Cold Bending Steel Beams: a State-of The-Art Engineering Solution that Meets Industry Challenges

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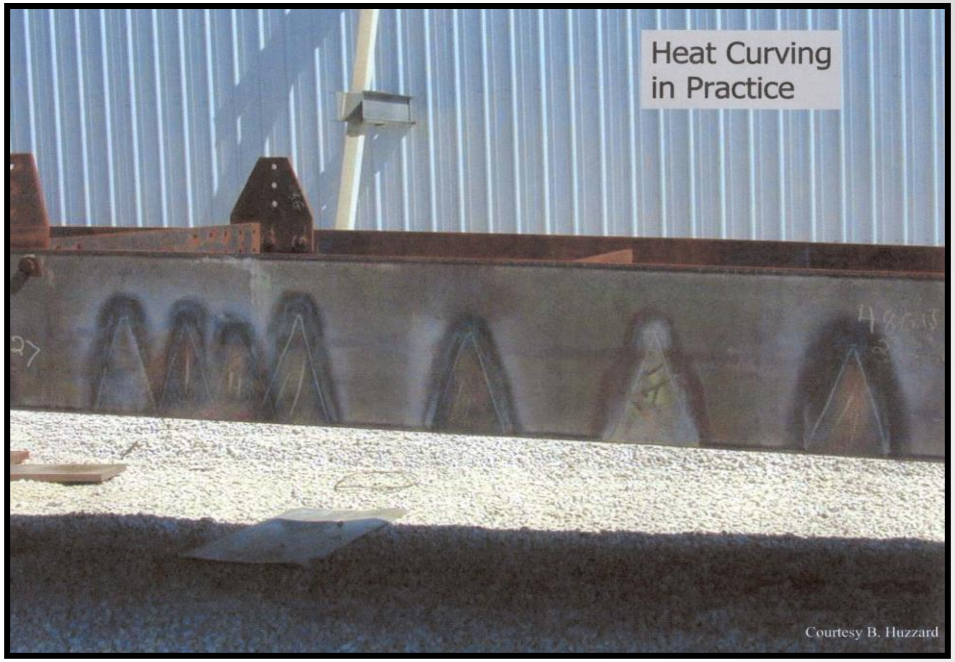
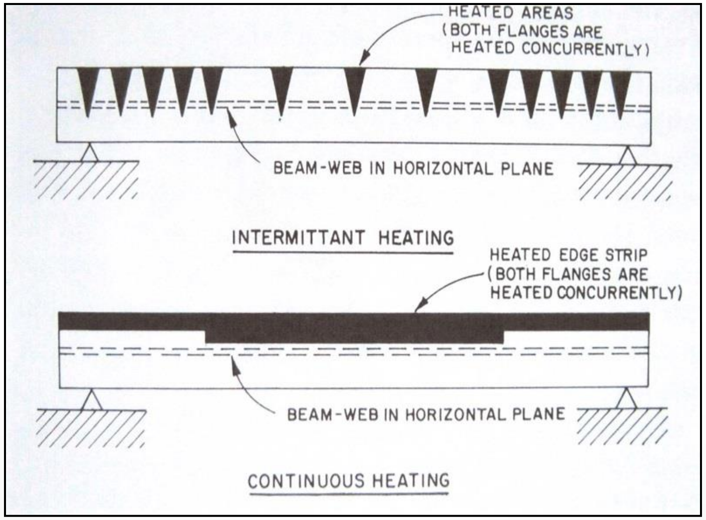
Horizontal Curves

Heat Curving

Continuous heat



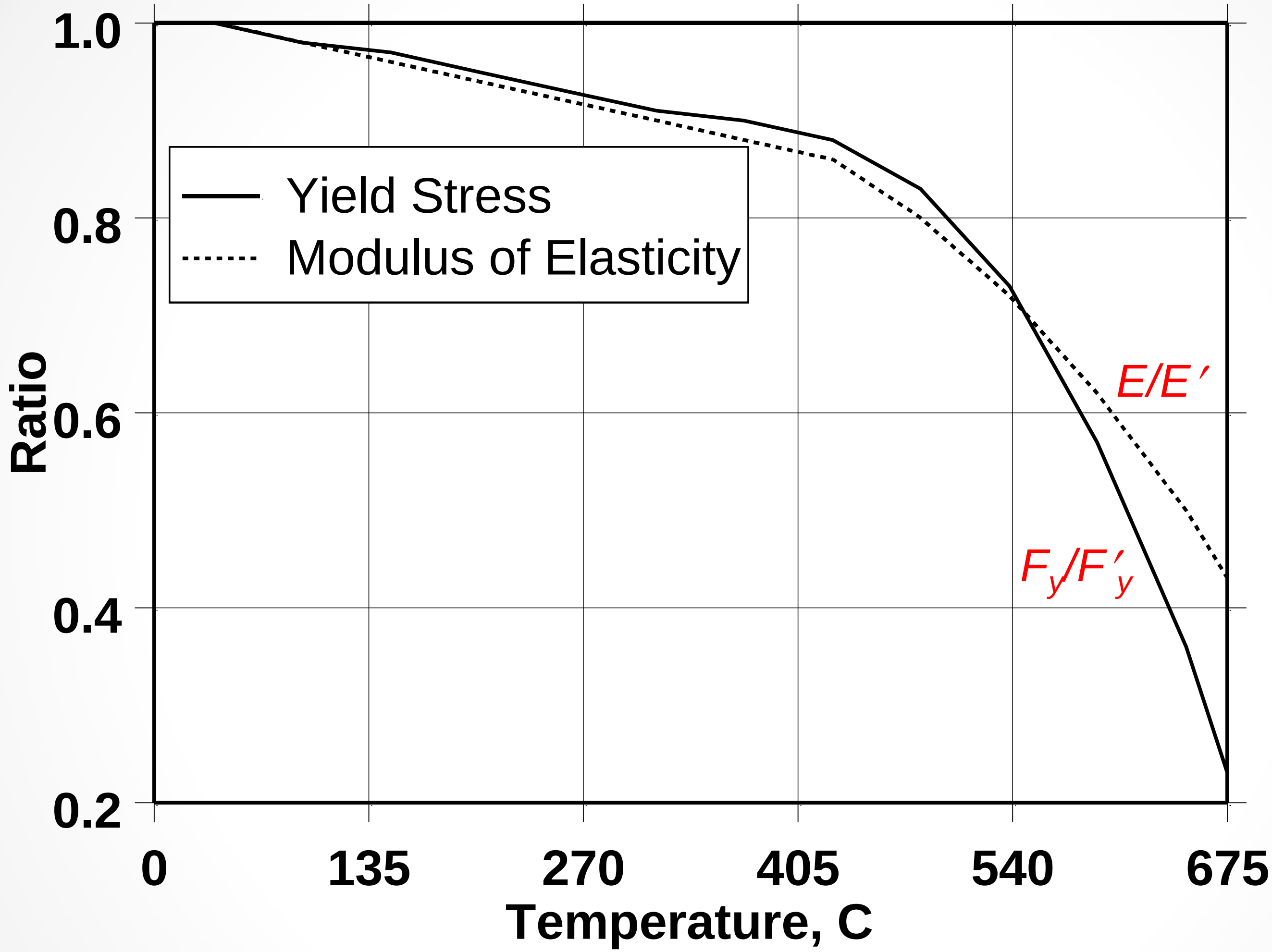
V heat (R > 300m)



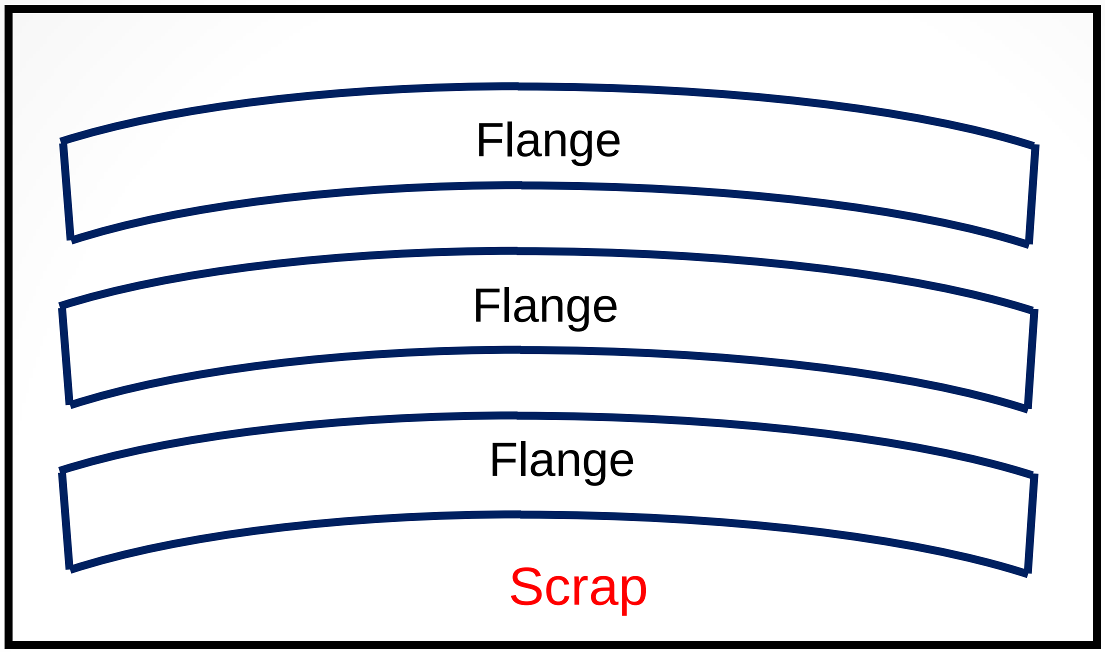
Drawbacks

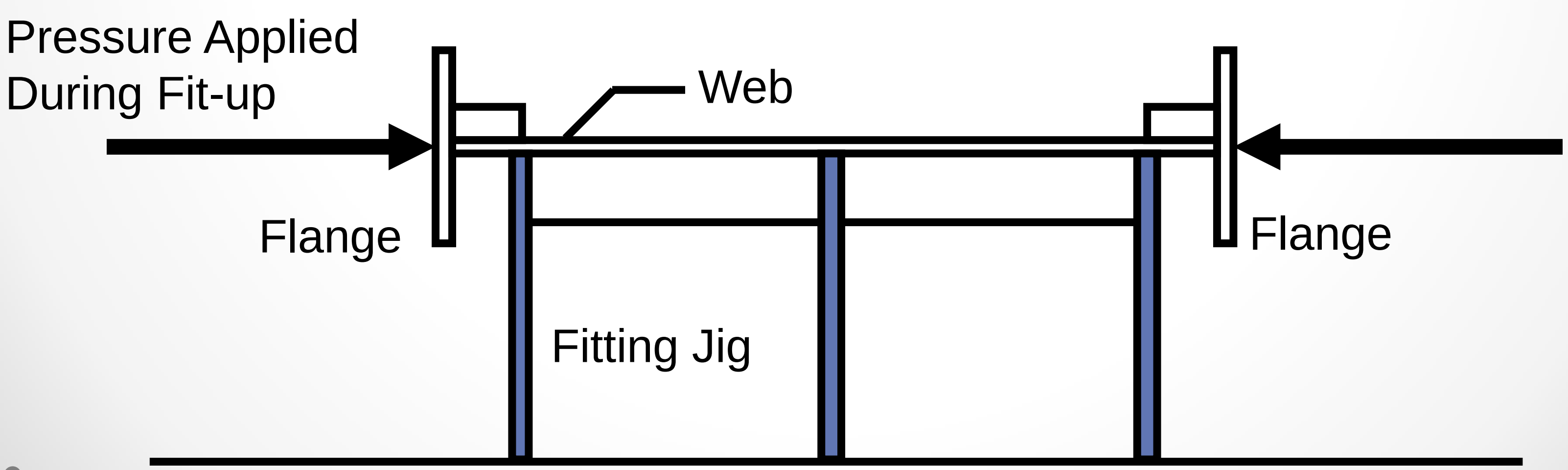
- Procedure is complex
- Numerical computations have to account for material and geometric non-linearity
- Temperature distribution along the flange width are not exactly uniform
- Analysis has to account for the girder behavior during heating and during cooling (natural cooling).
- During heating, heated zone elongates to form a larger outer radius
- During cooling, the heated portion shortens to form a reverse curvature

