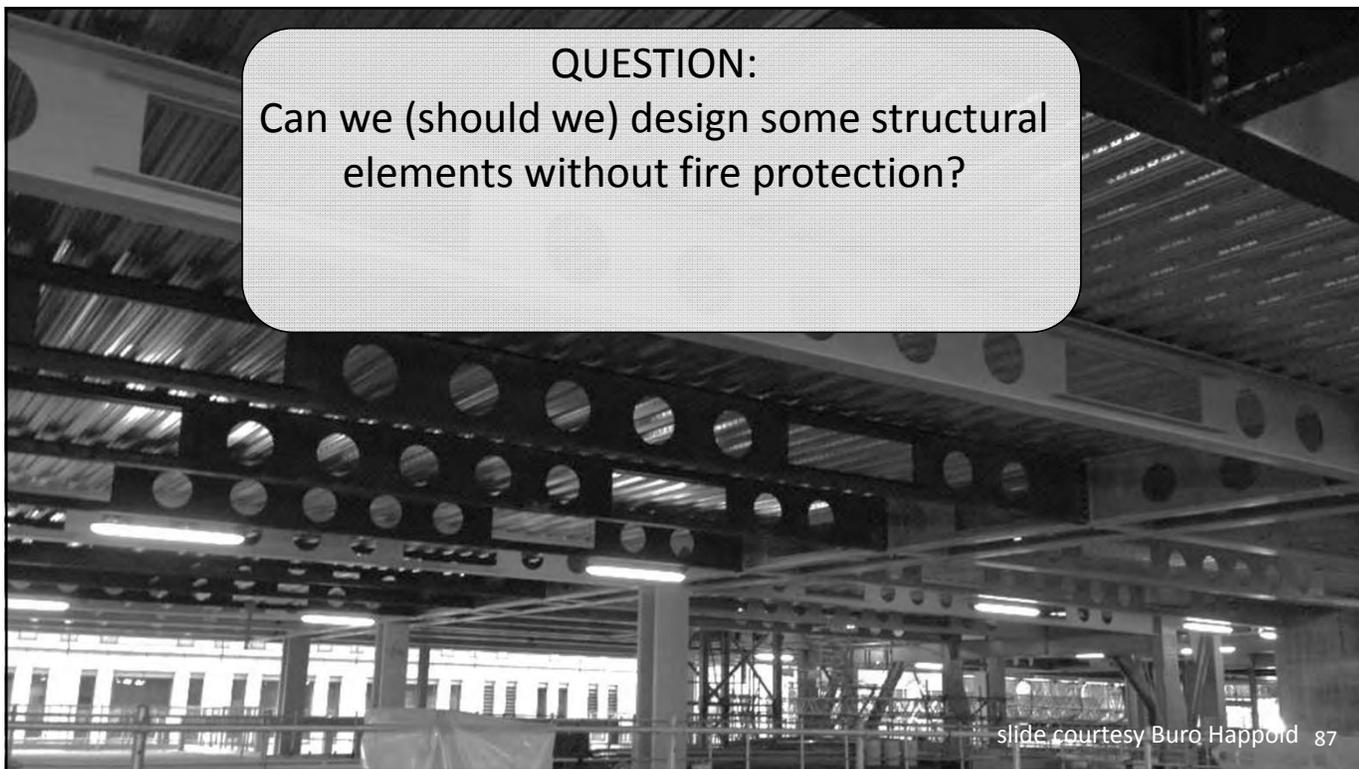
Cardington:

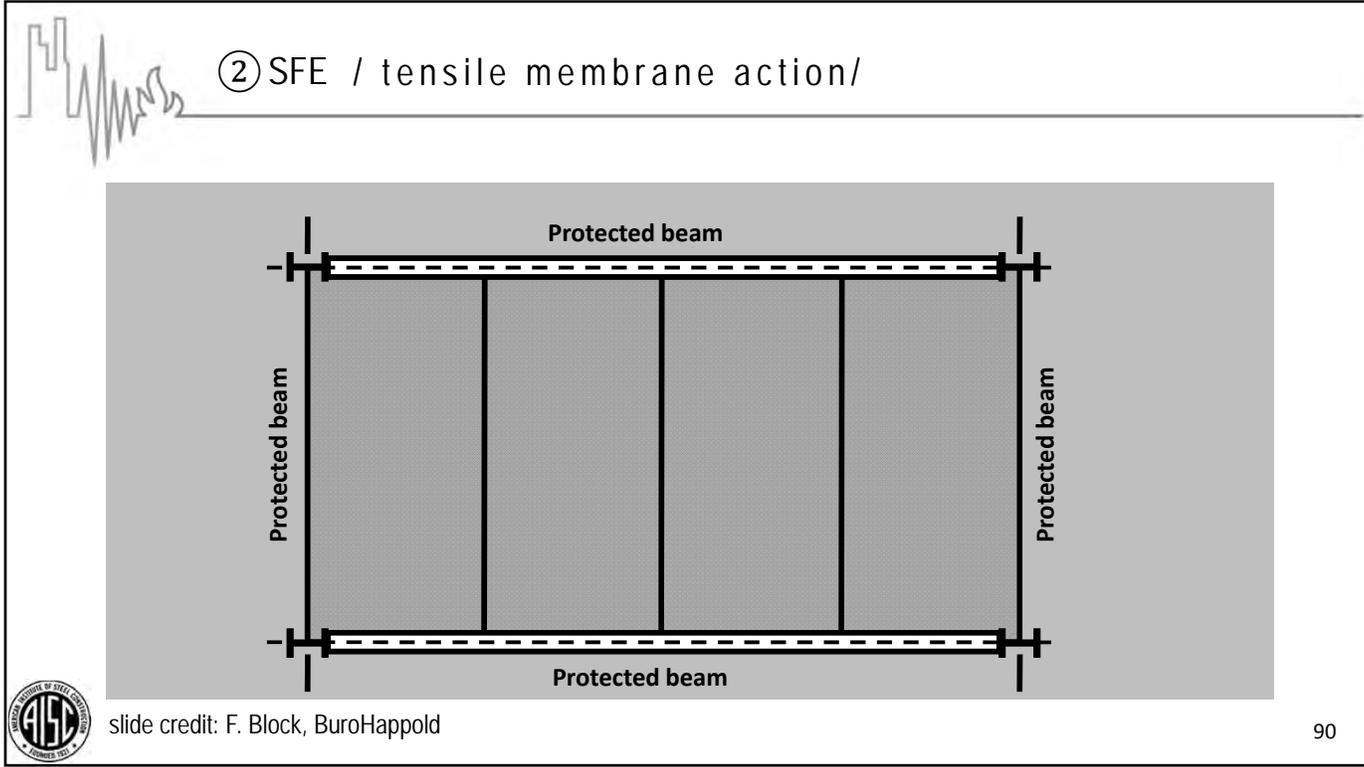
- End time: 123 min
- Max Tension: 359 KN

Modification:

- End time: 165 min
- Max Tension: 407 KN

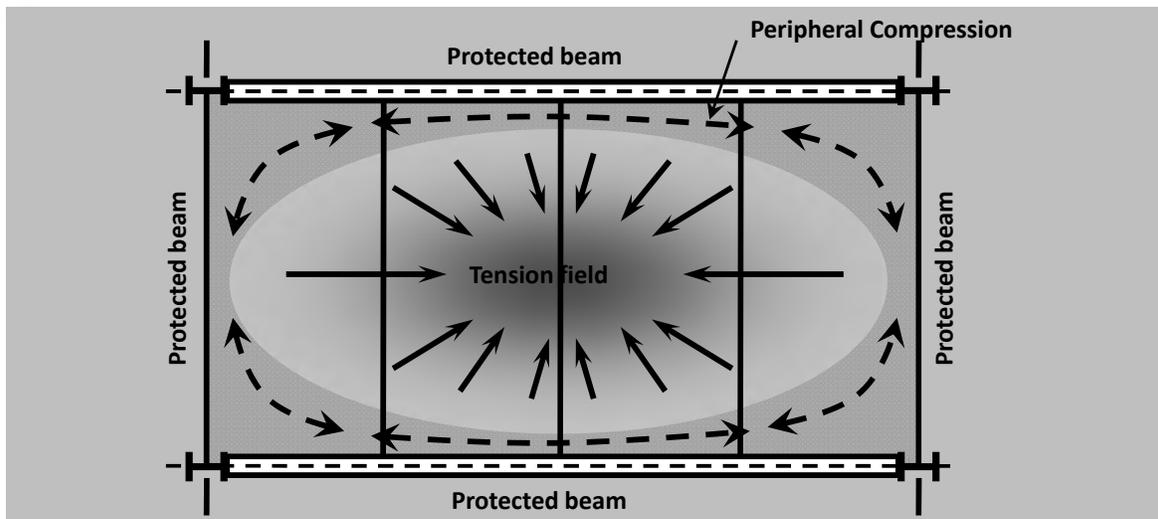
86







② SFE / tensile membrane action/



slide credit: F. Block, BuroHappold

91



② SFE / tensile membrane action/

5 Broadgate, UK
(SFE: BuroHappold)

- Accept local damage as long as stability of the overall building is maintained
- Utilize tensile membrane action (TMA)



image credit: Make Architects

92

② SFE / tensile membrane action/

green = unprotected beams

slide credit: F. Block, BuroHappold

93

② SFE / tensile membrane action/

green = unprotected beams

TMA allows to save ~40% of the fire protection cost

slide credit: F. Block, BuroHappold

94





② SFE
/ unprotected steel /

Hotel Arts, Barcelona
(SFE: SOM)

- unfireprotected exoskeleton steel-braced megaframe



② SFE

QUESTION:
Can we (should we)
design some structural
elements without fire
protection?



