Behavior and Capacity of Steel Perimeter Columns in a Fire

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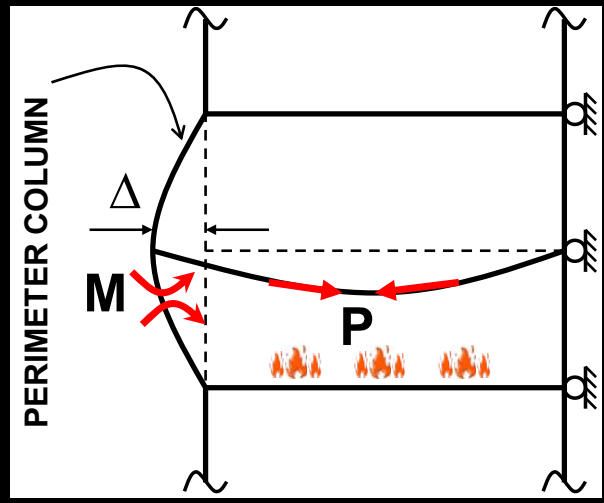
Background

Why perimeter columns?



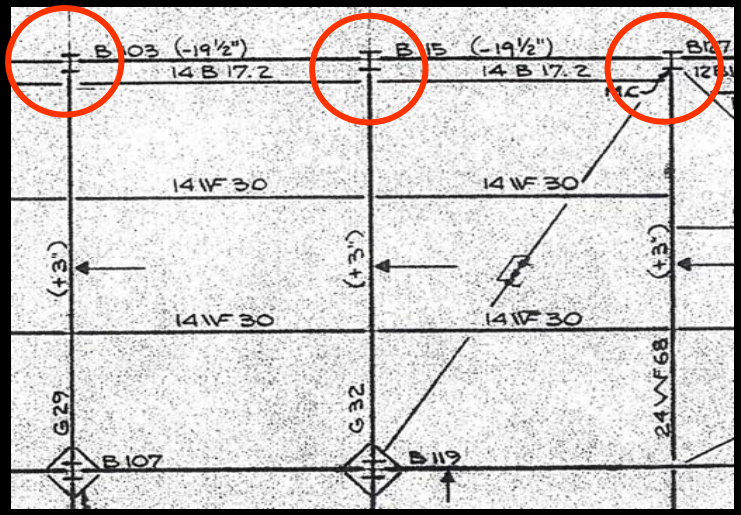
- Braced on 3 sides only
  - Critical connection
  - Induced deflections and moments
- Thermal gradients
  - Induces significant bending moments and moment reversals
- Combined P and M

Objective

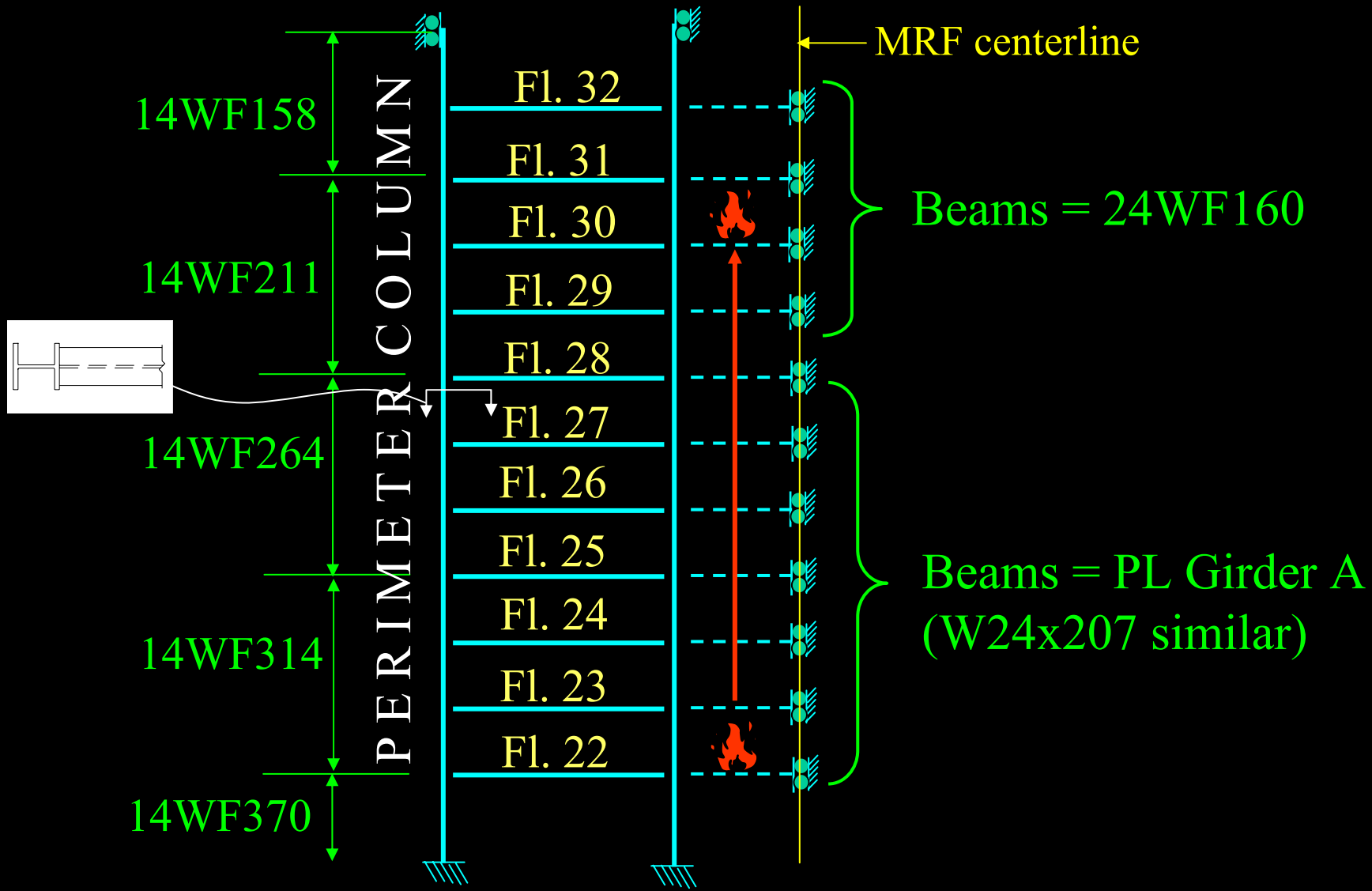
- Analyze the mechanics and capacity of steel wide-flanged (I-shaped) perimeter columns.

- Develop simple tools for practicing architects and engineers to predict the demand on steel perimeter columns subject to fire.

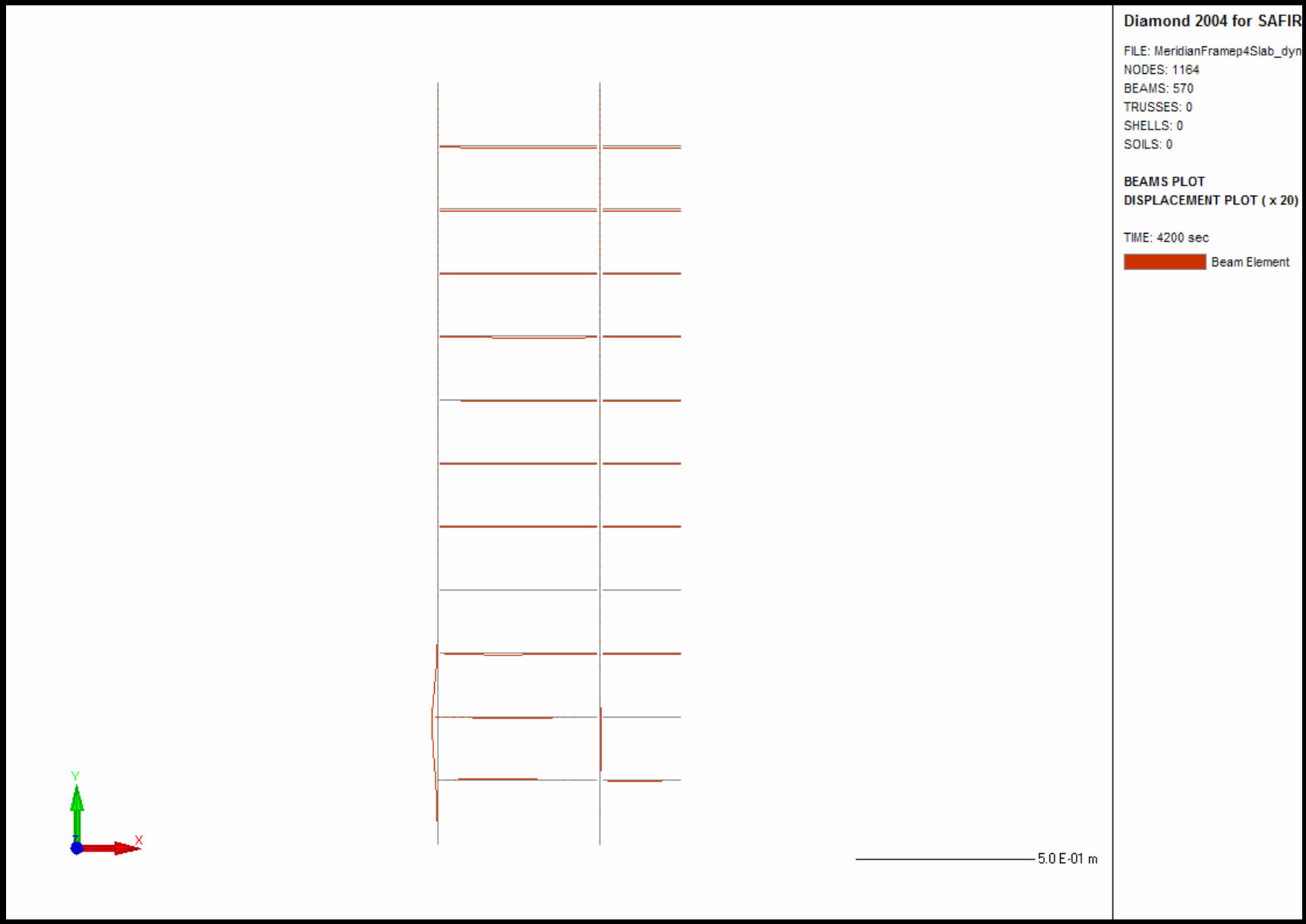
Prototype: One Meridian Plaza, Philadelphia, PA



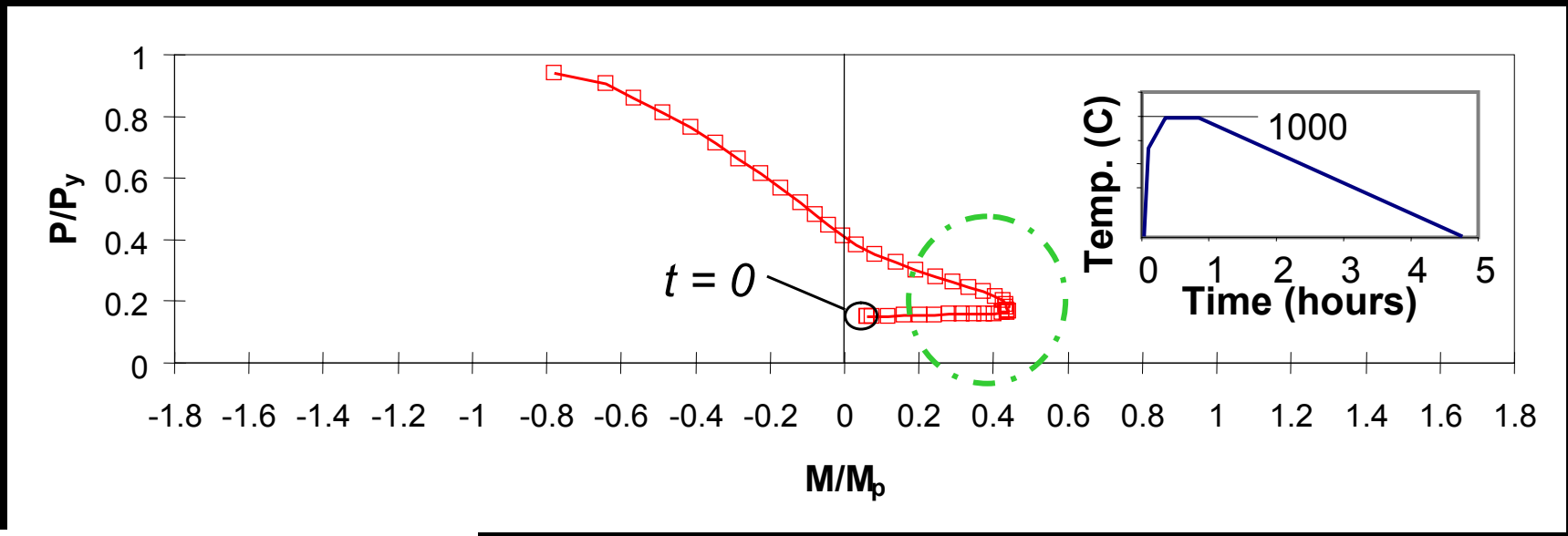
Prototype


MRF centerline
14WF158
14WF211
14WF264
14WF314
14WF370
PERIMETER COLUMN
Fl. 32
Fl. 31
Fl. 30
Fl. 29
Fl. 28
Fl. 27
Fl. 26
Fl. 25
Fl. 24
Fl. 23
Fl. 22
Beams = 24WF160
Beams = PL Girder A
(W24x207 similar)