Material Properties



Cut-Curving

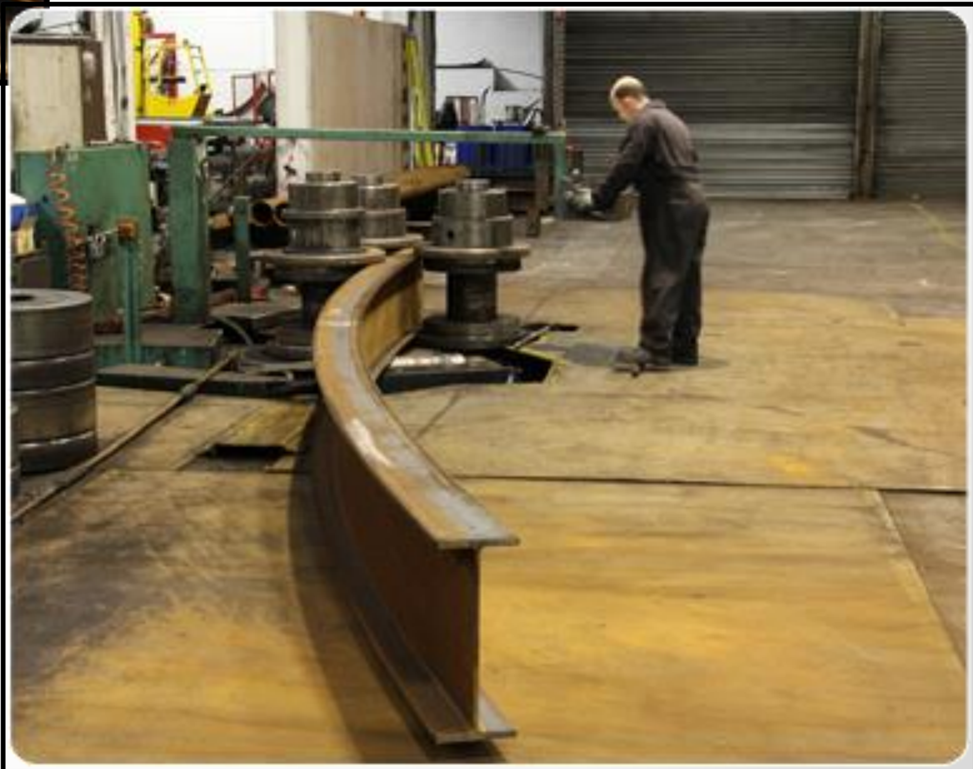

Flange
Flange
Flange
Scrap


Pressure Applied
During Fit-up
Web
Flange
Flange
Fitting Jig

Draw-Backs

- Too costly because of excessive waste
- Too much scrap for sharp curvatures
- Used for mild curvatures ($R > 300m$)
- Fit-up operation too complicated

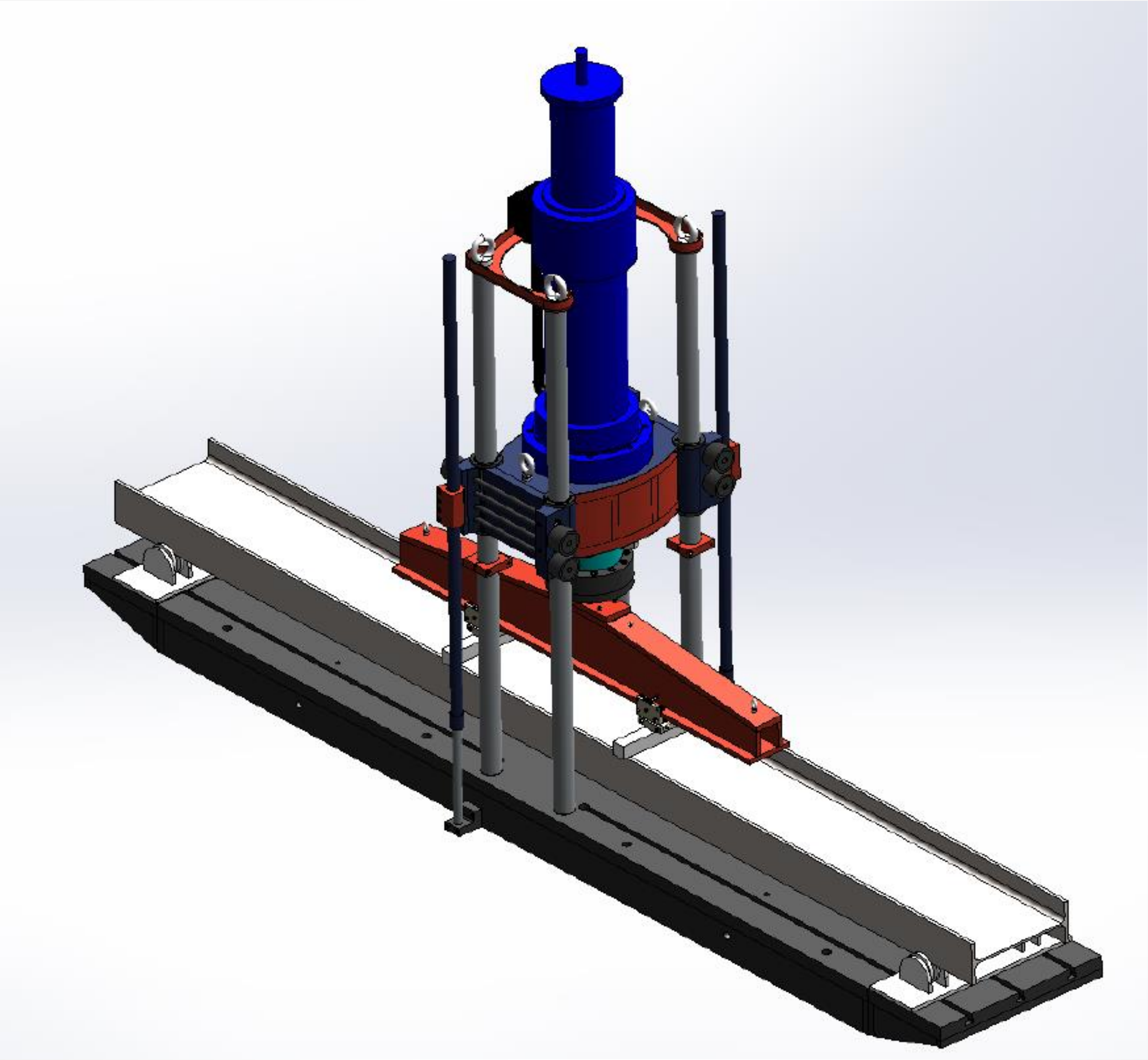
3-ROLLERS BENDING



- Mainly used in buildings
- Fit-up difficult for larger size bridge girders
- Perfect curve
-

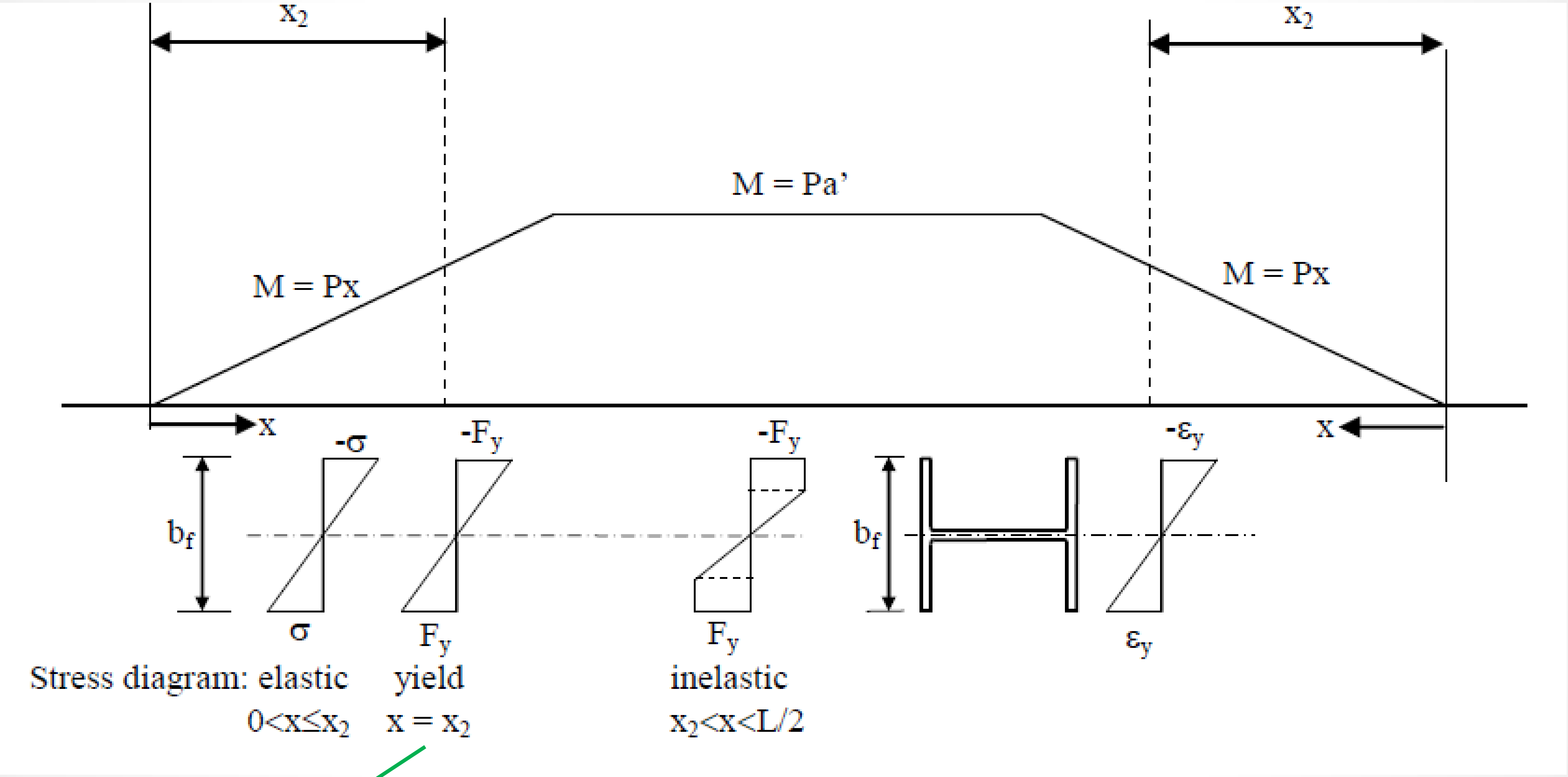
OTHER IDEAS?