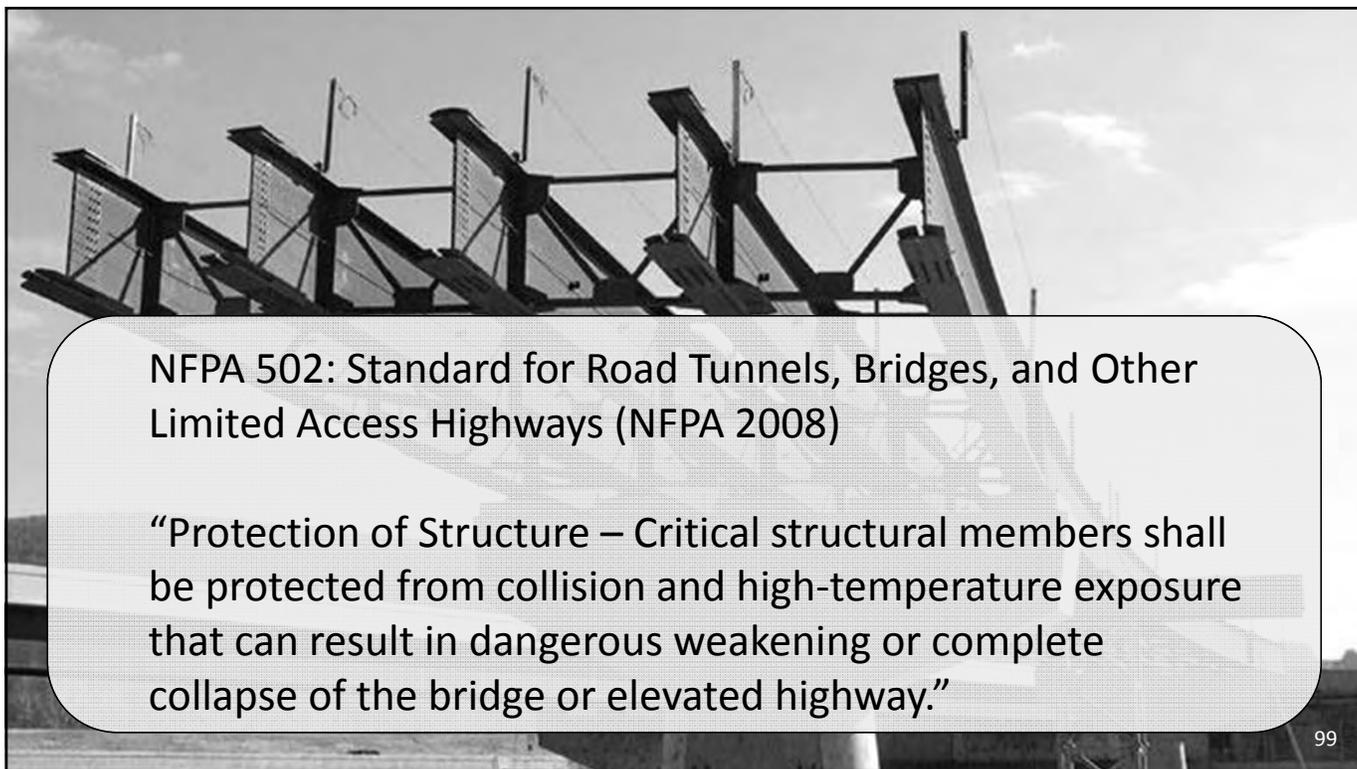


② SFE

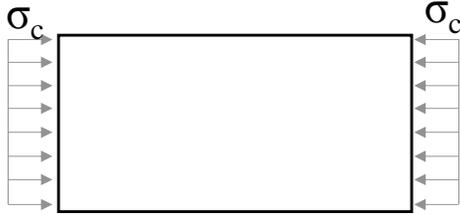
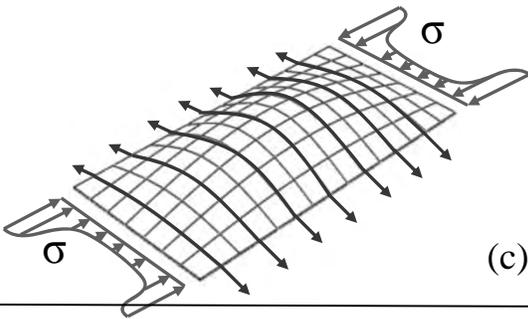
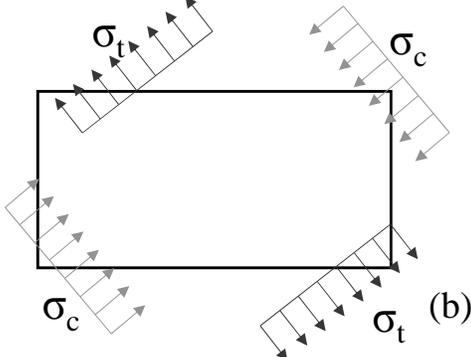
QUESTION:
Can we (should we)
design some structural
elements without fire
protection?