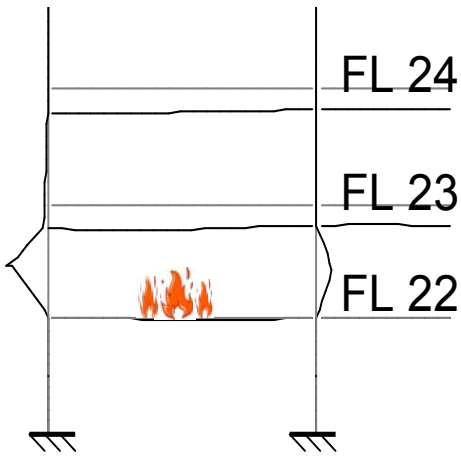
Predicting the Demands

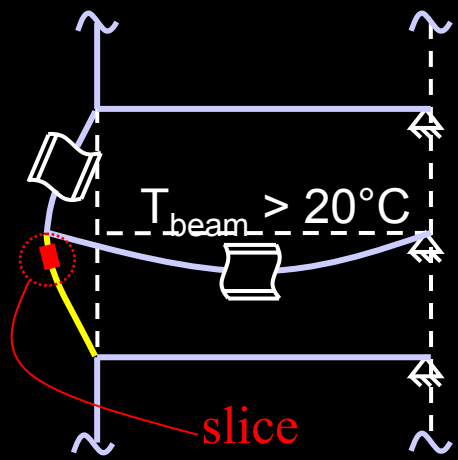


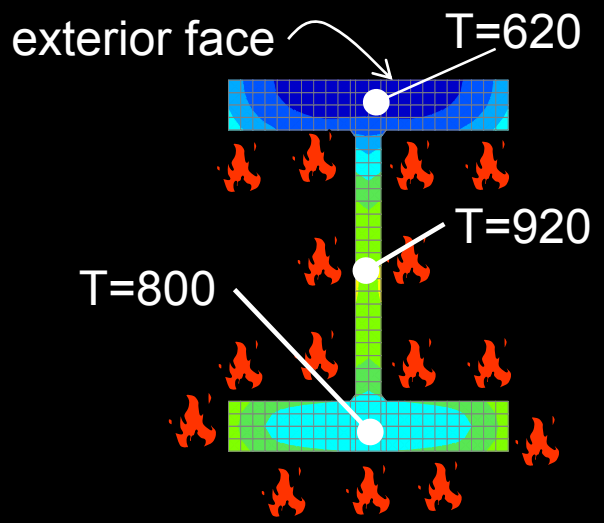
Perimeter Column Mechanics



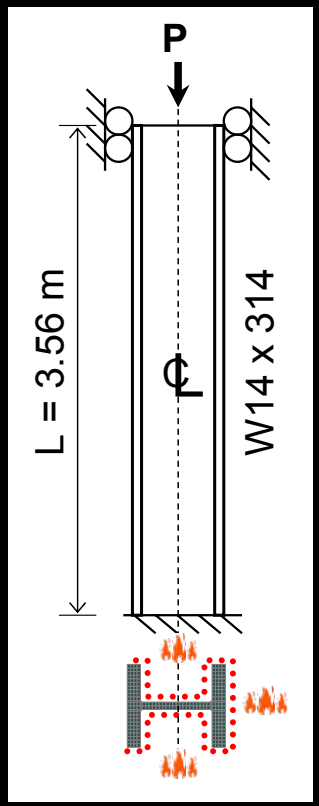
Beams protected,
Columns unprotected

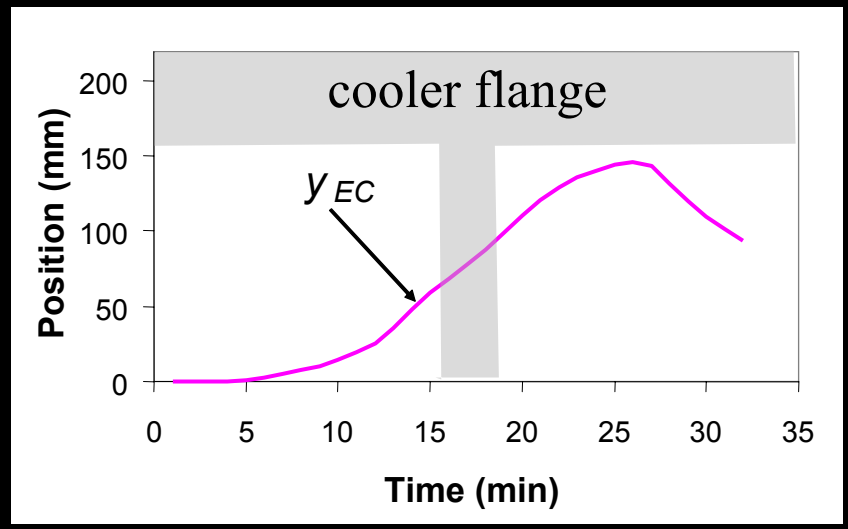


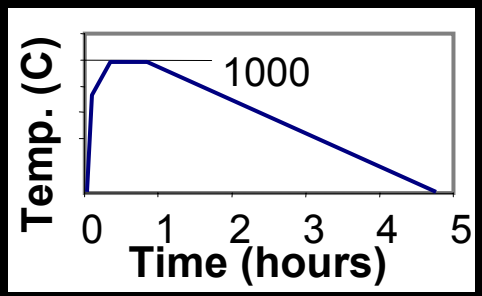


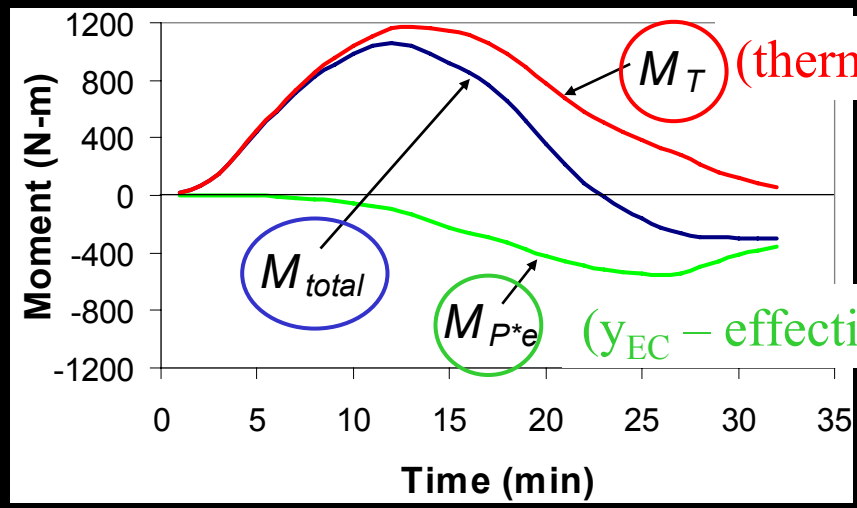


Perimeter Column Mechanics

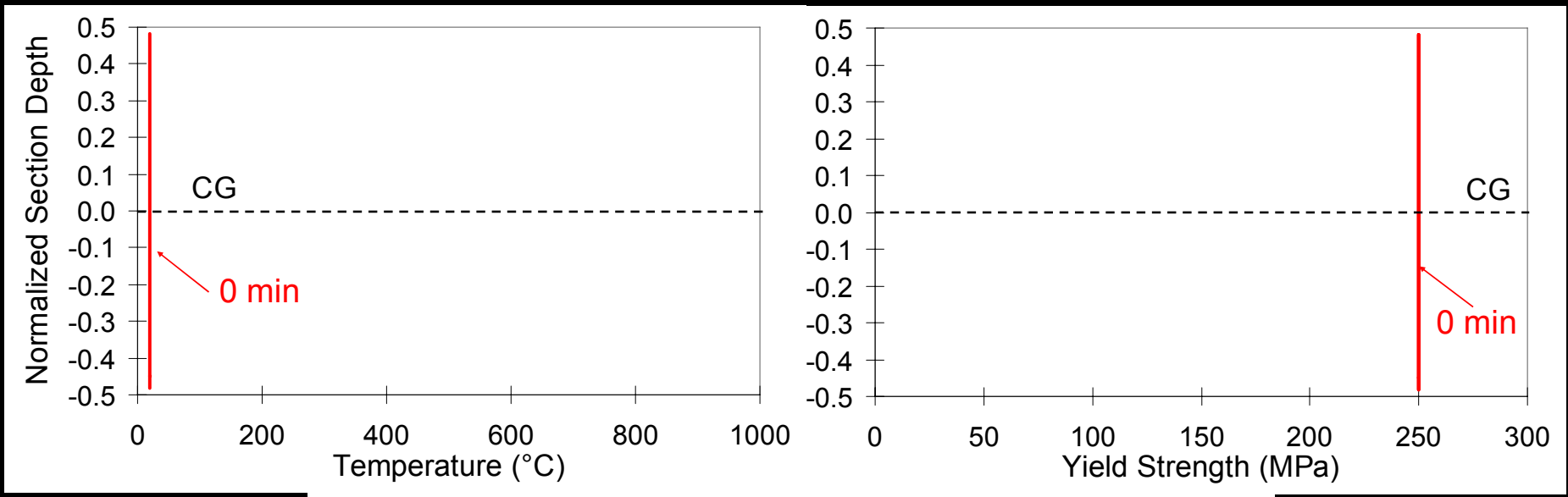


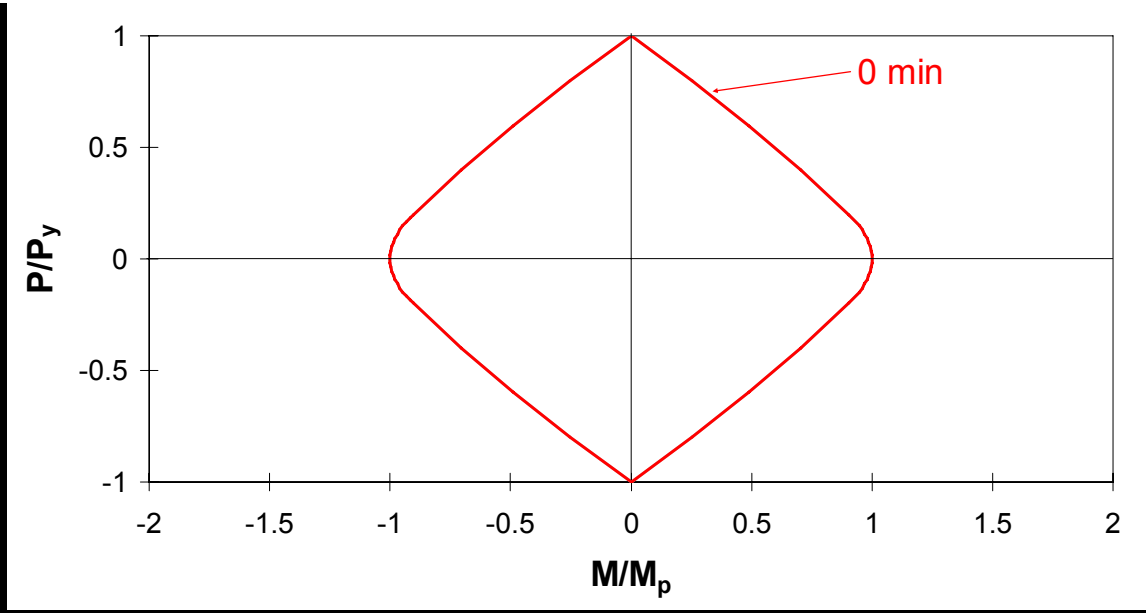




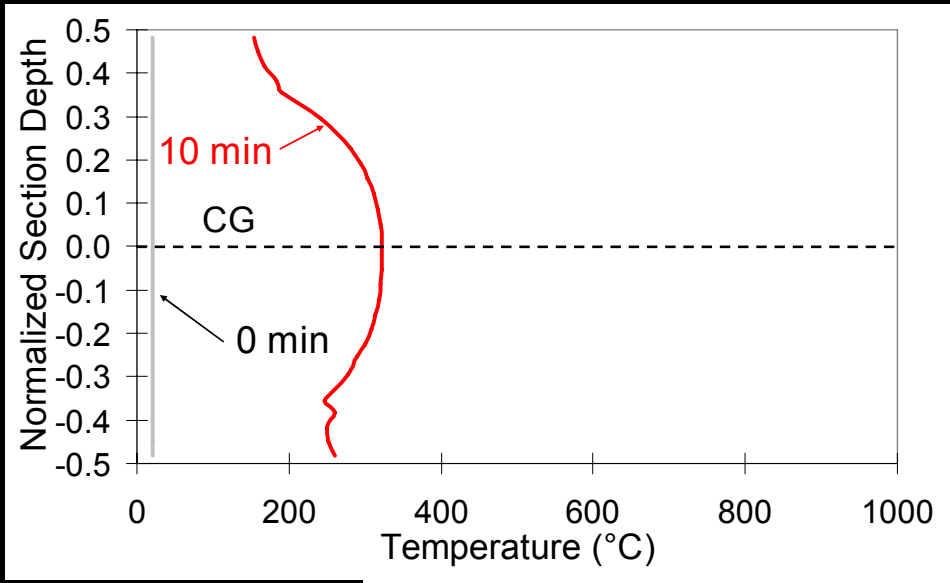


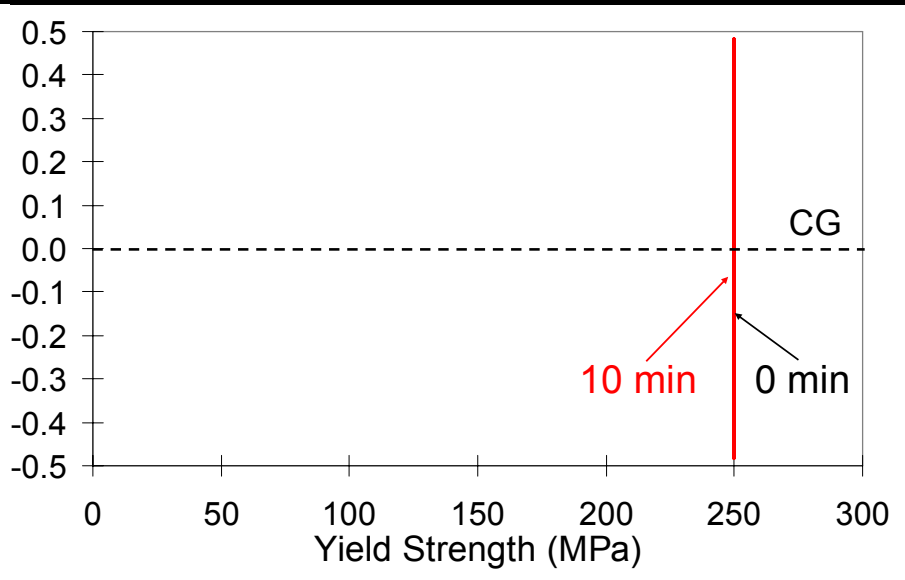
Predicting the Capacity

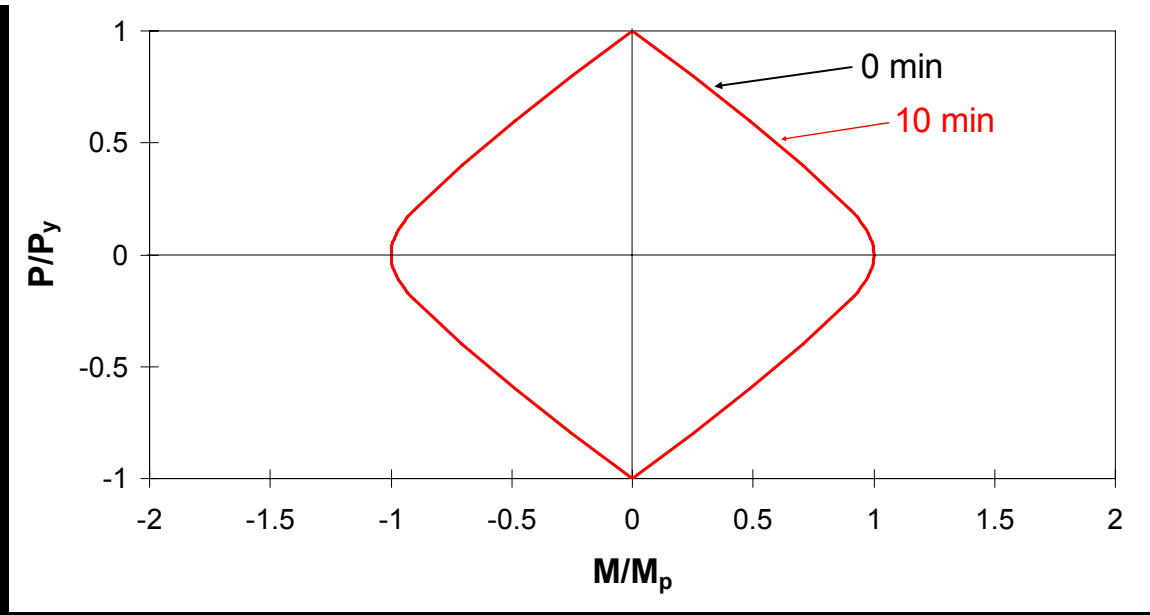




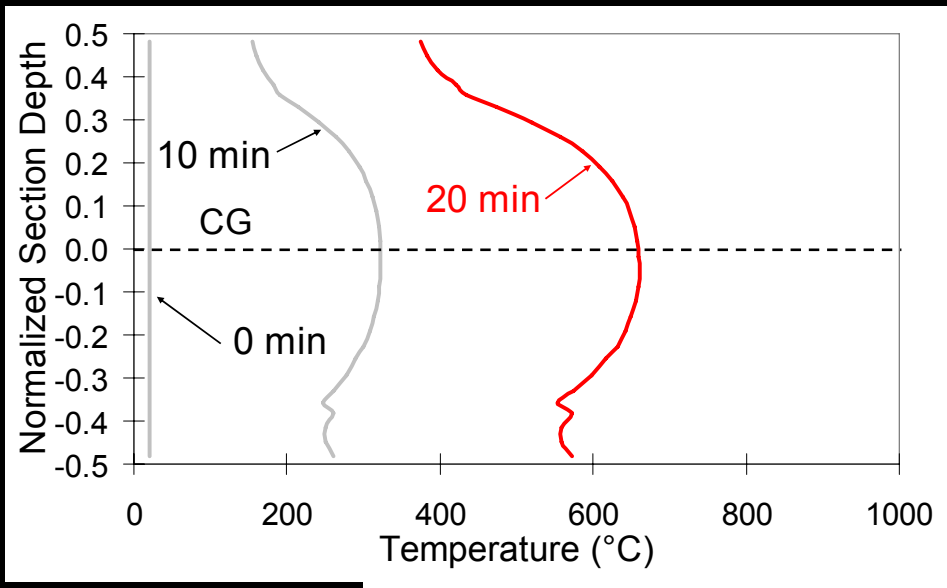