COLD BENDING



Analysis

$\tau = a'/L;\ \chi = x_2/a'$

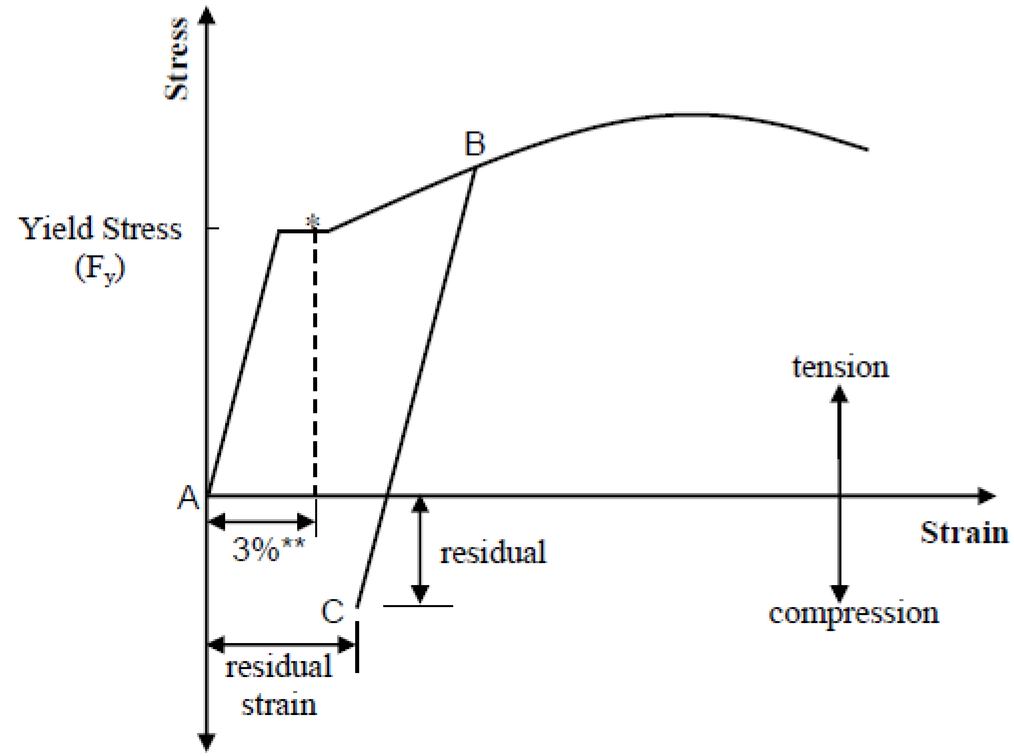


$$P = \frac{F_y t_f b_f^{\,2}}{3\tau\chi L}$$

$P_{flange} \leq 3.75 t_f^{\,2} F_y$ *(limit state of flange local buckling)*

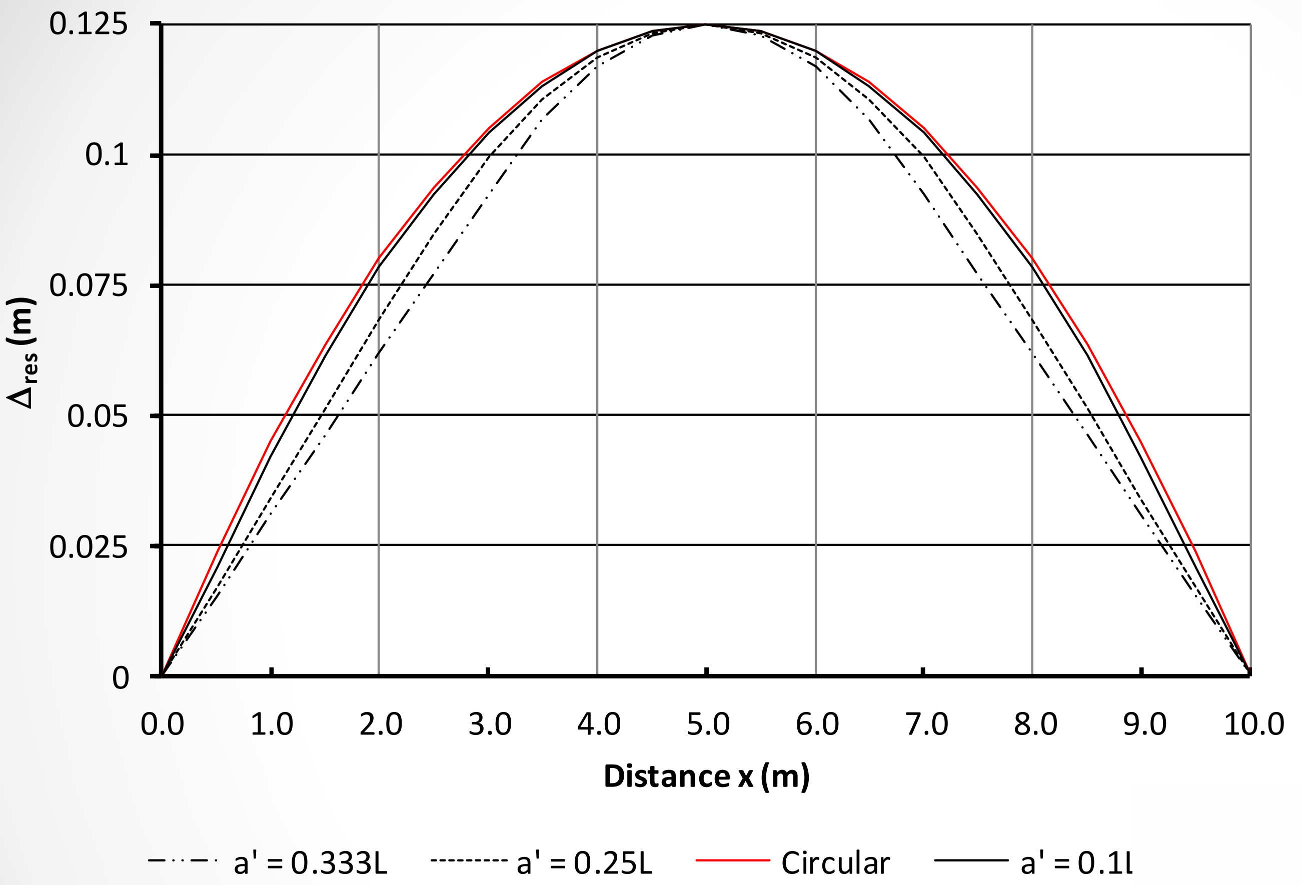
$L_p = 0.255 b_f \sqrt{\frac{E}{F_y}}$ *(lateral bracing limit)*

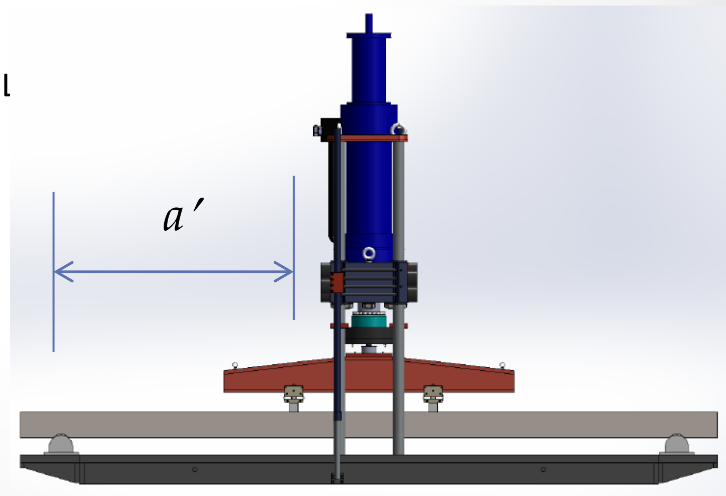
Stress-strain curve



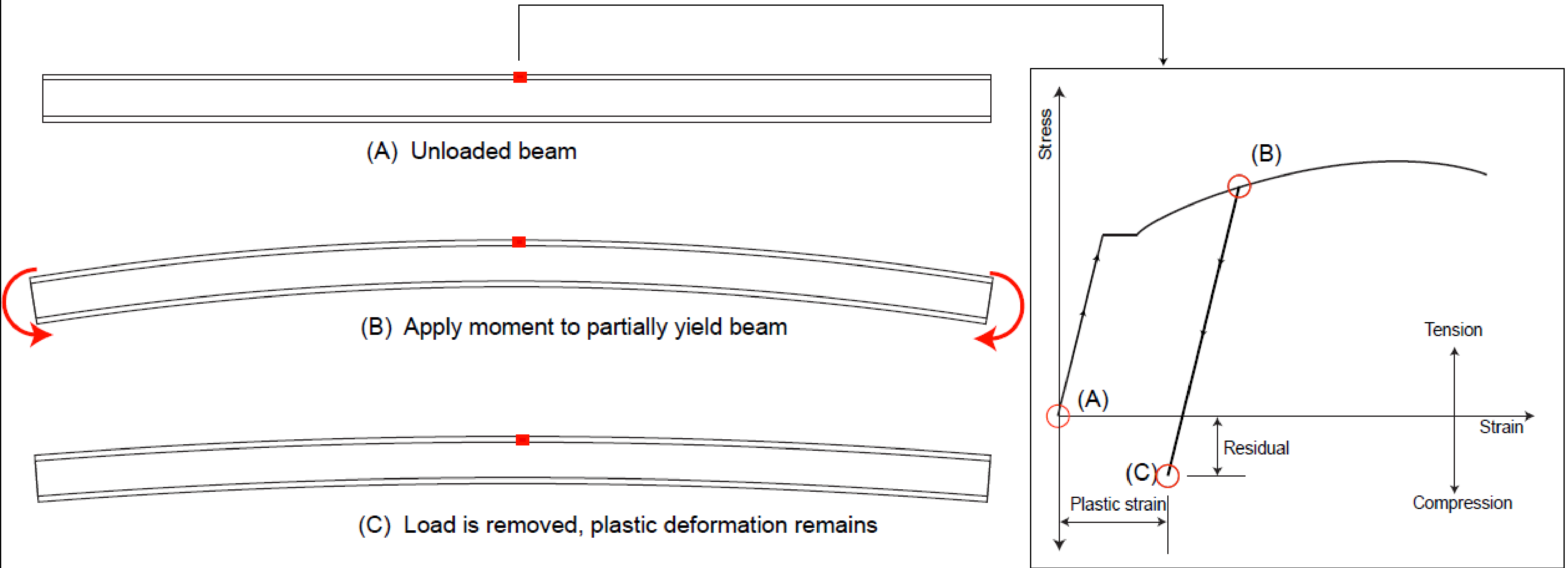
** yield plateau: length varies from 10 to 20 times the yield strain ε_y*
***typical value used by fabricators before steel properties are reduced (Lange 2009)*