SHORT ANSWER:
sometimes, no choice

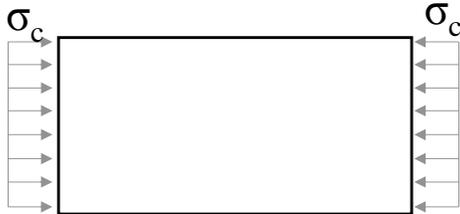
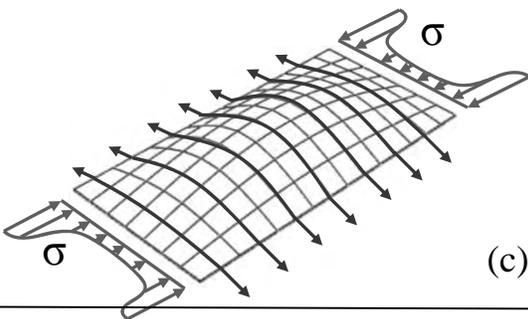
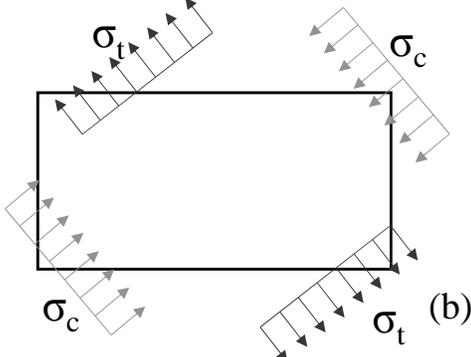
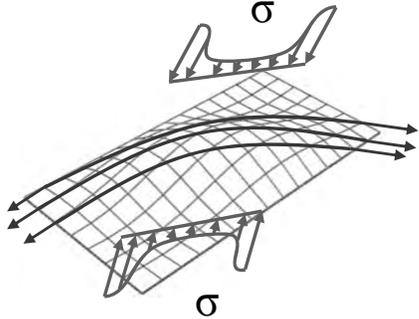