Predicting the Capacity

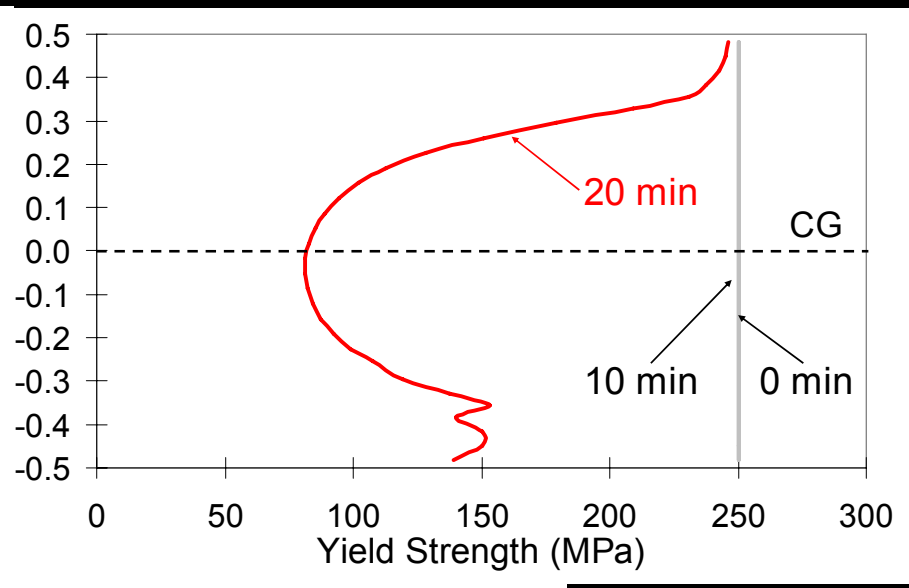


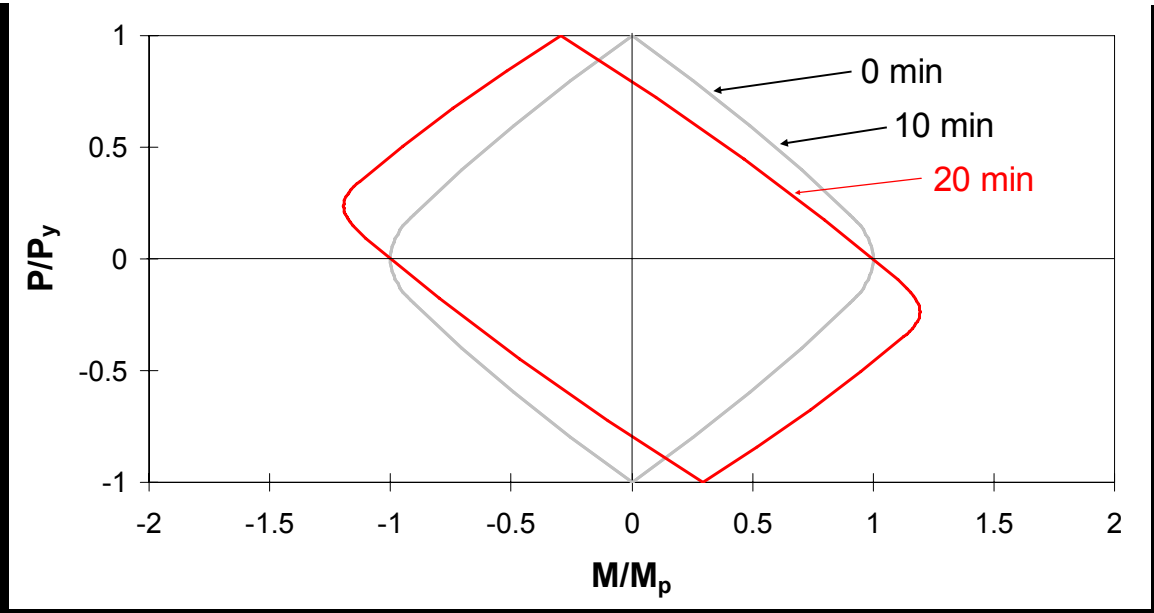




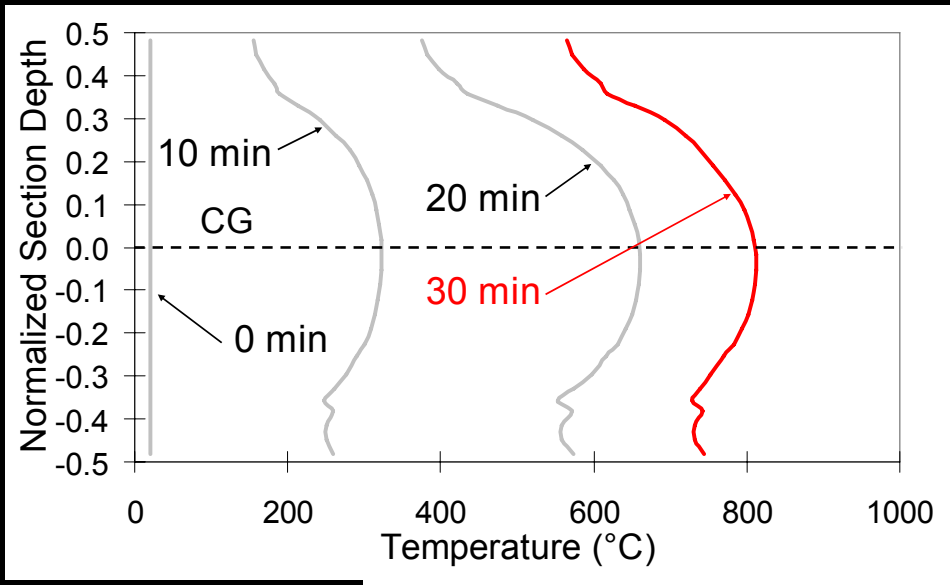
Predicting the Capacity

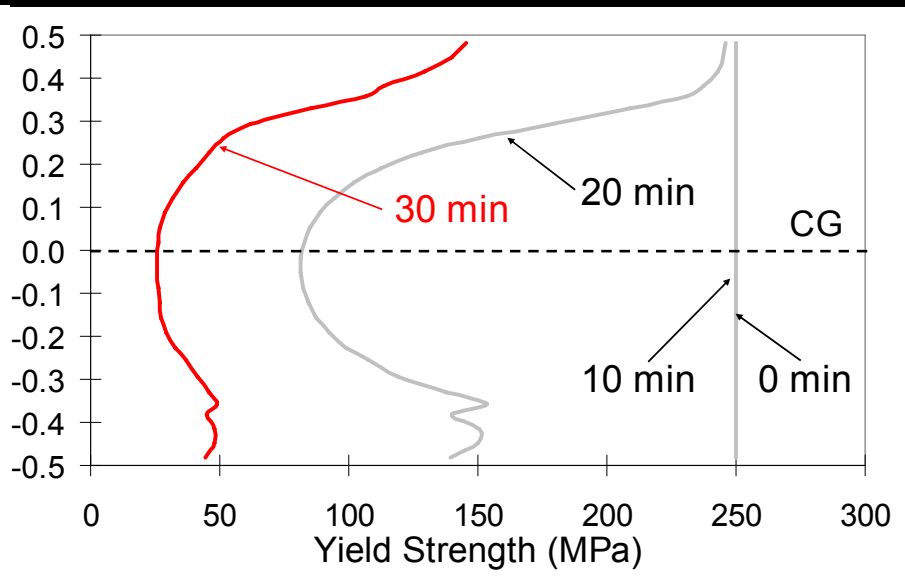


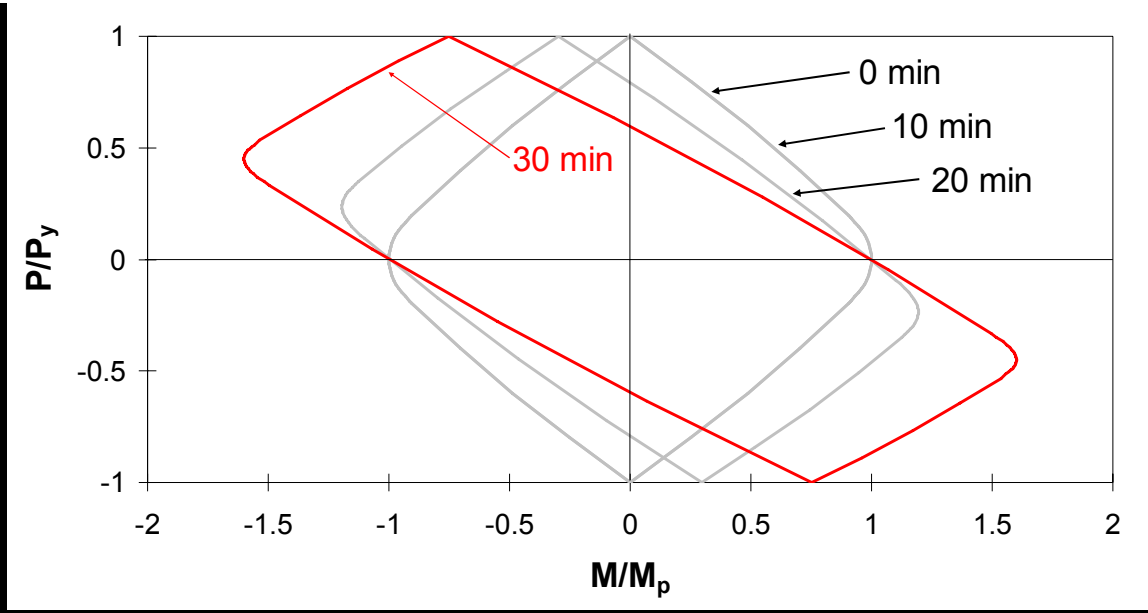




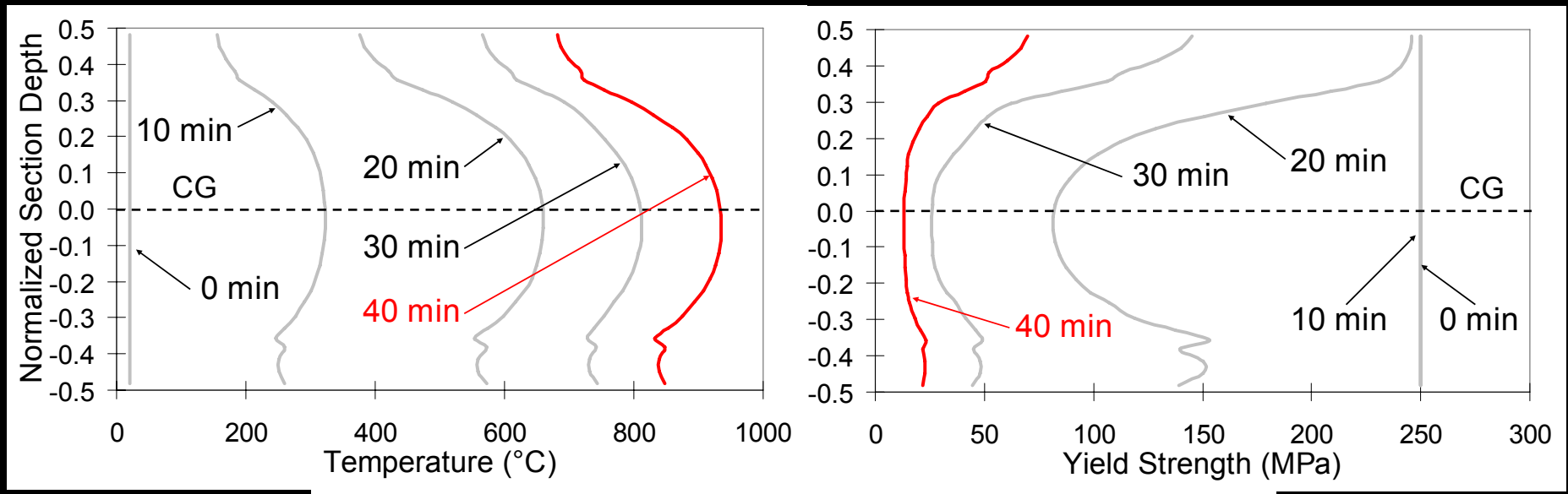
Predicting the Capacity

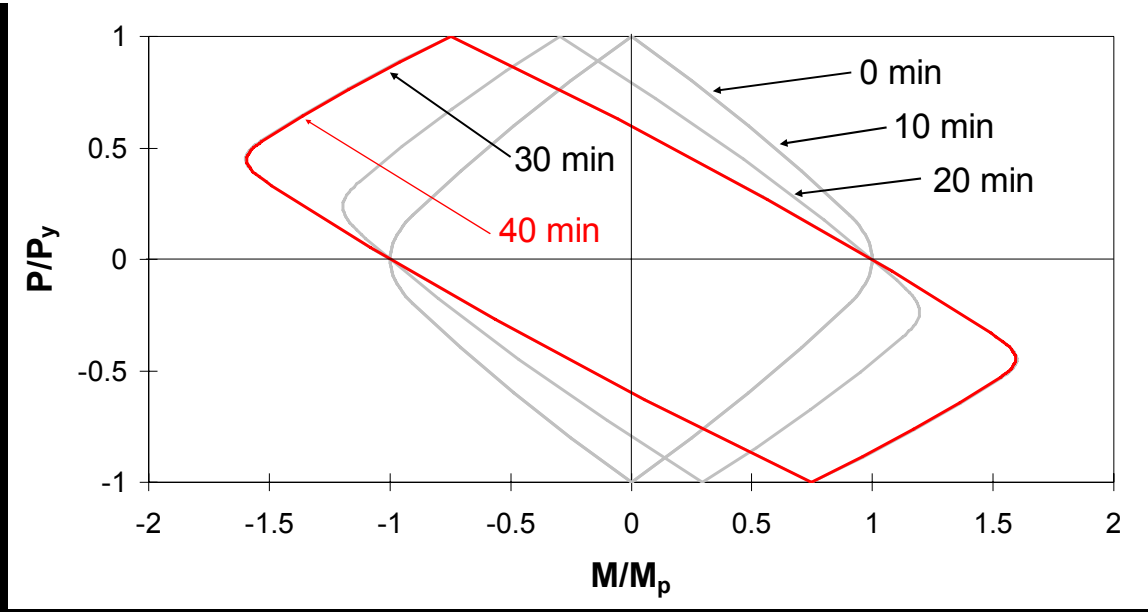




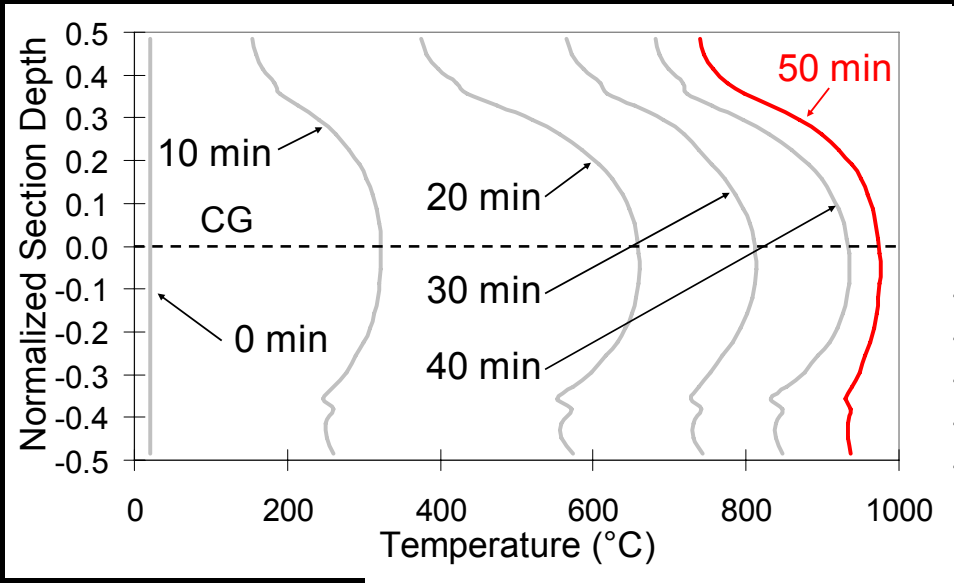


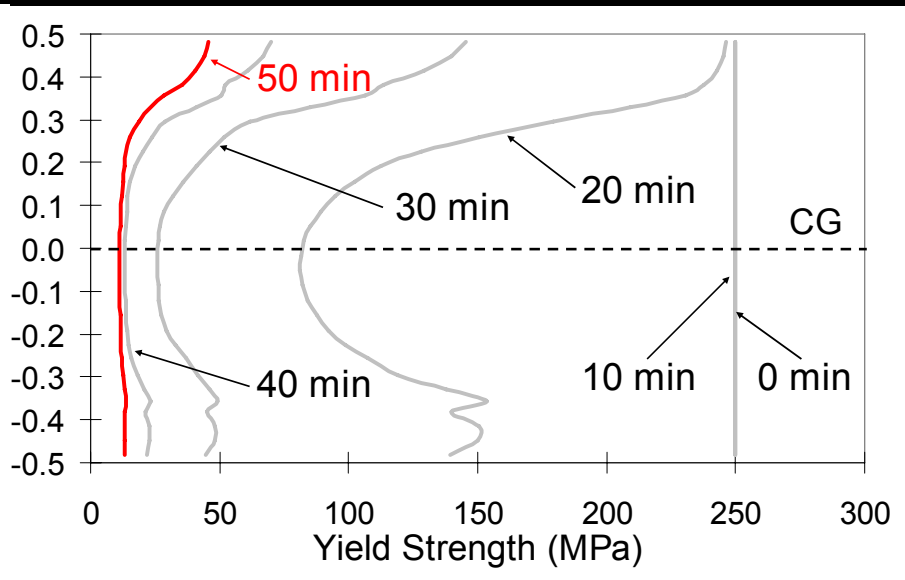
Predicting the Capacity

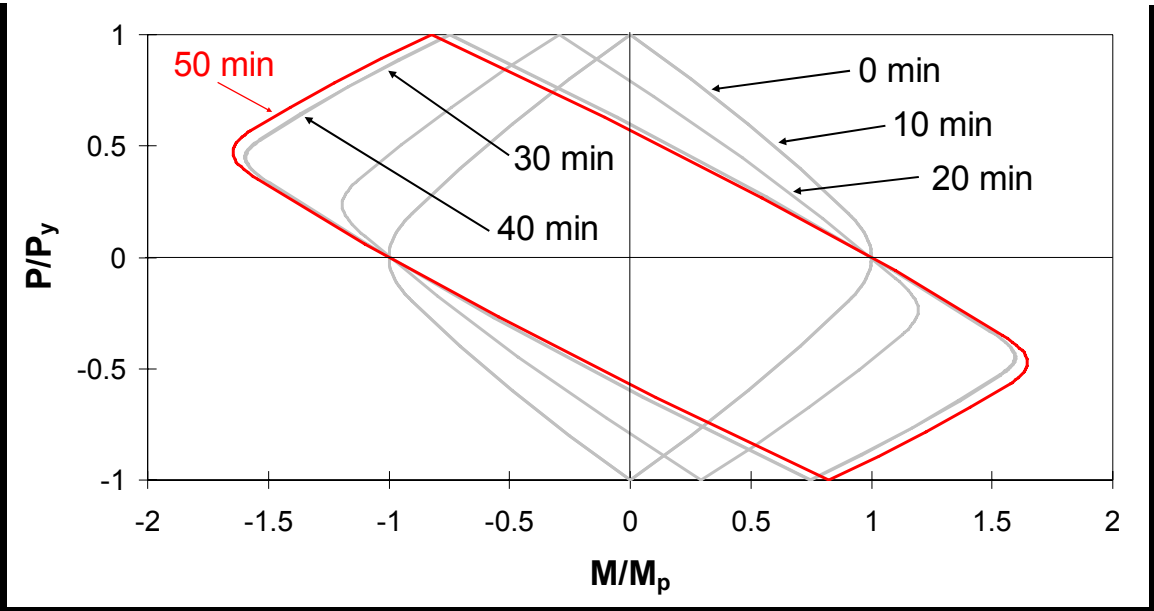




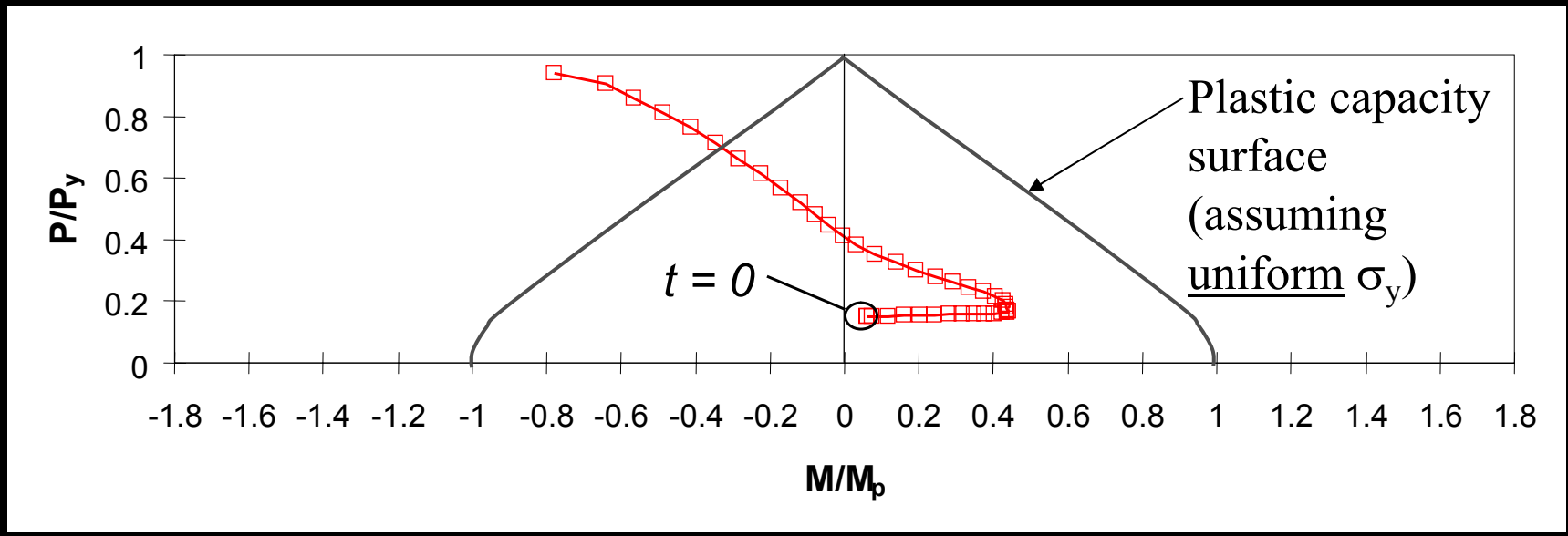
Predicting the Capacity

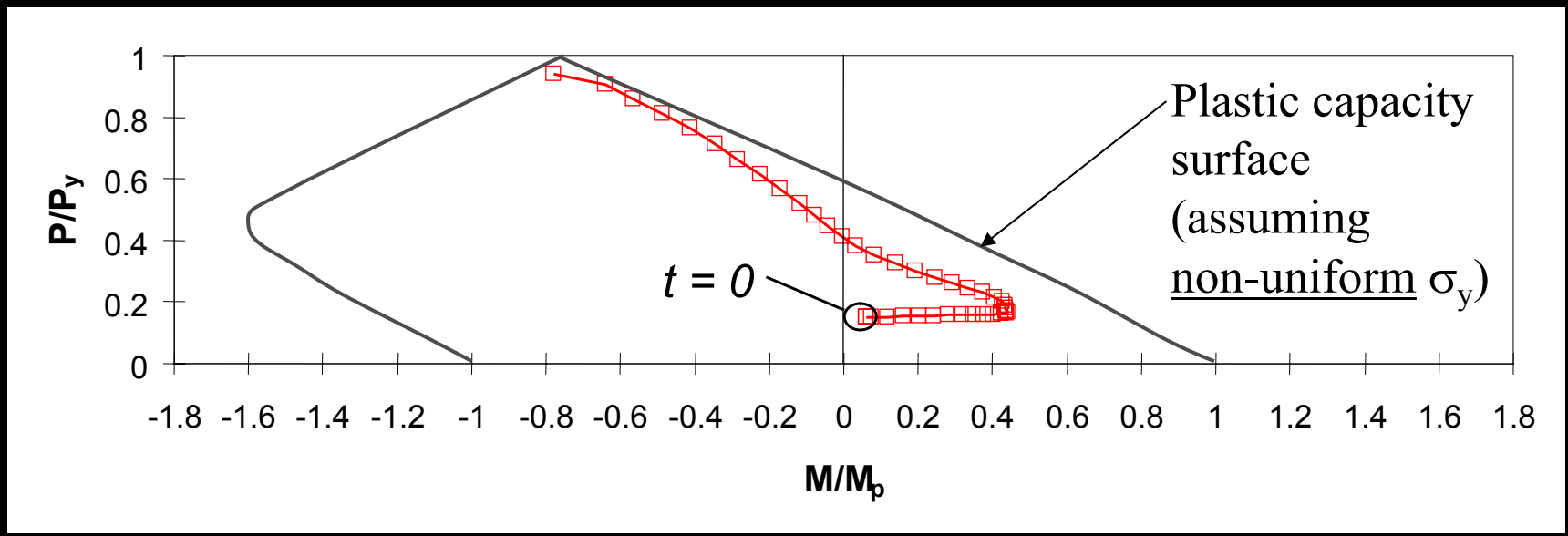






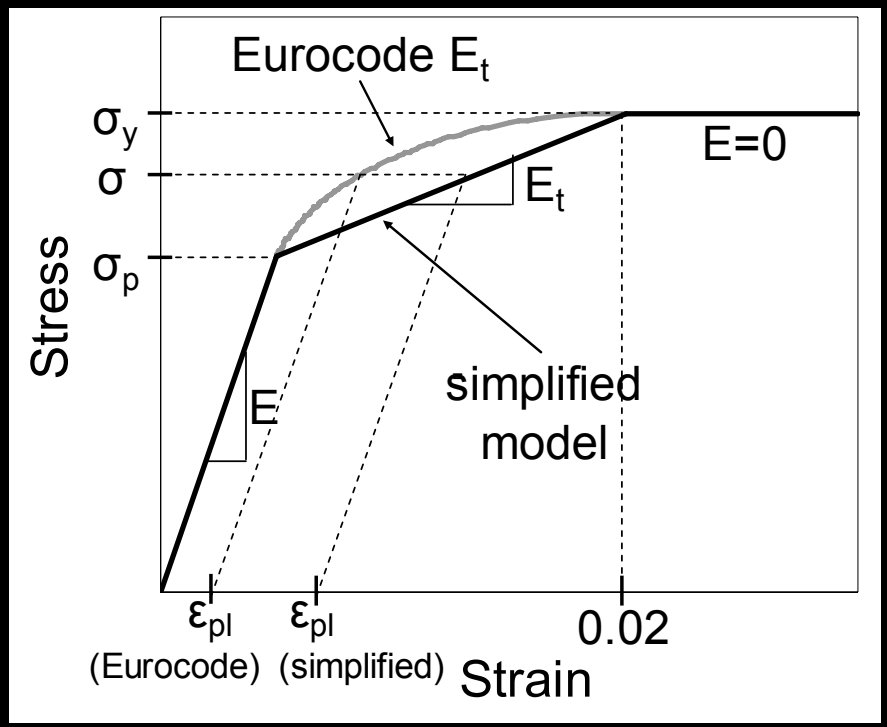
Predicting the Capacity