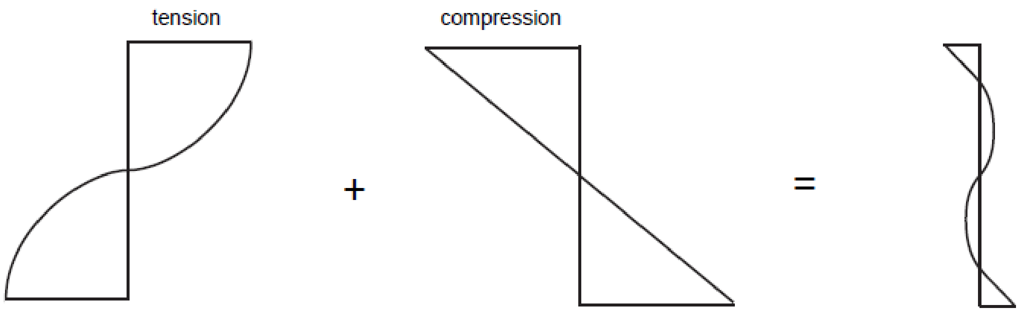
Idealization





Cold Bending Advantages





Partially plastic yield-

Elastic unloading (springback)

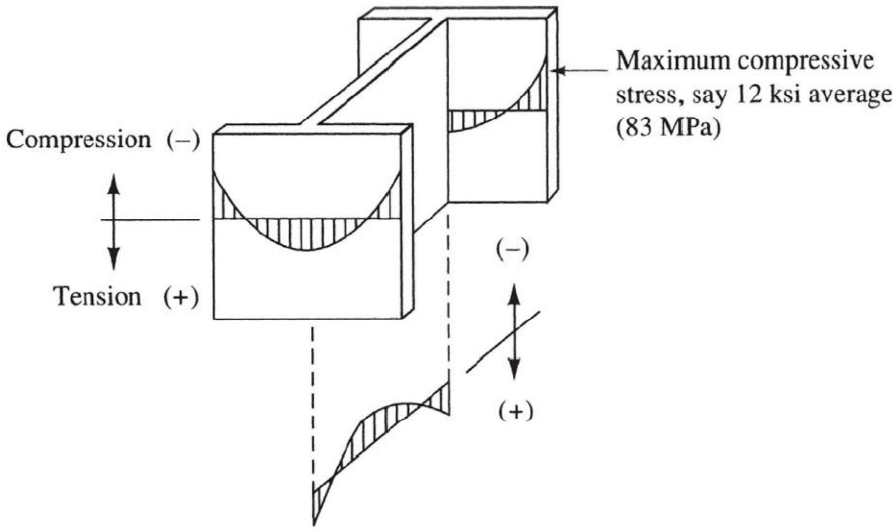
Residual stresses from plastic bending

Shanley, F.R. (1957). *Strength of Materials*, McGraw-Hill Book Company, New York, NY.

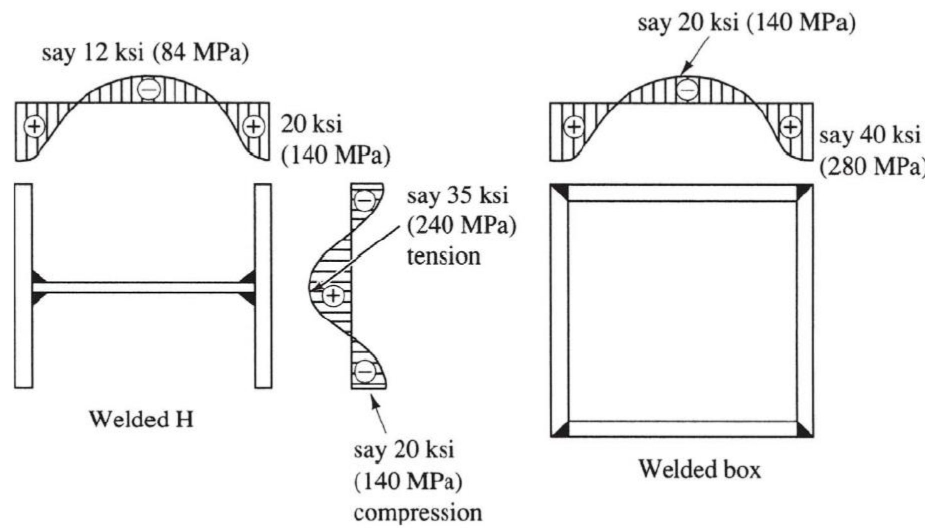
Increased yield stress, capacity? Engineers need to be careful about this one…. Cold bending residual stresses can counteract increased yield stress.

Residual Stresses

- *Flexural stiffness is reduced by the presence of cold bending residual stresses.*