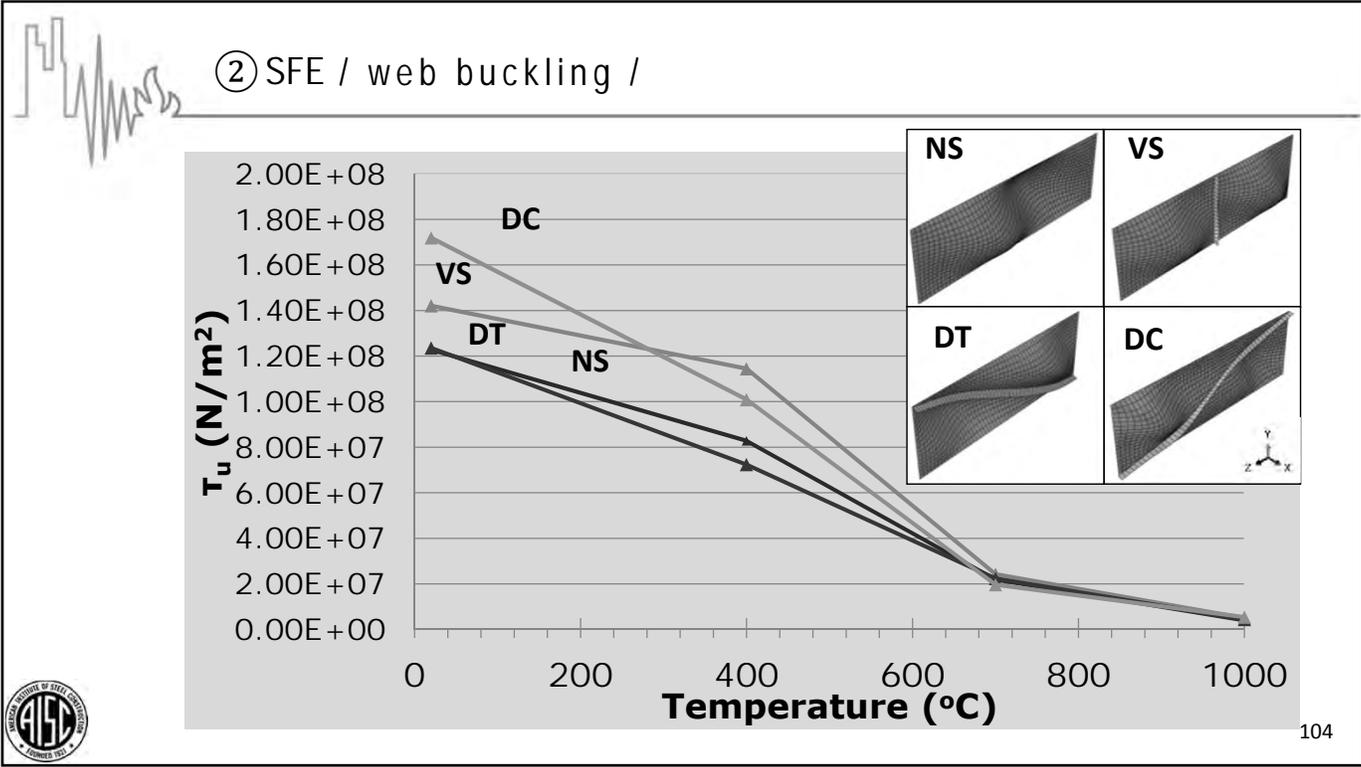
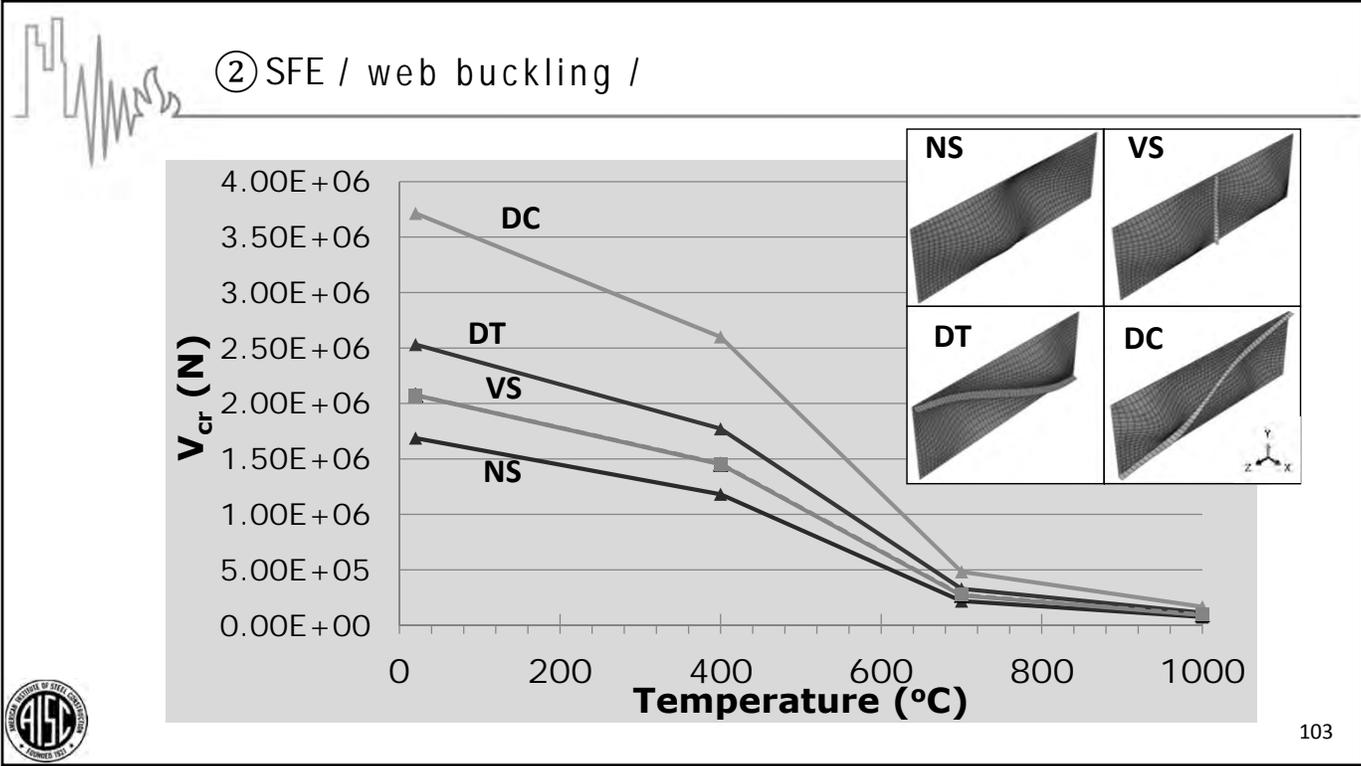
| | Elastic state | |
|--------------------|---------------|--|
| pure axial loading | <p>(a)</p> | |
| pure shear loading | <p>(b)</p> | |

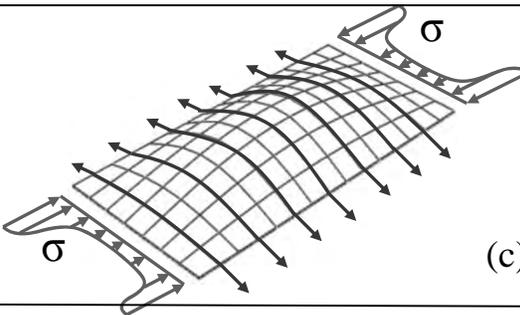
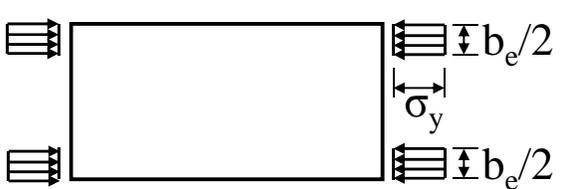
| | Elastic state | Postbuckling |
|--------------------|--|---|
| pure axial loading |  <p>(a)</p> |  <p>(c)</p> |
| pure shear loading |  <p>(b)</p> | |