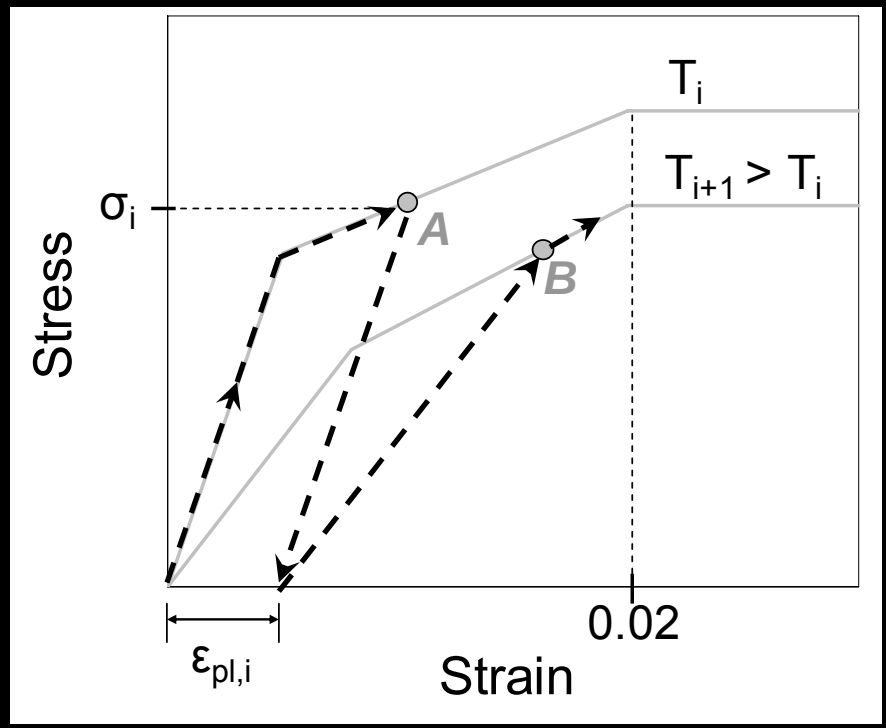


Predicting the Demands

Steel Material Model



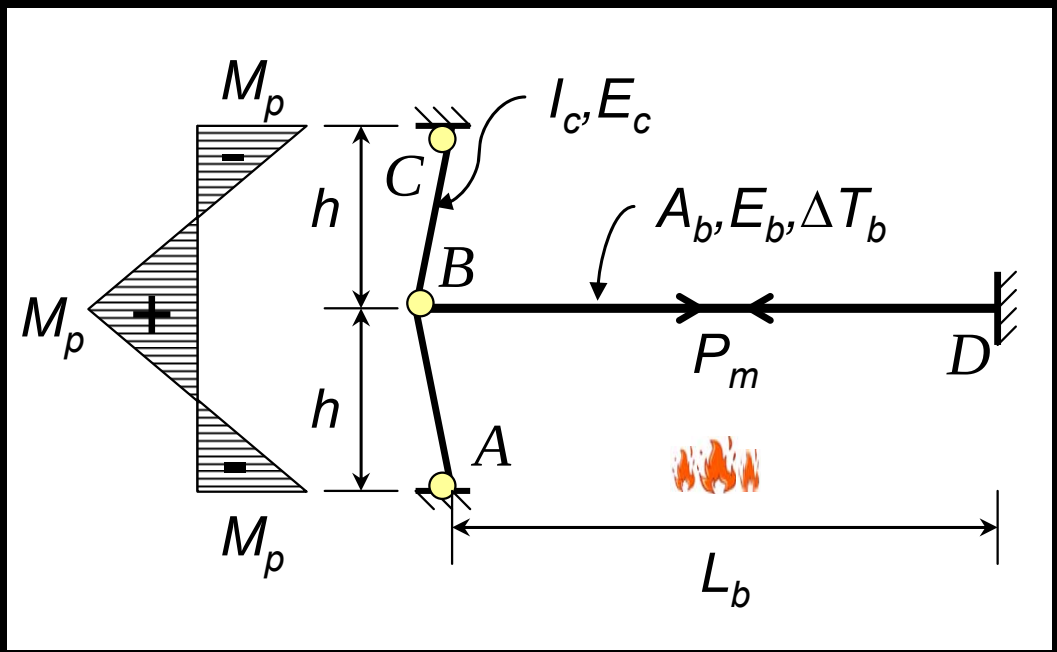
ε_{pl} = plastic strain

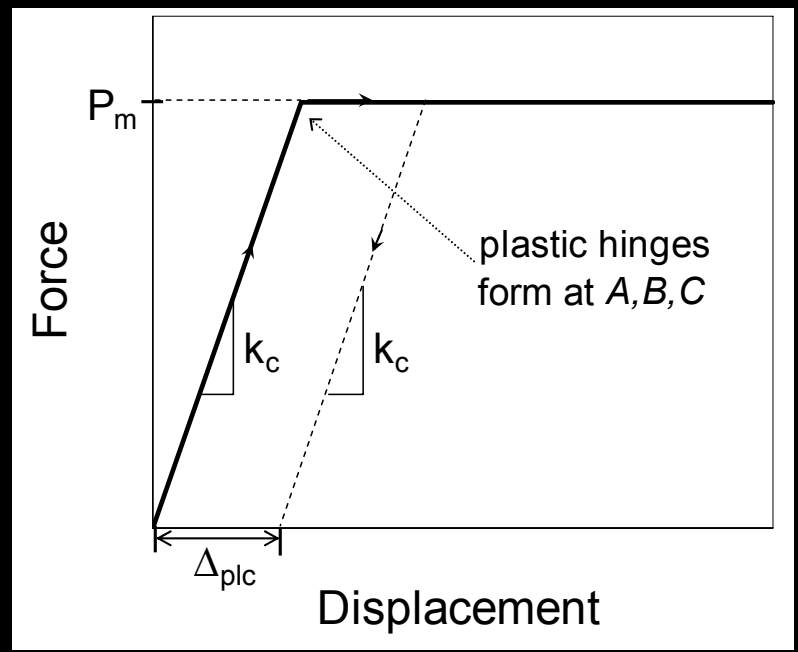


Transition from time step i to time step i+1

Predicting the Demands

Column Mechanism Model





$$P_m = \frac{4M_p}{h}$$

Δ_{plc} = plastic column deformation

Predicting the Demands

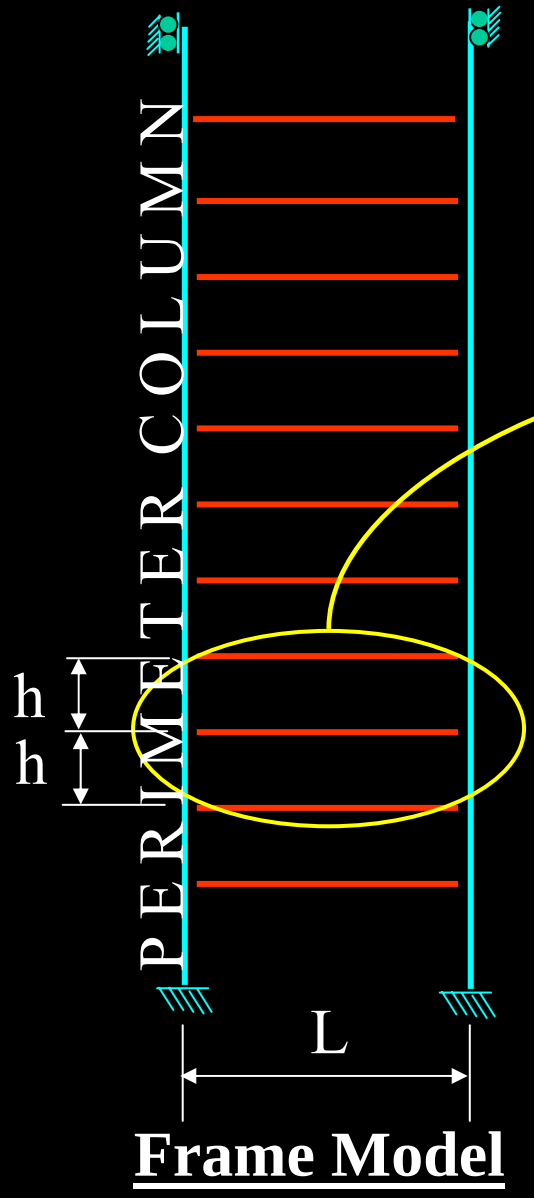
$$\frac{P}{k_c} + \Delta_{pl,c} = \alpha \Delta T_b L_b - \frac{P}{k_b} - \varepsilon_{pl,b} L_b \quad \longrightarrow \textit{mat'l = linear}$$

$$\frac{P}{k_c} + \Delta_{pl,c} = \alpha \Delta T_b L_b - \left(\frac{P_p}{k_b} + \frac{(P - P_p)}{k_{b,t}} \right) - \varepsilon_{pl,b} L_b$$