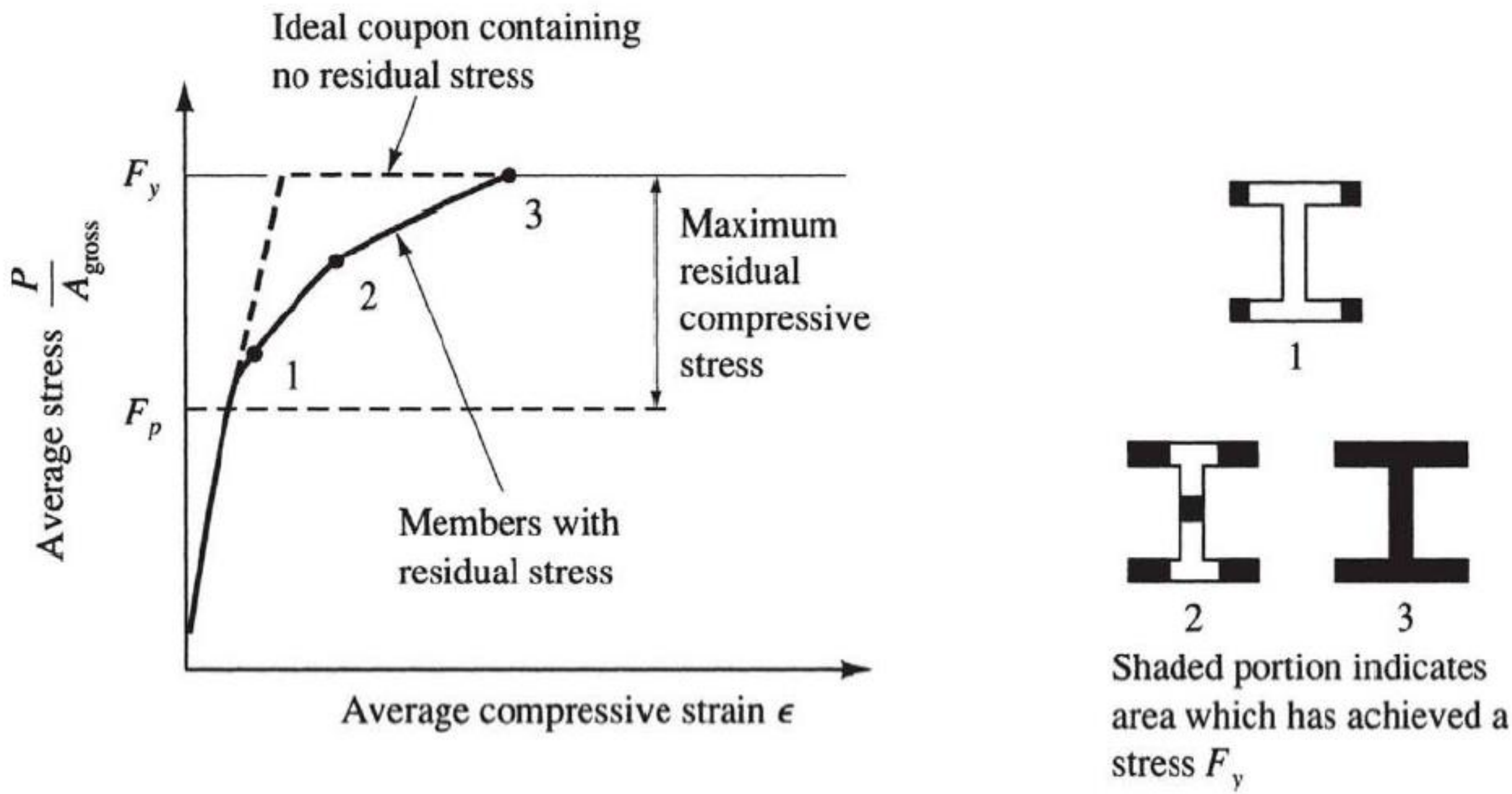


ROLLED BEAMS



WELDED SHAPES

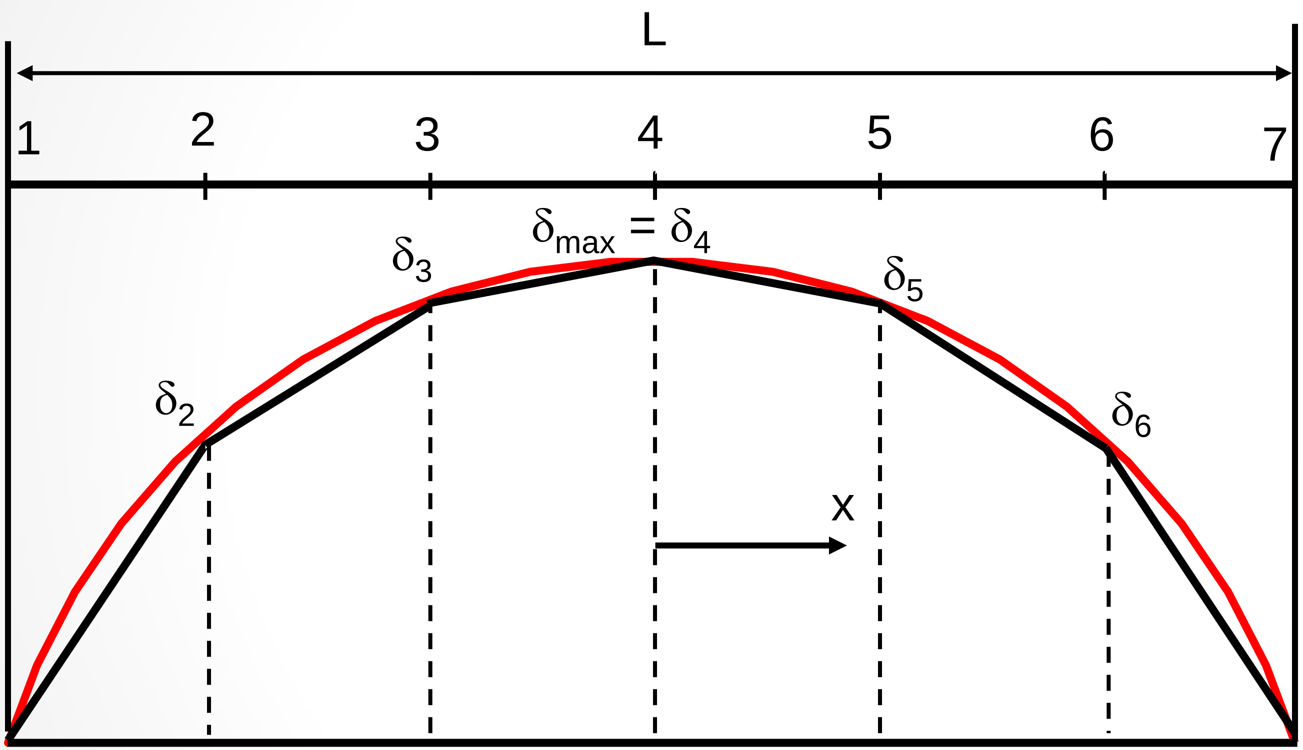
Influence of Residual Stress on Average Stress-Strain Curve