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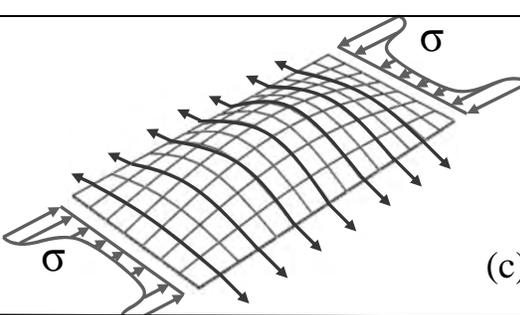
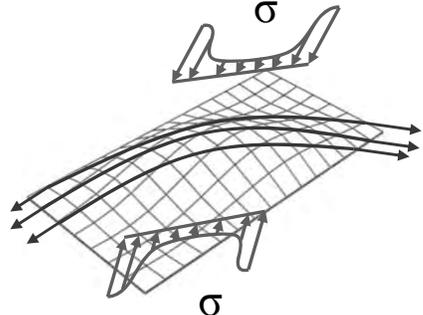
| | Elastic state | Postbuckling |
|--------------------|--|---|
| pure axial loading |  <p>(a)</p> |  <p>(c)</p> |
| pure shear loading |  <p>(b)</p> |  <p>(d)</p> |

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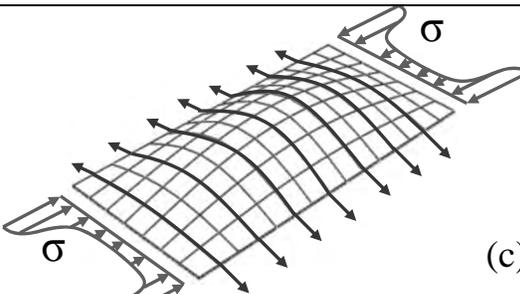
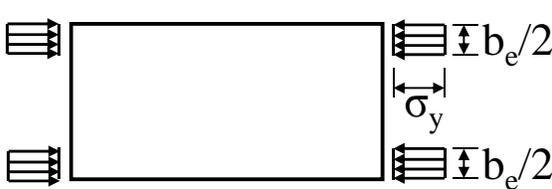
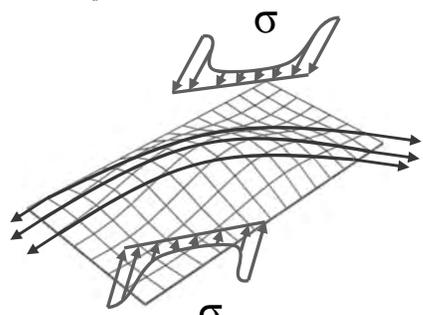
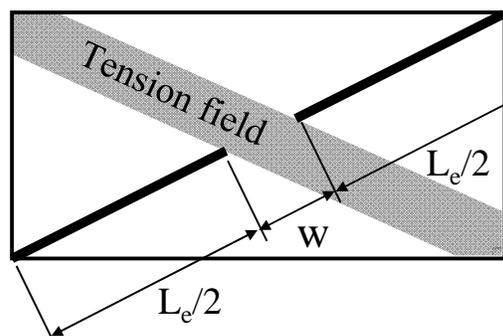


| | Postbuckling | Equivalence condition at postbuckling stage |
|--------------------|--|---|
| pure axial loading |  <p>(c)</p> |  <p>(e)</p> |
| pure shear loading | | |

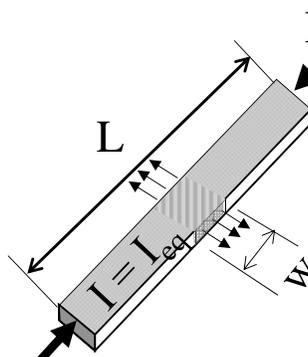
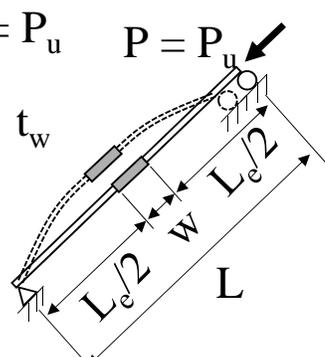
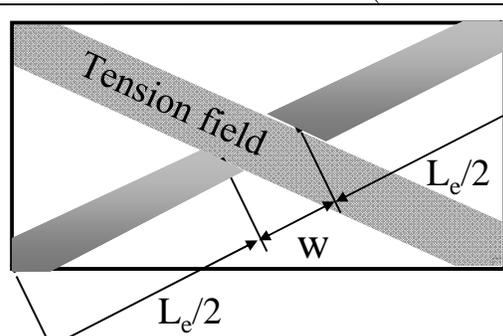
105

| | Postbuckling | Equivalence condition at postbuckling stage |
|--------------------|--|---|
| pure axial loading |  <p>(c)</p> |  <p>(e)</p> |
| pure shear loading |  <p>(d)</p> | |

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| | Postbuckling | Equivalence condition at postbuckling stage |
|--------------------|--|---|
| pure axial loading |  <p>(c)</p> |  <p>(e)</p> |
| pure shear loading |  <p>(d)</p> |  <p>(f)</p> |

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| | |
|---|--|
|  <p>② SFE / web buckling /</p> |   |
|  |  <p>(f)</p> |