$$\longrightarrow \textit{mat'l = nonlinear}$$

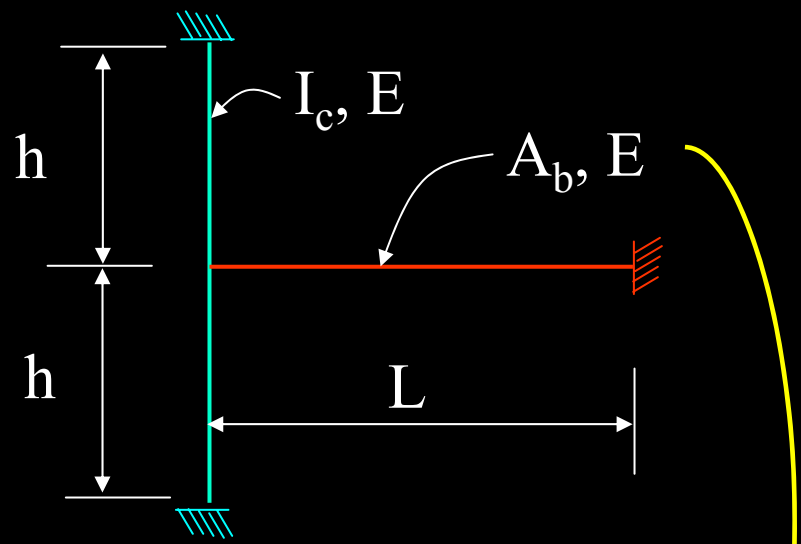
coln deflection (Δ) = beam thermal expansion – beam axial shortening

Predicting the Demands



Frame Model

Subassembly Model

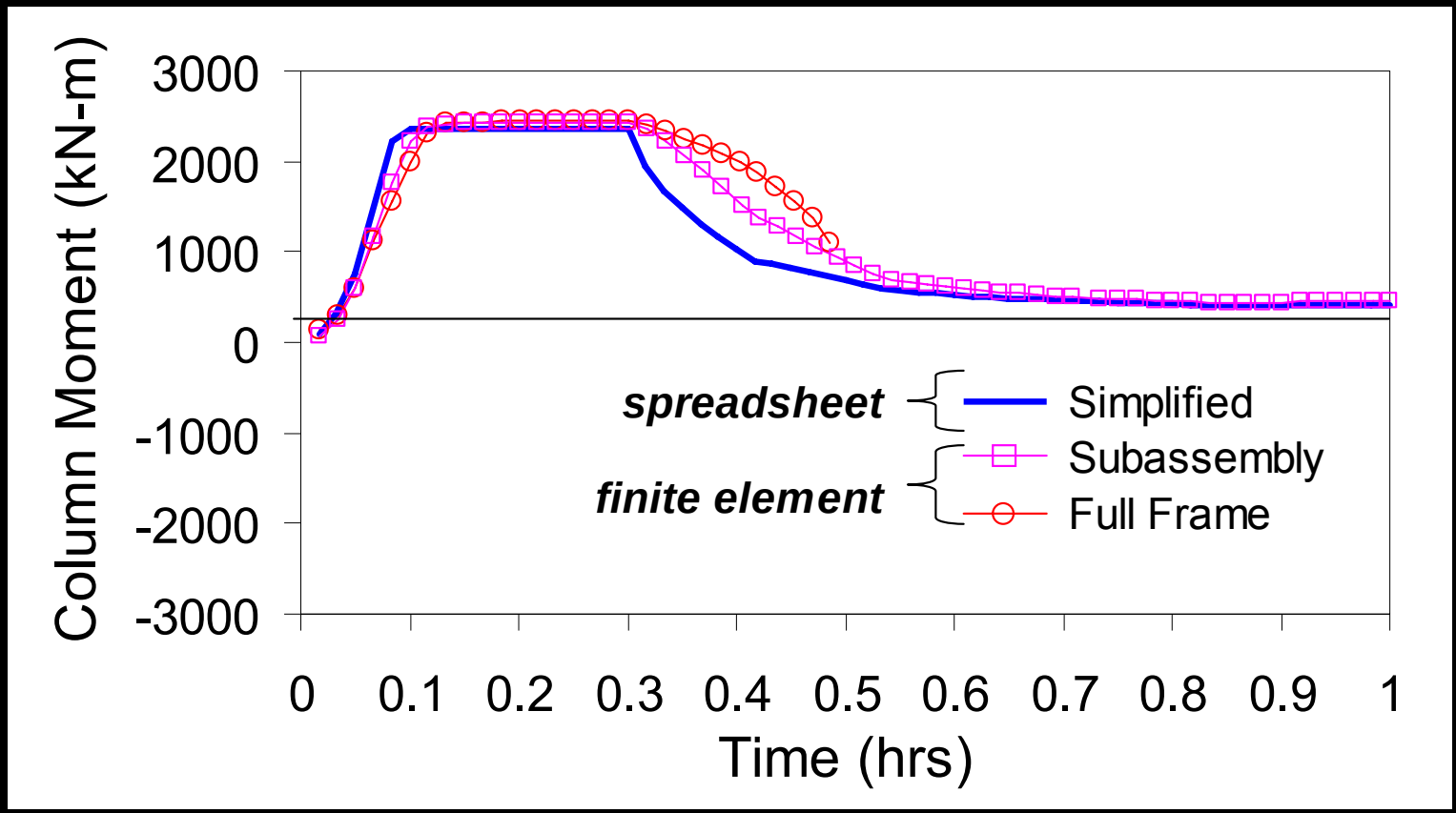


Beam-Spring Model

$k_c = 24EI_c/h^3$

$k_b = A_bE/L$

Predicting the Demands



Summary & Conclusions

- Thermal gradients in the steel section cannot be neglected because they will affect both the capacity and the demands placed on the member.
  - Alters the P-M interaction diagram
  - Induces (reverses) bending moments due to shift in effective centroid

Summary & Conclusions