Tampa Steel Concept

Apply smaller loads at uniform intervals to achieve desired curvature

Idealization of Curve

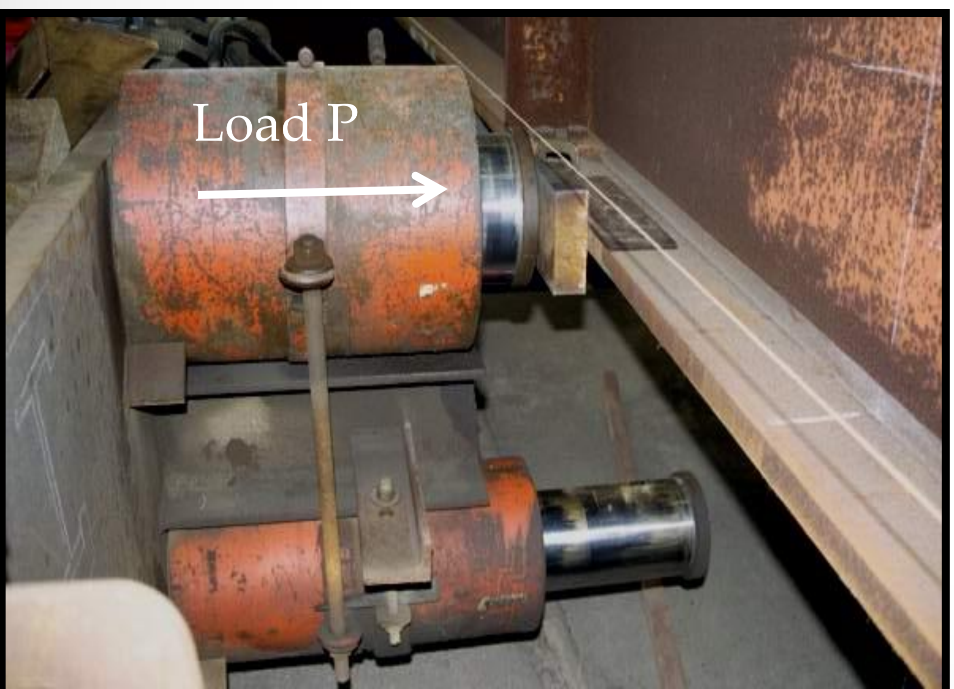


$$\delta_{max} \approx \frac{L^2}{8R}$$

$$\delta = \delta_{max} - R + \sqrt{R^2 - x^2}$$

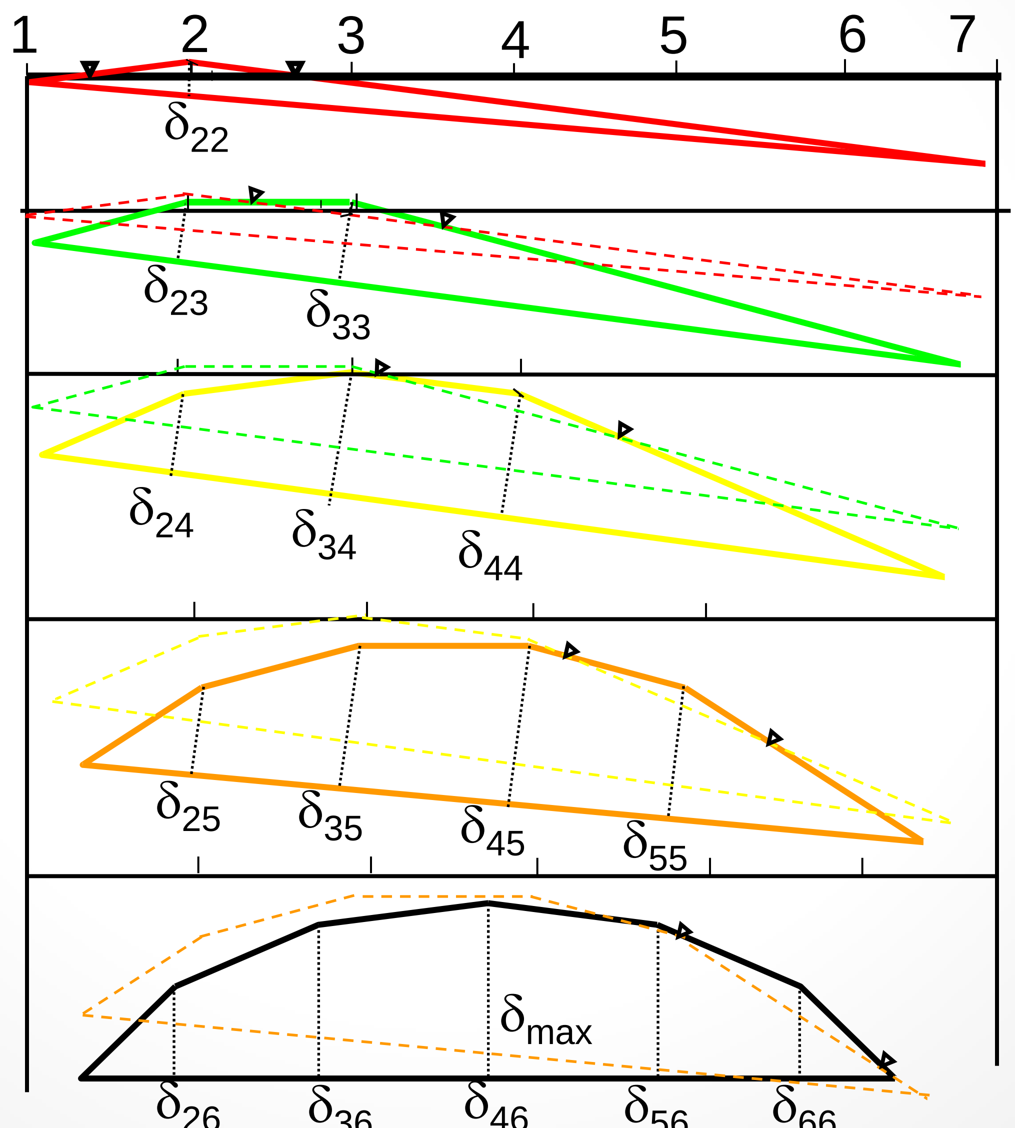

S


S


Load P


L_i

OFFSETS δ_{ii}, δ_{ij}

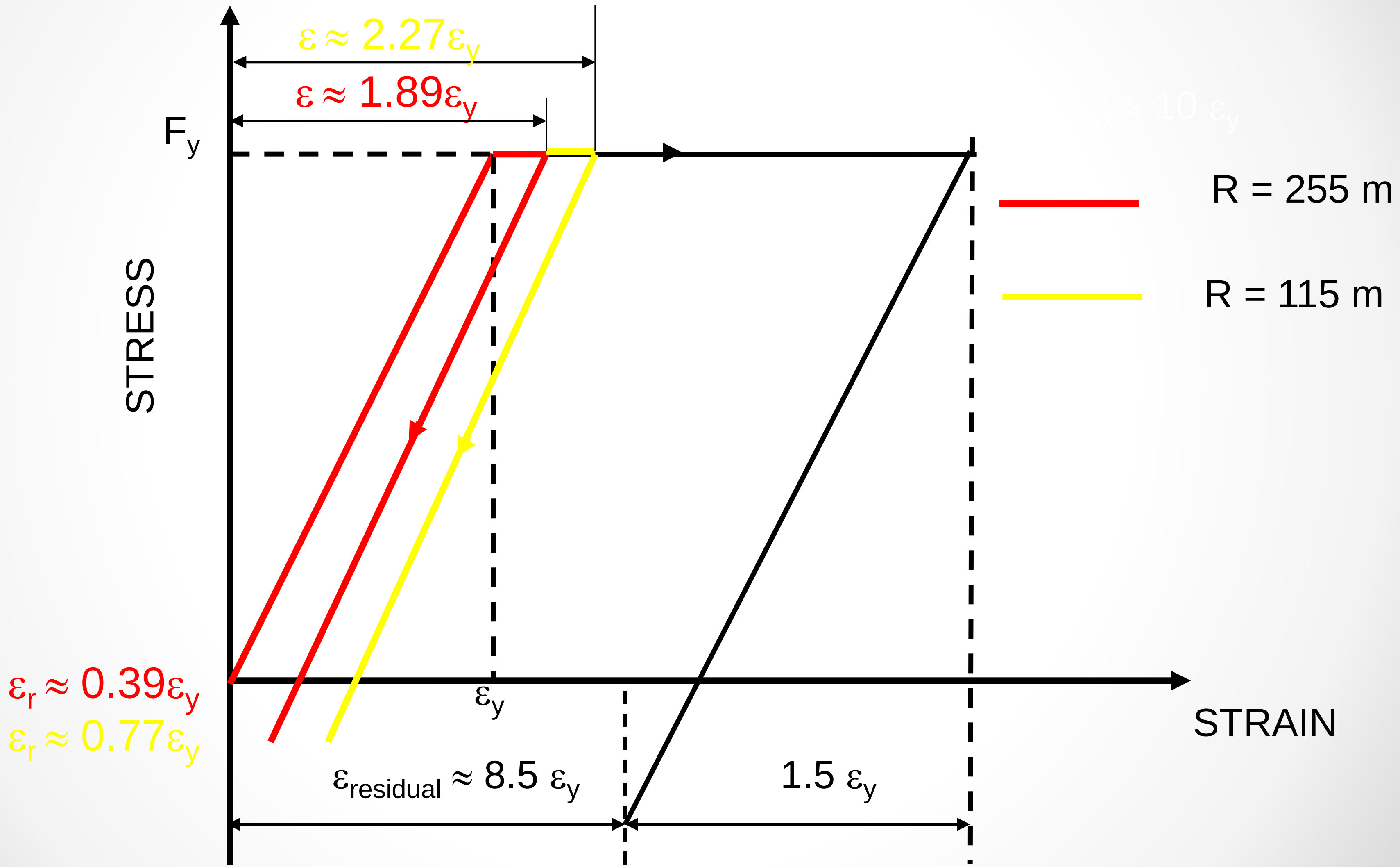


Test Girder

Loading Details

Test Girder after Curving

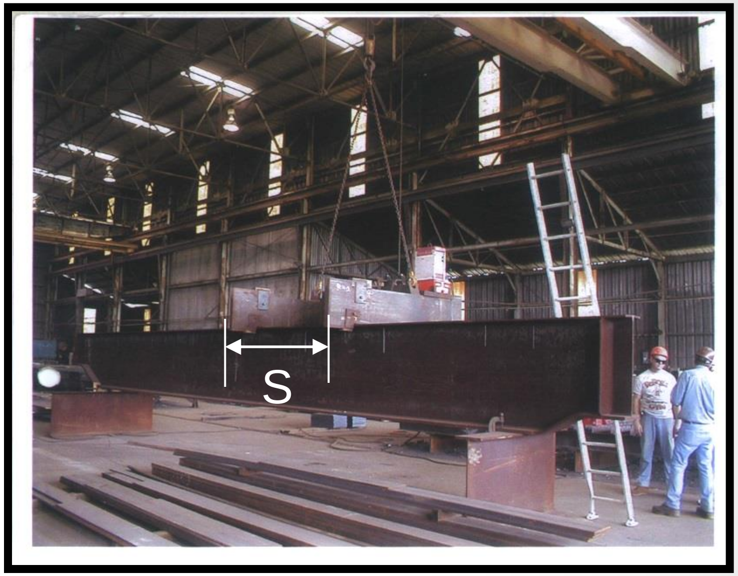
Idealized Stress-Strain Curve

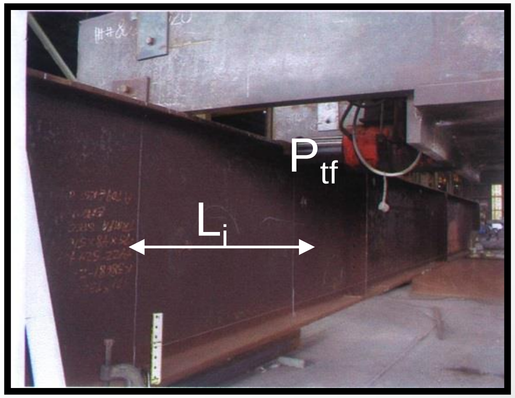


FORMULATION

PARAMETERS:

- Load Frame Spacing S
- Bending Loads P_{tf}, P_{bf}
- Deflection Δ within span S
- Segment Length L_i
- Number of Segments n
- Offsets





LOAD FRAME SPACING (S)

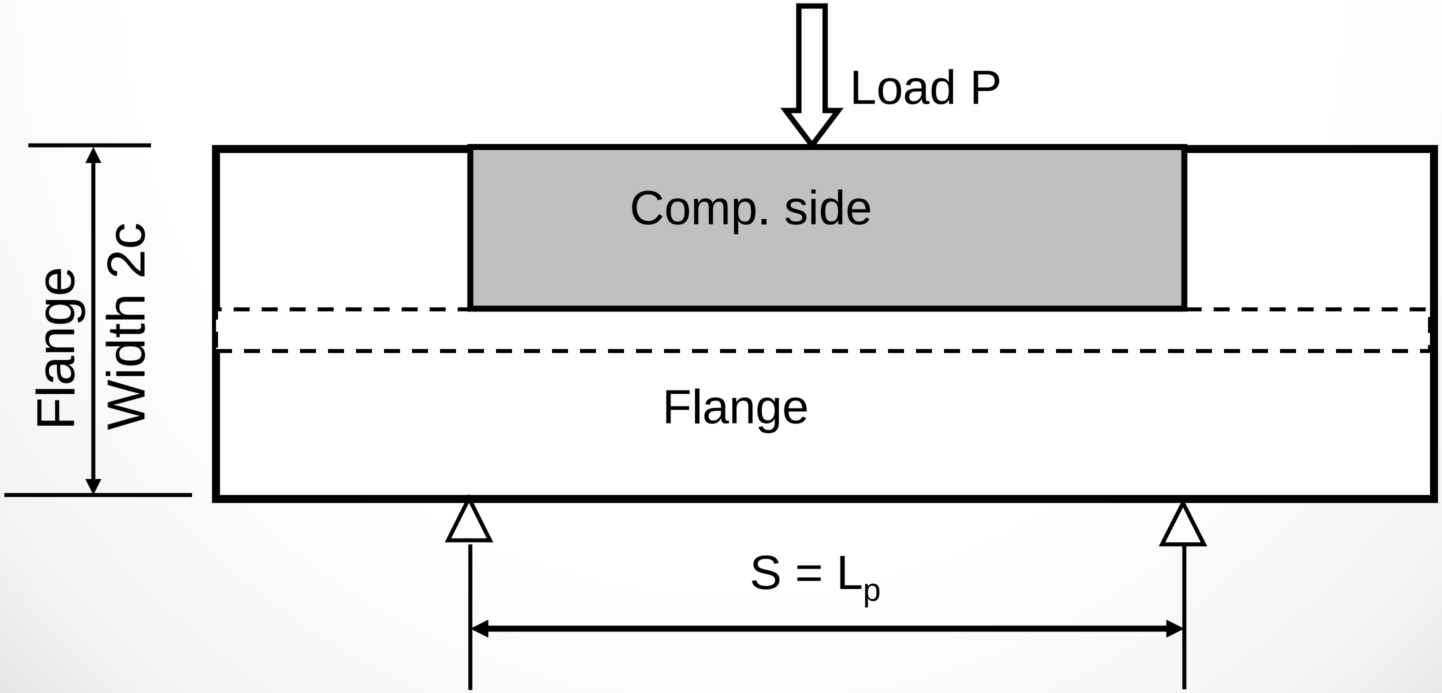
Based on lateral bracing limit:

S = 14.4c for Grade 250 steel

S = 12.2c for Grade 345 steel

For unsymmetrical sections use c_{tf}

$$S = 1.76 r_t \sqrt{\frac{E}{F_y}}$$



BENDING LOADS (P_{tf}, P_{bf})

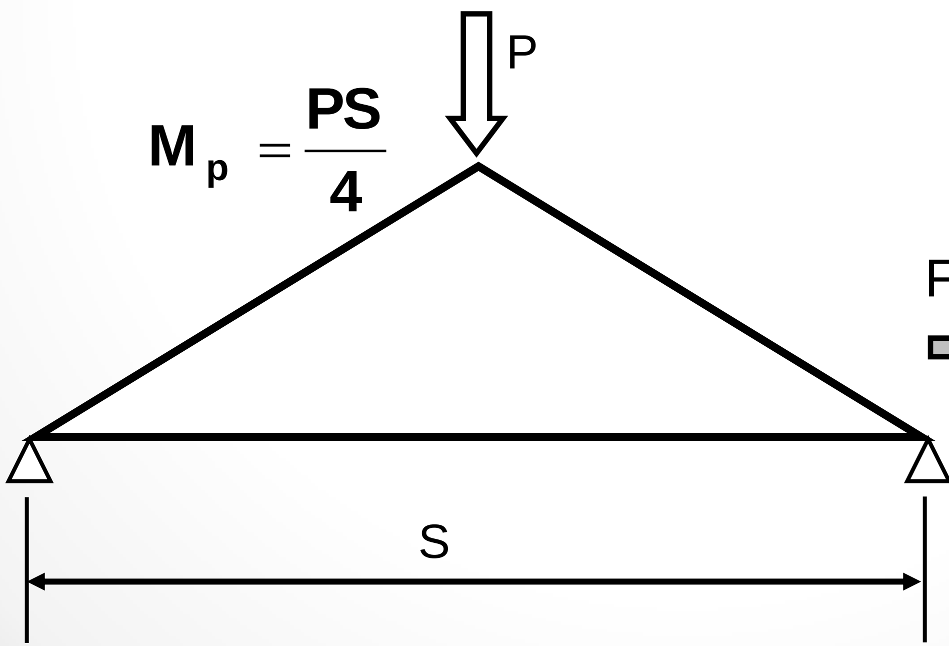
From simple beam plastic load analysis:

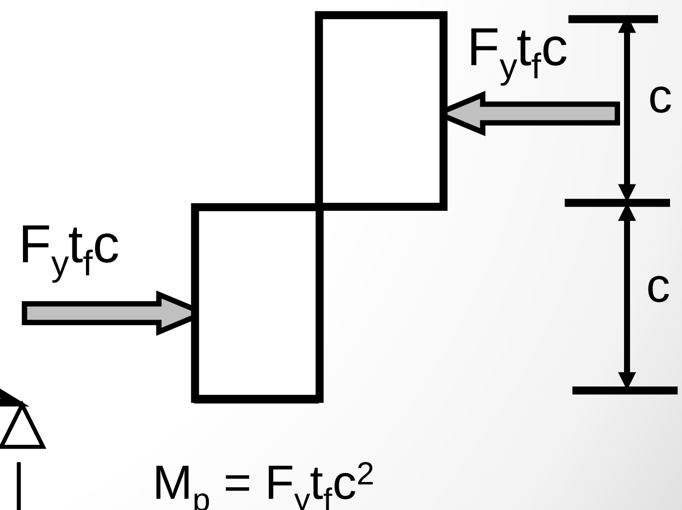
$$P = \frac{4F_y t_f c^2}{S}$$

S ← Constant

Top Flange: P_{tf} based on t_{tf}, c_{tf}

Bot. Flange: P_{bf} based on t_{bf}, c_{bf}

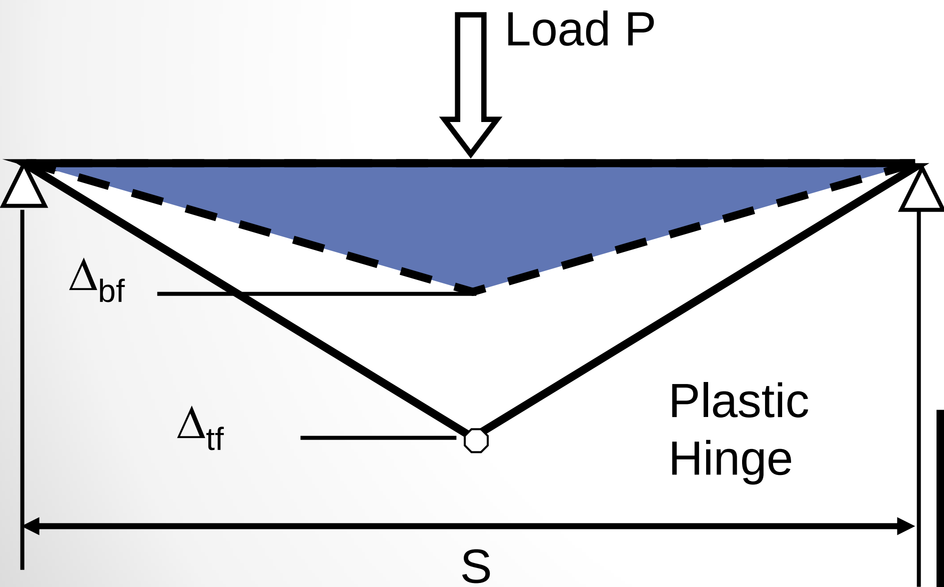




$M_p = F_y t_f c^2$

DEFLECTION Δ

$$\Delta = \frac{13 F_y S^2}{216 E c}$$



$c_{tf} \leq c_{bf}$

$P_{tf} \leq P_{bf}$

$\Delta_{tf} \geq \Delta_{bf}$

set Δ = cte = Δ_{tf}

$\Rightarrow \Delta \geq \Delta_{bf}$???

Set P = P_{bf},

Load in cycles

$m = \Delta_{tf} / \Delta_{bf}$

$P \geq P_{bf}$

(on-going research)

SEGMENT LENGTH L_i

$$L_i = \frac{4R\Delta}{S}$$

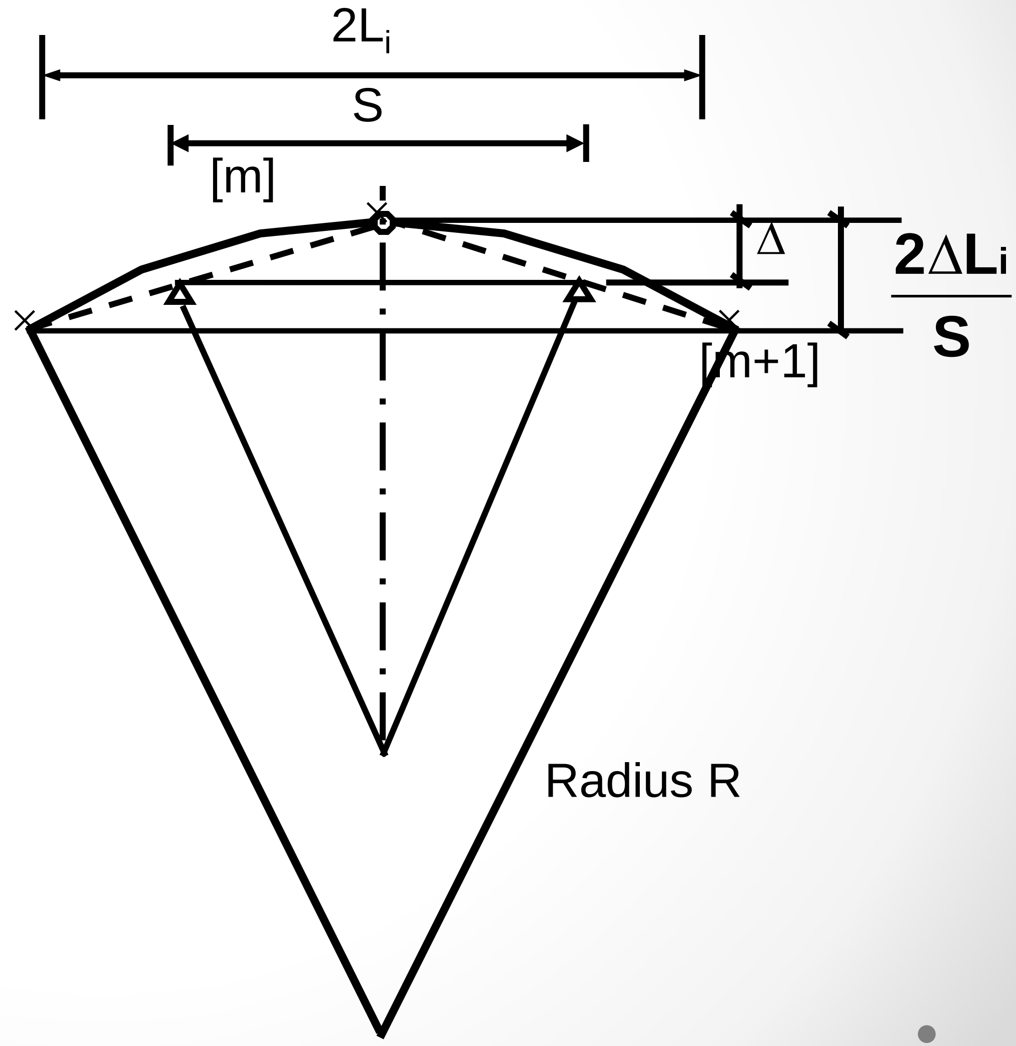
Δ_{tf}

Constant

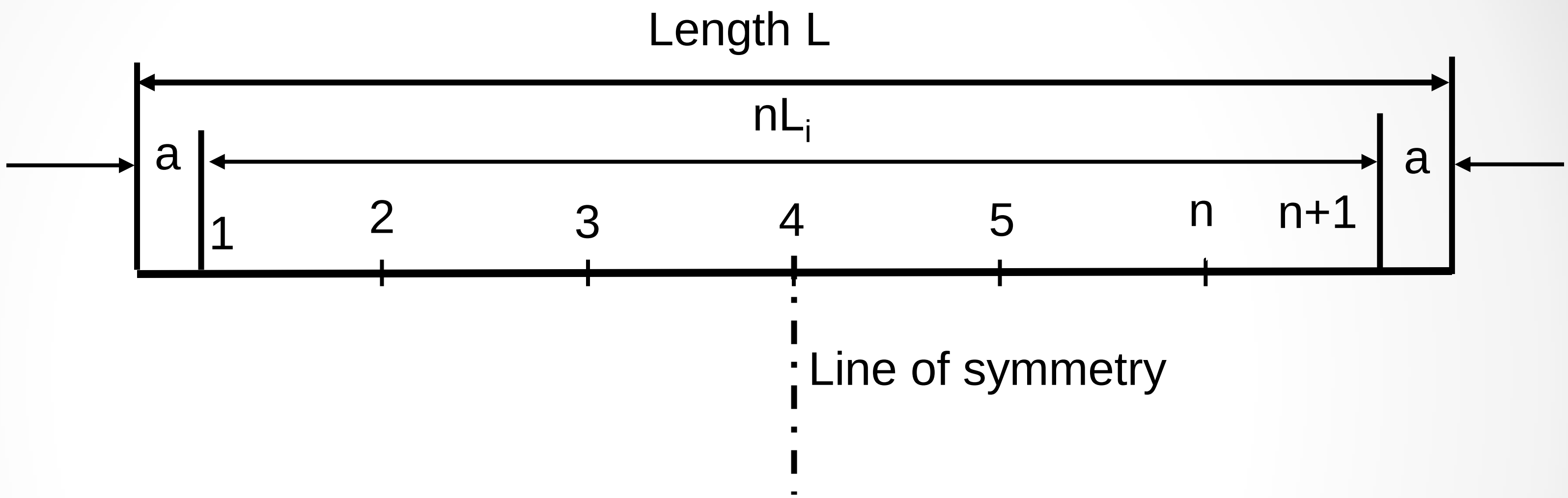
$$\delta \approx \frac{l^2}{8R}$$

$2\Delta L_i/S$

$2L_i$



NUMBER OF SEGMENTS



Round-down to the nearest even integer ←

$$n = \frac{L - S}{L_i}$$

→ adjust

$$L_i = \frac{(L - S)}{n}$$

Cold Bending Challenges

"There are two concerns we have to address," Wendt says. "I think they fear this is very expensive, and it's not. And I think people are afraid of structural concerns, and that's seldom a problem. We've rolled thousands of pieces of steel and hundreds of fabrications and we've become comfortable working with these curved sections."

Ross, C. (2002). "The Art of Bending". *Modern Steel Construction*, American Institute of Steel Construction, October 2002.

But if an A/E or GC is not willing to design with bent steel, unless an owner is adamant about it the design will shift to other alternatives. In our opinion, the other options are typically not the best options, but are comfortable. Benders need to make everyone involved with the process feel comfortable with the bending option! MSC

Winters-Downey, E. (2006). "A Conversation with a Bender". *Modern Steel Construction*, July 2008, American Institute of Steel Construction, Chicago, IL.

Ricker writes in a frustrated tone that deflections of cambered beams don't always match the calculations.

Ricker, D.T. (1989). "Cambering Steel Beams." *Engineering Journal, AISC*, 4th Quarter, 136-142.

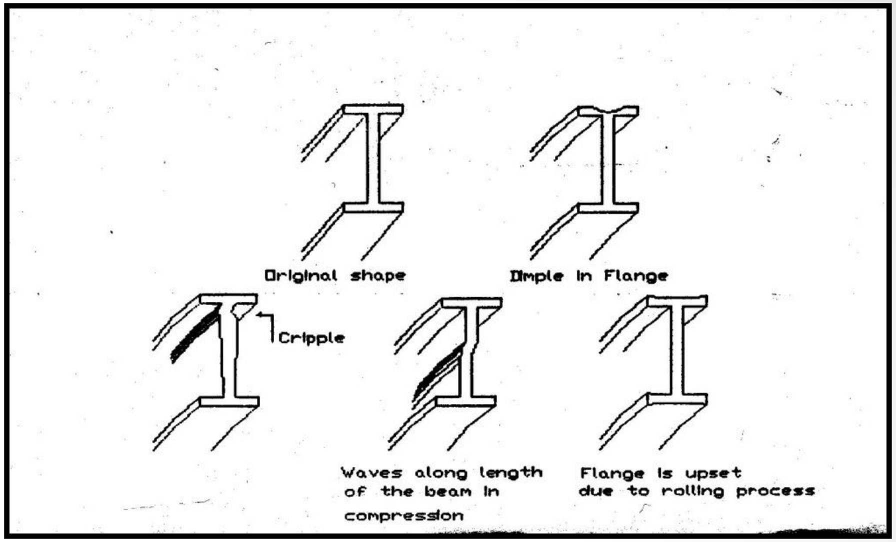
Cold-bending can cause material fracture leading to scrap.