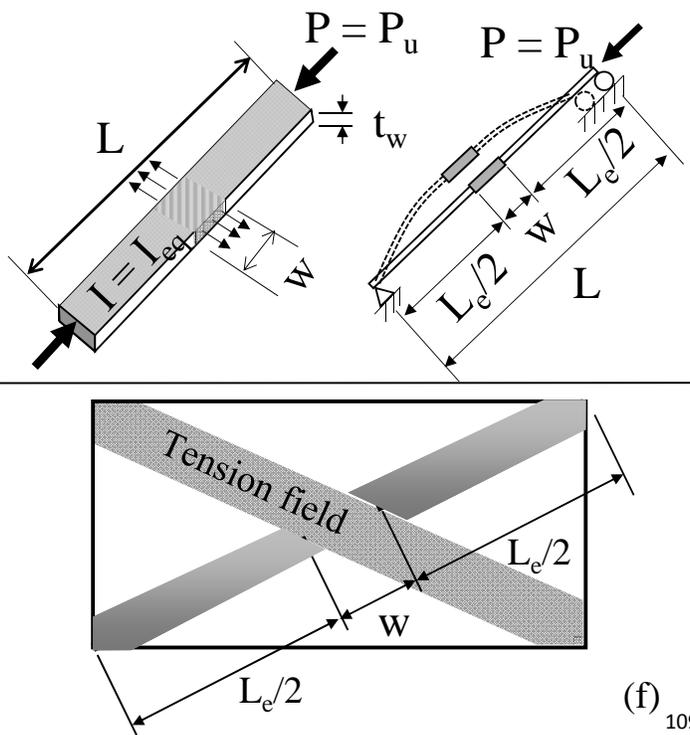
108



② SFE
/ web buckling /

The challenge is then to predict:

- 1) the width of the tension field, w
- 2) the axial load on this equivalent column, and
- 3) convert that axial load to a shear load.

(f) 109



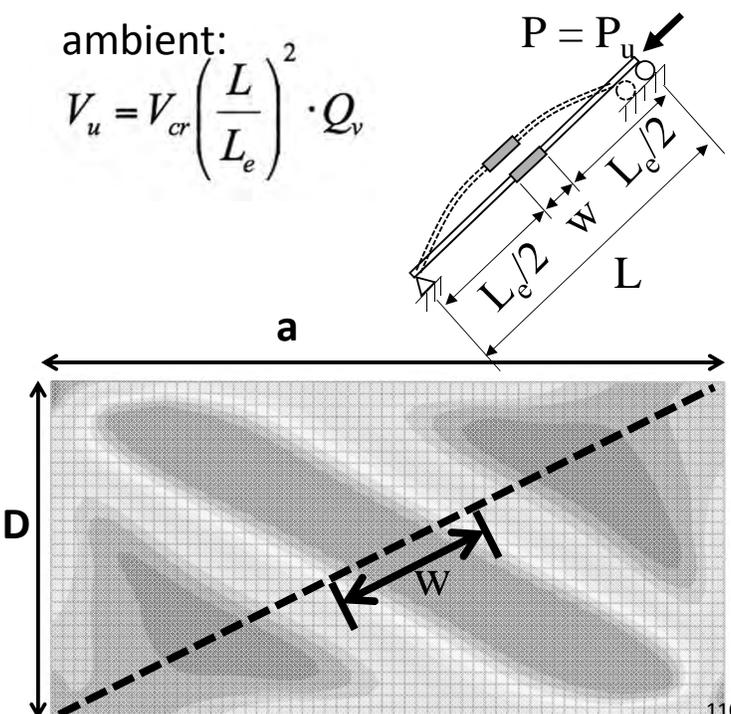
② SFE
/ web buckling /

Finding w :

- calibrated with 60 FE models
- considers slenderness (D/t_w), aspect ratio (a/D) and scale (D)



ambient:

$$V_u = V_{cr} \left(\frac{L}{L_e} \right)^2 \cdot Q_v$$


a

D

110



② SFE
/ web buckling /

Finding w :

- calibrated with 60 FE models
- considers slenderness (D/t_w), aspect ratio (a/D) and scale (D)
- validated with 84 test specimens at ambient temperature



ambient:

$$V_u = V_{cr} \left(\frac{L}{L_e} \right)^2 \cdot Q_v$$

| Set | V_u/V_u^{Exp} | |
|------------|-----------------|-----------|
| | Mean | Std. Dev. |
| A (n=27) | 1.04 | 0.08 |
| B (n=57) | 1.20 | 0.41 |
| A+B (n=84) | 1.15 | 0.35 |

Set A:

- $26 \text{ ksi} \leq \sigma_y \leq 61 \text{ ksi}$
- $100 \leq D/t_w \leq 300$; $1.0 \leq a/D \leq 3.0$
- $t_f/t_w \leq 5$

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② SFE
/ web buckling /

- same w as ambient
- β considers material effects:
 - ✓ 1.2 for $\sigma_y = 250 \text{ MPa}$
 - ✓ 1.15 for $\sigma_y = 345 \text{ MPa}$
- $\sqrt{K_{E,T}/k_{y,T}}$ considers temperature effects