- However, other studies (not discussed here) have shown that if $T_{max} < 400°C$ in the column, the gradients are smaller and have less effect, and therefore uniform temperature is a reasonable approximation.

- In this case, the spring-beam model provides a reasonable estimation of the perimeter column behavior.

Future Studies

- 2D vs. 3D modeling of fire-exposed building frame
- Recent grant from NIST & NSF (with Dr. V. Kodur at MSU)
  - Experiments of beam-columns in a furnace
  - Parametric FE Analyses
    - Plate slenderness (local buckling), orientation of gradient, P & M combinations, fire, insulation
  - Develop design guidelines

Acknowledgement

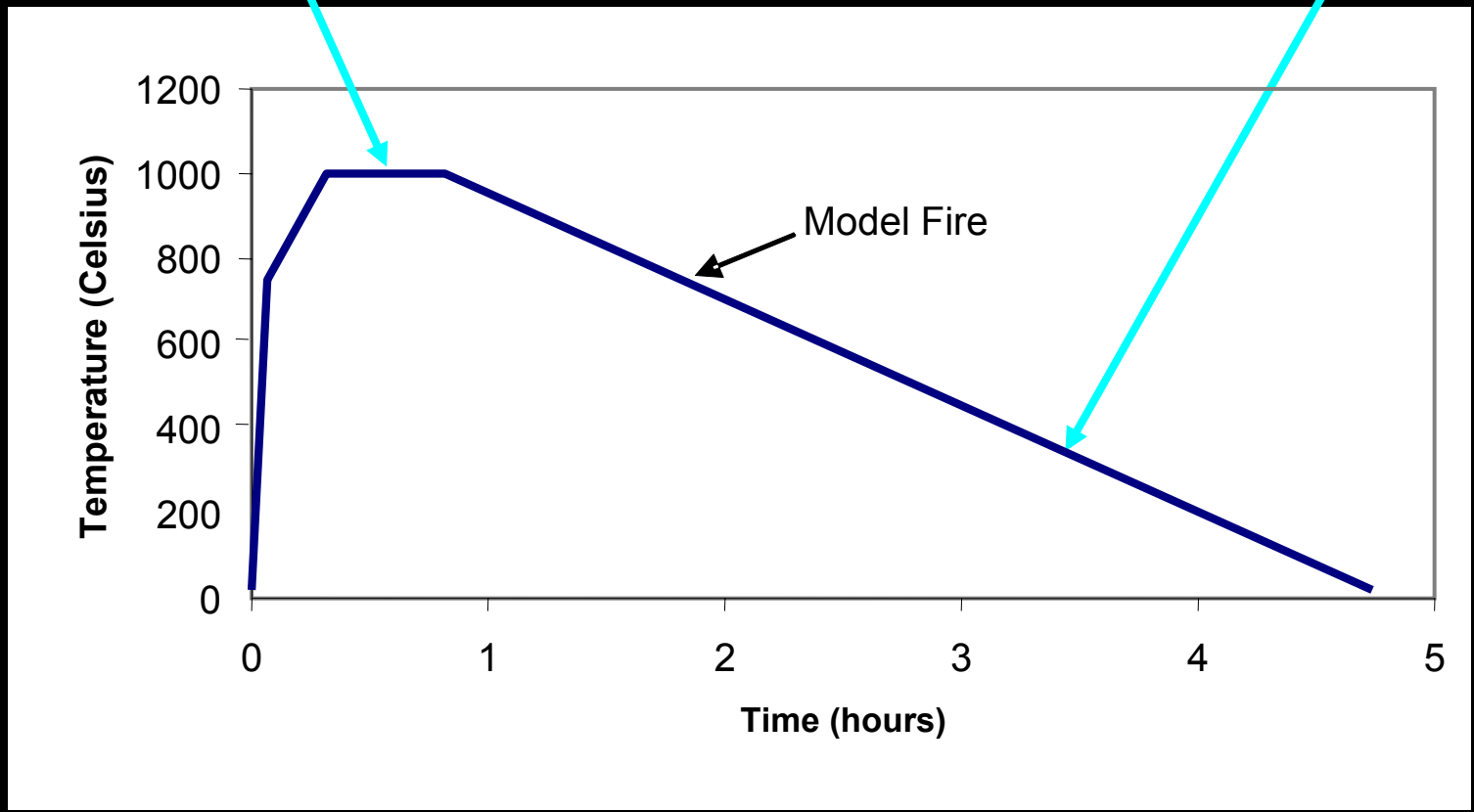
- U.S. Department of Homeland Security (DHS) Fellowship