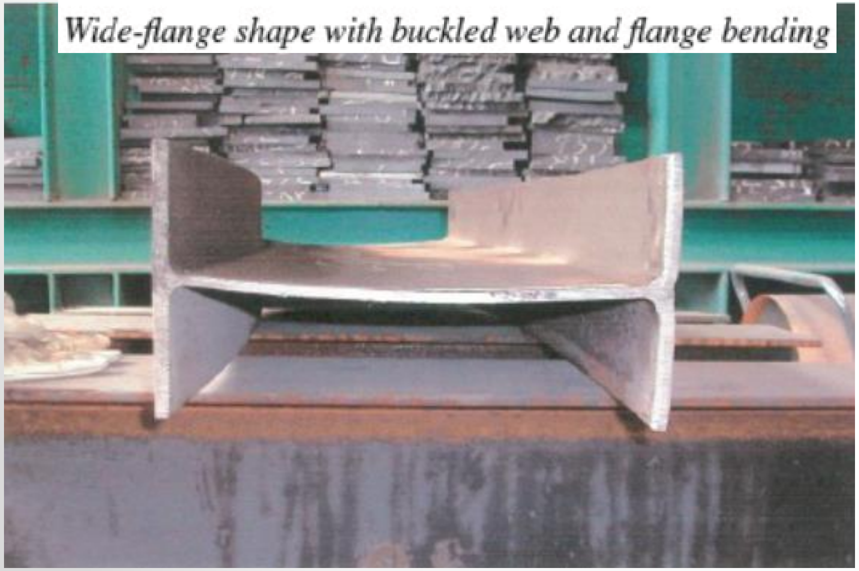
AISC (2002). "Meet the experts-bending steel". *Modern Steel Construction*, American Institute of Steel Construction, June 2002.

Fatigue resistance?
Fracture toughness?
Geometric limits on bending?

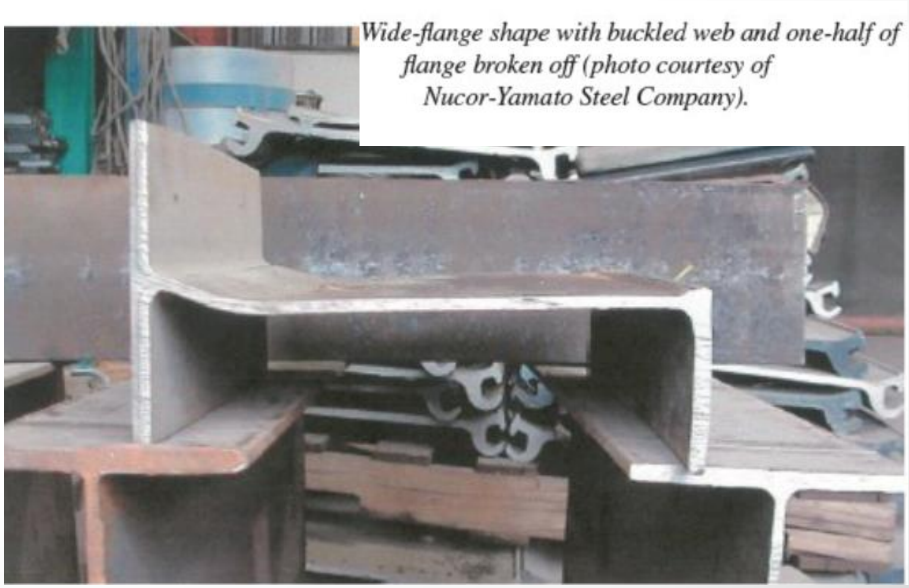
Challenges ?

- Cracking, Fracture
- Flange Upsets
- Dimples
- Web Crippling





Wide-flange shape with buckled web and flange bending



Wide-flange shape with buckled web and one-half of flange broken off (photo courtesy of Nucor-Yamato Steel Company).

Challenges ?

- Effects on Steel mainly fracture characteristics
- Does it lead to a permanent reduction in the ductility and fracture resistance of steel?
- Effects if steel is loaded beyond plastic limits
- ANSWERS ? Specific need for full-scale testing.

How could it be assessed - 1?

- Perform visual inspection using NDT techniques
- Instrument to measure loads, offsets, strains and web movement

How could it be assessed - 2?

Perform in-depth material testing of the bent zone, e.g.

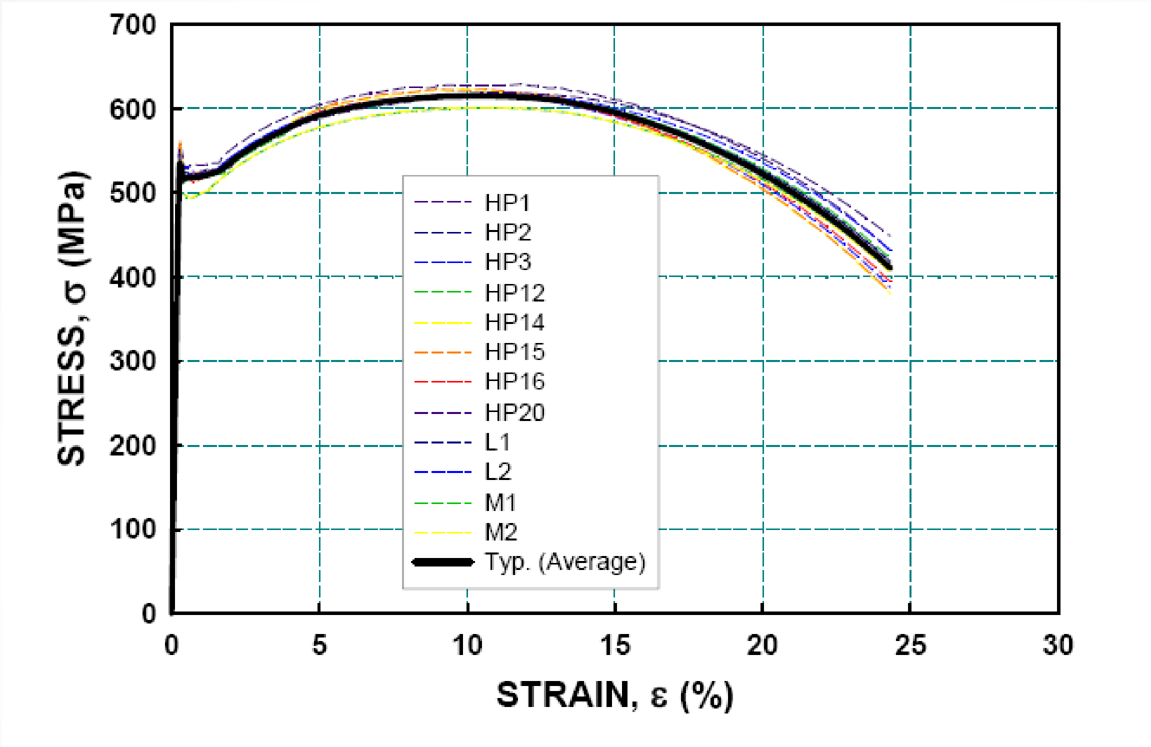
- Charpy V-notch test
- Fracture sensitivity
- Tensile strength
- Brinell hardness

How could it be assessed – 3?

Check for compliance with AASHTO Requirements

Property	ASTM A709 Grade 345	ASTM A709 HPS 485W
Plate Thickness	up to 5 cm (2 in.)	up to 10 cm (4 in.)
Yield Strength	345 MPa (50 ksi)	485 MPa (70 ksi)
Tensile Strength	min. 404 MPa (min. 58 ksi)	620 – 758 MPa (90 – 110 ksi)
Min. Elongation 5 cm (2 in.)	21%	19%
Toughness: CVN Fracture Critical Zone 3	35 m-N @ -12C (25 ft-lbf @ 10F) > 6.35 cm (to 2.5 in.)	47 m-N @ -23C (35 ft-lbf @ -10F) > 6.35 cm (to 4in.)

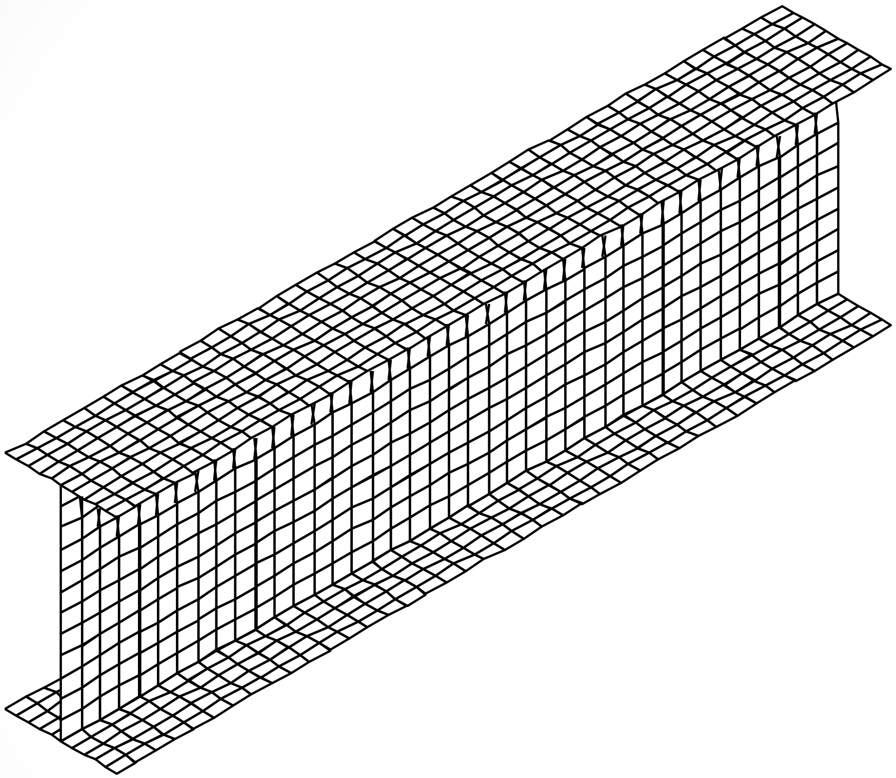
HPS 485W



Results of FHWA Tensile Tests on HPS 485W Specimens.

Wright W, Candra H, Albrecht P. "*Fracture Toughness of A 709 Grade HPD -485W Steel*". Draft FHWA Report, Washington, D.C, 2005.

How could it be assessed – 4?



3D Finite Element Modeling

Specifications

- Develop criteria and specifications for consideration by AASHTO
  - Limits on strain
  - Limits on applied load
  - Limits on minimum radius
- Guidelines for localized damage repair
- Guidelines for inspection
- Fabrication aids

Acknowledgment

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Tampa Steel Erecting Company, *Tampa, Florida*

Thank You!

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