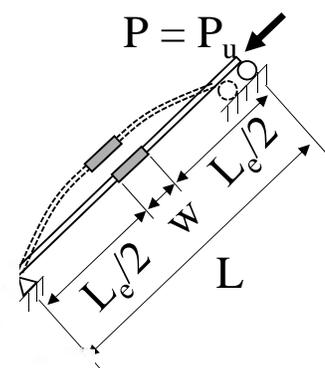


ambient:

$$V_u = V_{cr} \left(\frac{L}{L_e} \right)^2 \cdot Q_v$$

elev. temp:

$$V_u^T = V_{cr}^T \left(\frac{L}{L_e^T} \right)^2 \cdot Q_v^T$$

$$L_e^T = (L - w) \cdot \beta \cdot \sqrt{\frac{k_{E,T}}{k_{y,T}}}$$


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② SFE / web buckling /

| Specimen | a/D | D/t _w | D (m) | T (°C) | σ _y (MPa) | V _u ^T (kN) | V _u ^{Exp} (kN) | V _u ^T /V _u ^{Exp} |
|----------|-----|------------------|----------|-----------|-------------------------|-------------------------------------|---------------------------------------|--|
| TG3 | 1.0 | 153 | 0.305 | 20 | 288 | 82.4 | 79.85 | 1.03 |
| | | | | 400 | 288 | 59.2 | 67.63 | 0.87 |
| | | | | 565 | 166 | 34.2 | 34.34 | 0.99 |
| | | | | 700 | 66 | 13.6 | 17.15 | 0.79 |
| TG4 | 1.0 | 113 | 0.305 | 20 | 233 | 109.4 | 111.8 | 0.98 |
| | | | | 400 | 233 | 74.8 | 77.1 | 0.97 |
| | | | | 700 | 54 | 17.2 | 15.94 | 1.08 |





WHY SFE?

SAFETY (*efficiency*)

COST (*economy*)

ENCOURAGE INNOVATION (*elegance*)

Lewis Library, Princeton University
Architect: Frank Gehry

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CONCLUSIONS

Broadgate Exchange House
SFE: SOM

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④ CONCLUSIONS

| QUESTION | ANSWER |
|--|---|
| Do concrete structures perform better in fire than steel structures? | ALL materials have some form of weakness in fire. |
| | |
| | |



④ CONCLUSIONS

| QUESTION | ANSWER |
|---|---|
| Do concrete structures perform better in fire than steel structures? | ALL materials have some form of weakness in fire. |
| Does the fire resistive rating imply the <i>time</i> that the structural integrity is maintained? | no |
| | |





④ CONCLUSIONS

| QUESTION | ANSWER |
|---|---|
| Do concrete structures perform better in fire than steel structures? | ALL materials have some form of weakness in fire. |
| Does the fire resistive rating imply the <i>time</i> that the structural integrity is maintained? | no |
| Are there codes/standards that permit anything other than a prescriptive approach? | yes: NFPA 5000 (2012) IBC (2012) |



④ CONCLUSIONS

| QUESTION | ANSWER |
|--|---------------------------|
| Do we need to consider thermal gradients or can we just assume an average temperature? | It depends (beam-columns) |
| | |
| | |





④ CONCLUSIONS

| QUESTION | ANSWER |
|--|---------------------------|
| Do we need to consider thermal gradients or can we just assume an average temperature? | It depends (beam-columns) |
| Do structural failures <i>always</i> happen during the heating phase? | no (connections) |
| | |



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④ CONCLUSIONS

| QUESTION | ANSWER |
|--|---|
| Do we need to consider thermal gradients or can we just assume an average temperature? | It depends (beam-columns) |
| Do structural failures <i>always</i> happen during the heating phase? | no (connections) |
| Can we (should we) design some structural elements without fire protection? | <ul style="list-style-type: none"> • we can (TMA) • sometimes no choice (bridges) |



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④ CONCLUSIONS

- Typical design for fire (prescriptive) does not consider the structural response
- Performance based design for fire, aka structural fire engineering (SFE), considers the *real* fire and the *real* response of the structure to that fire
- SFE offers opportunities to design steel structures that are efficient, economical, and elegant



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ACKNOWLEDGEMENTS

My CRUE:

- Spencer Quiel (Lehigh U)
- Serdar Selamet (Bogazici U)
- Jonathan Glassman (Exponent)
- Negar Elhami Khorasani (U Buffalo)

Sponsors:

- NSF
- NIST
- AISC



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THANK YOU

Questions?

<https://garlock.princeton.edu>



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Polling Question

Which of the following is false regarding Structural Fire Engineering (SFE)?

- A. In SFE, fire is treated as a “load”
- B. SFE is based on standard fire tests such as ASTM E119
- C. In SFE one sets 'performance objectives' regarding how the structure should perform.
- D. SFE depends on structural behavior and thus it is an engineered approach to fire design



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PDH Certificates

Within 2 business days...

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!



PDH Certificates

Within 2 business days...

- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.



There's always a solution in steel.

Thank You

Please give us your feedback!
Survey at conclusion of webinar.