Thank You

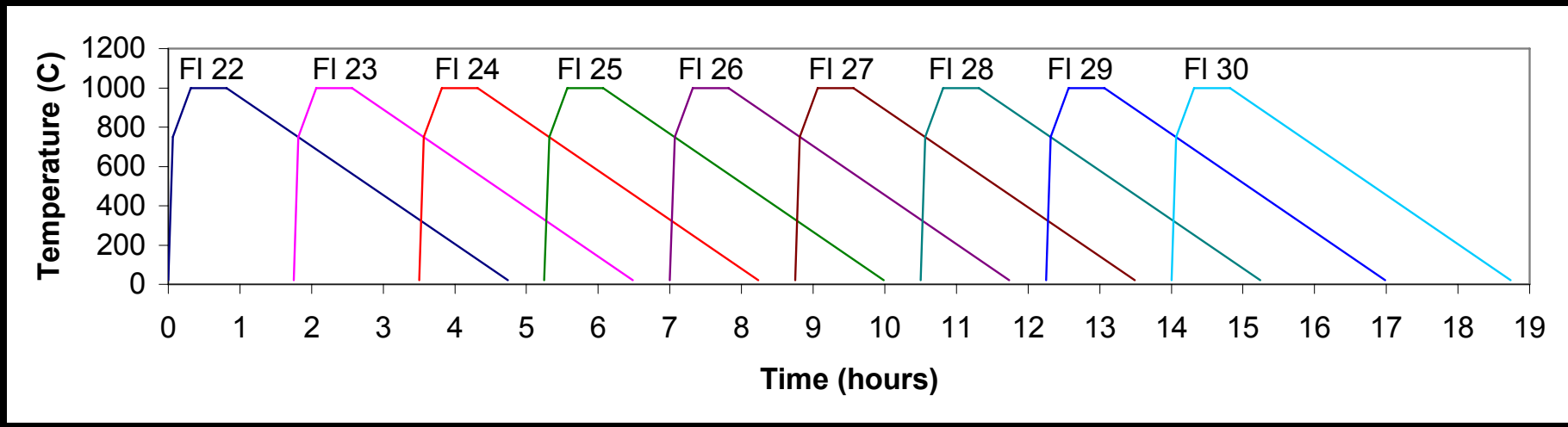
Prototype

T_{max} = 1000º C
(based on Eurocode compartment model fire)

Decay rate = 5º C per minute
(based on data from large compartment tests)



Perimeter Column: Prototype

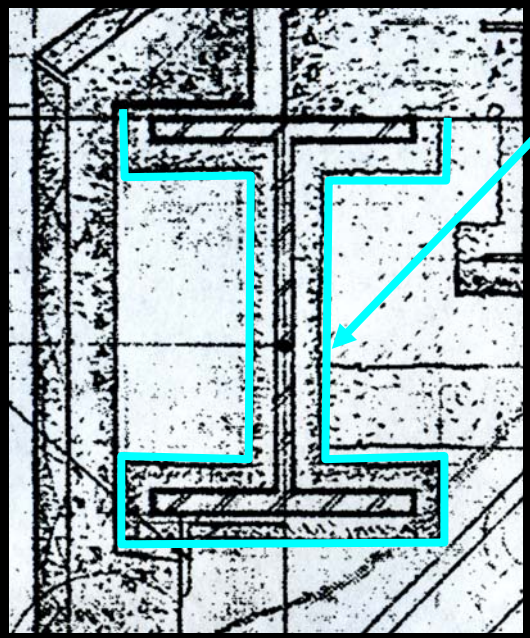


- Time-history reasonably consistent with observations during the fire event.

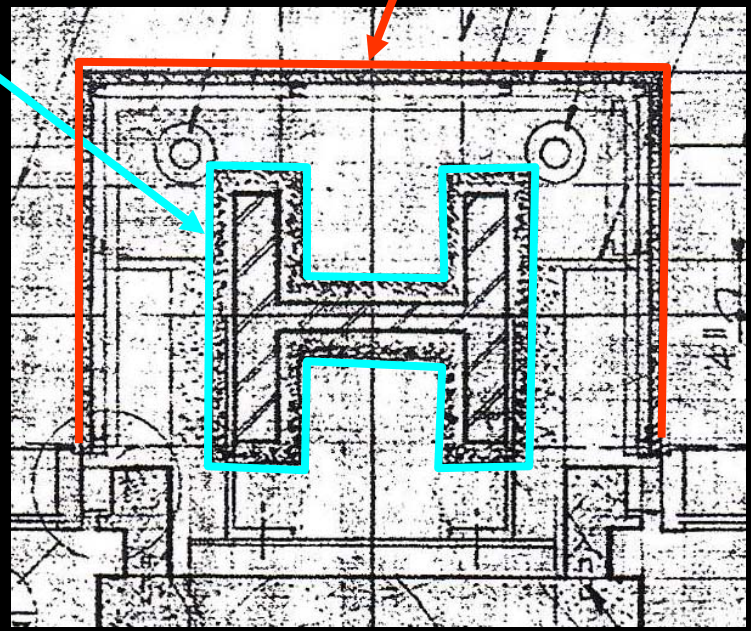
Equivalent to BOCA Type 1B construction

1½" spray-on

¾" plaster

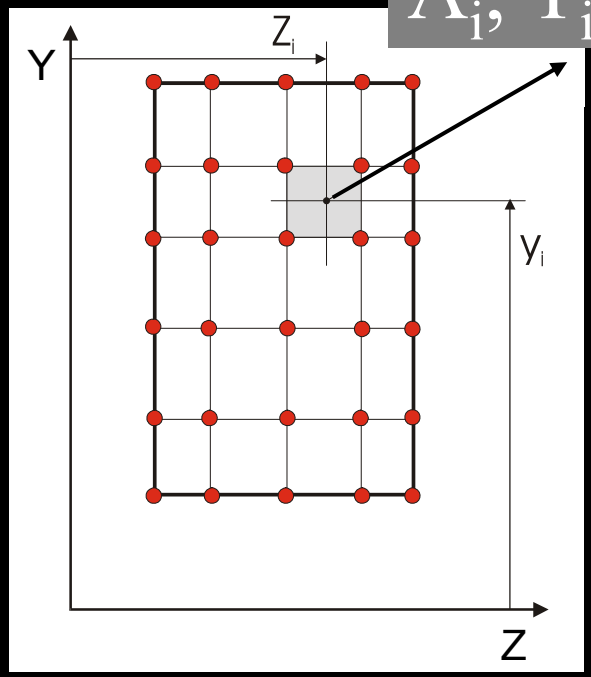


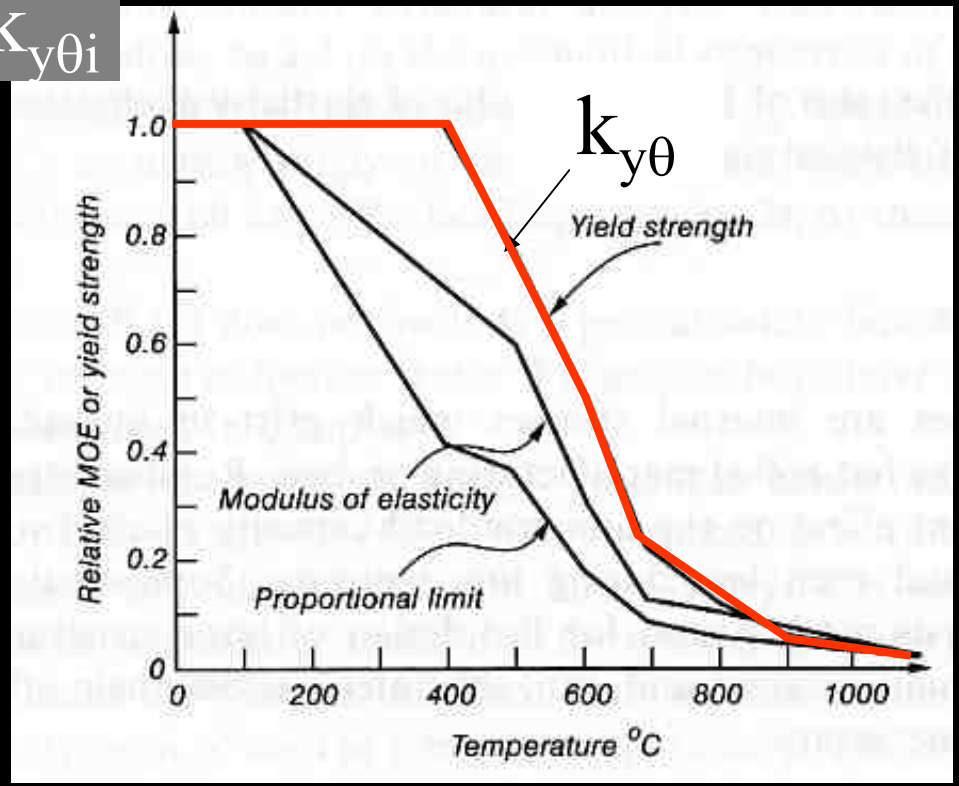
Beam Detail
(2-hour rated)



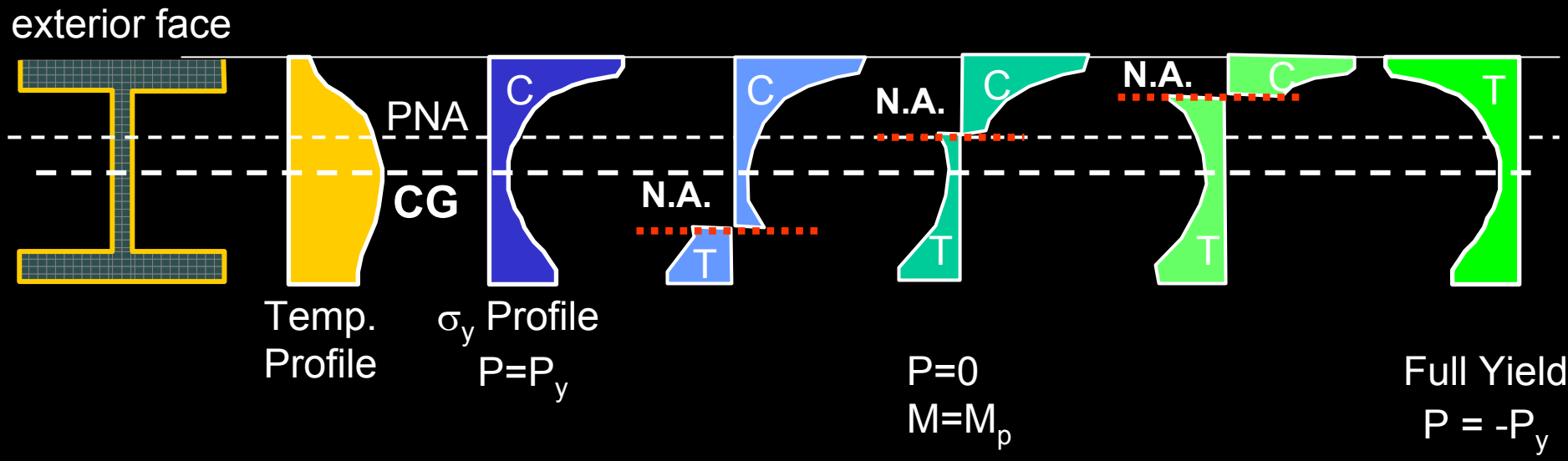
Column Detail
(3-hour rated)

A_i, T_i, $k_{y\theta i}$

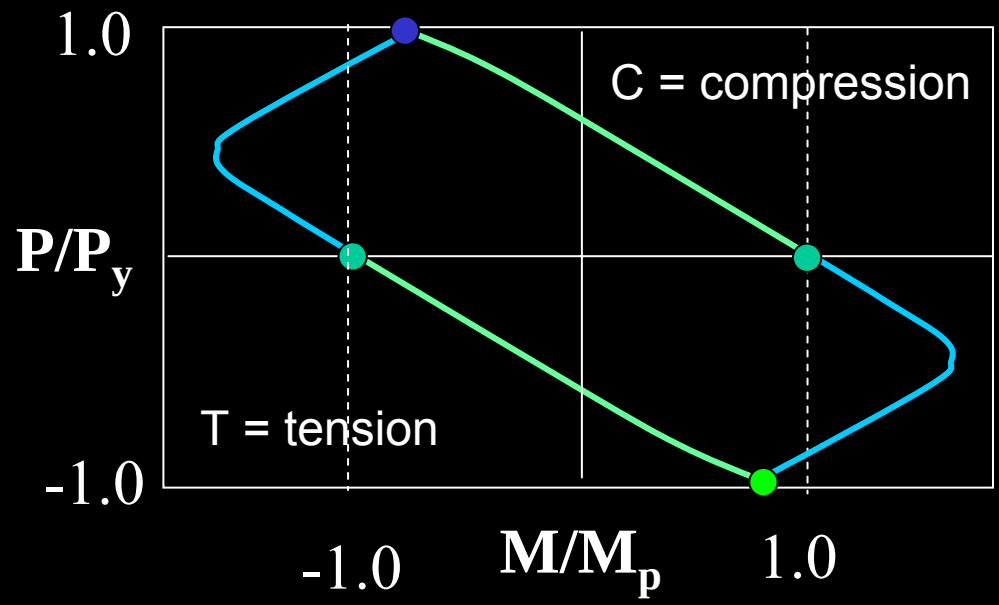


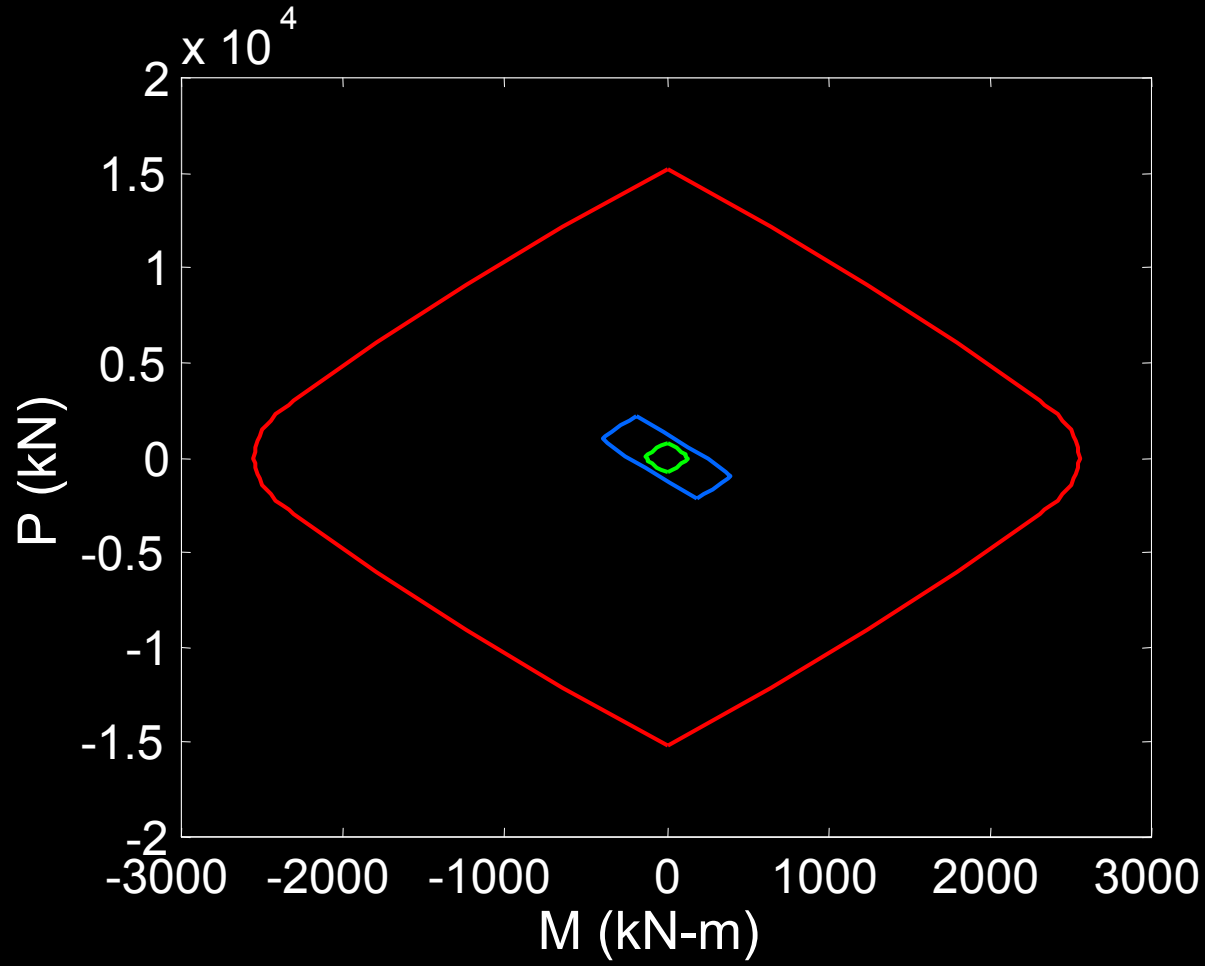


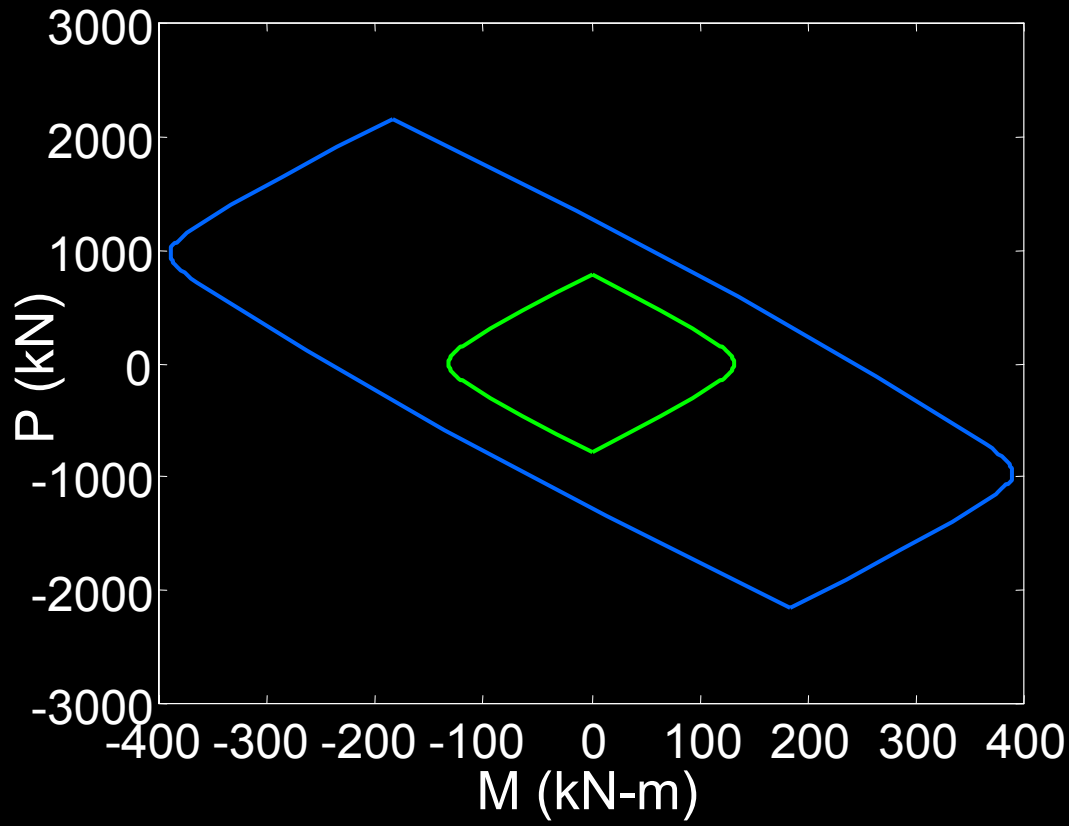
Constructing the P-M diagram



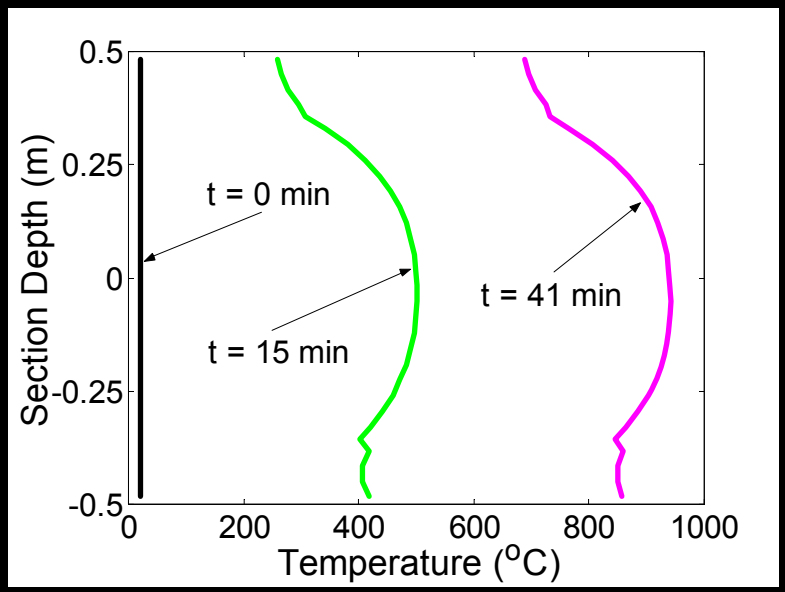
$M = M_{CG}$

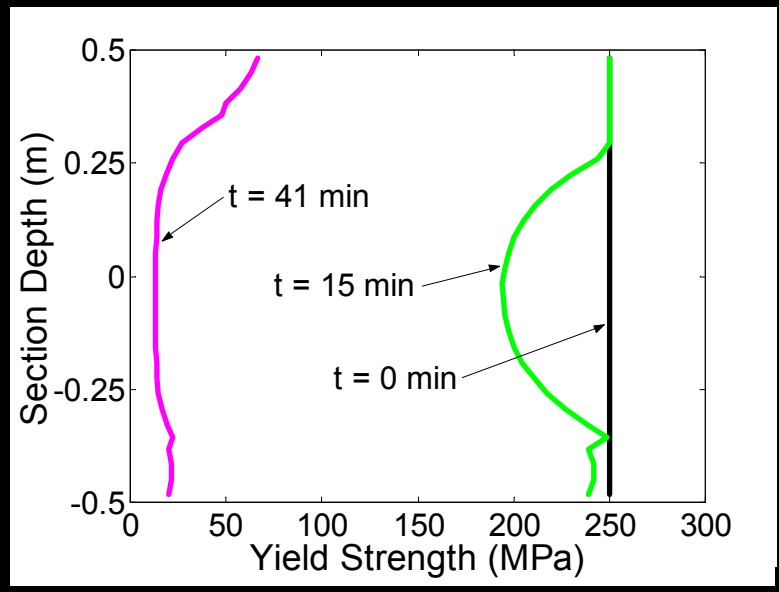


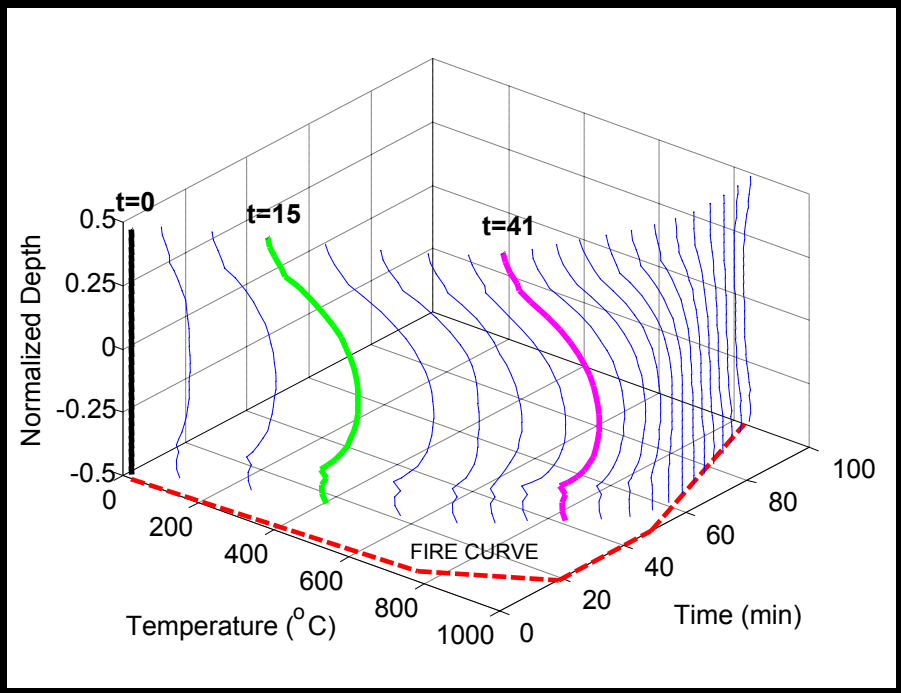

x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
P (kN)
-3000
-2000
-1000
0
1000
2000
3000
M (kN-m)

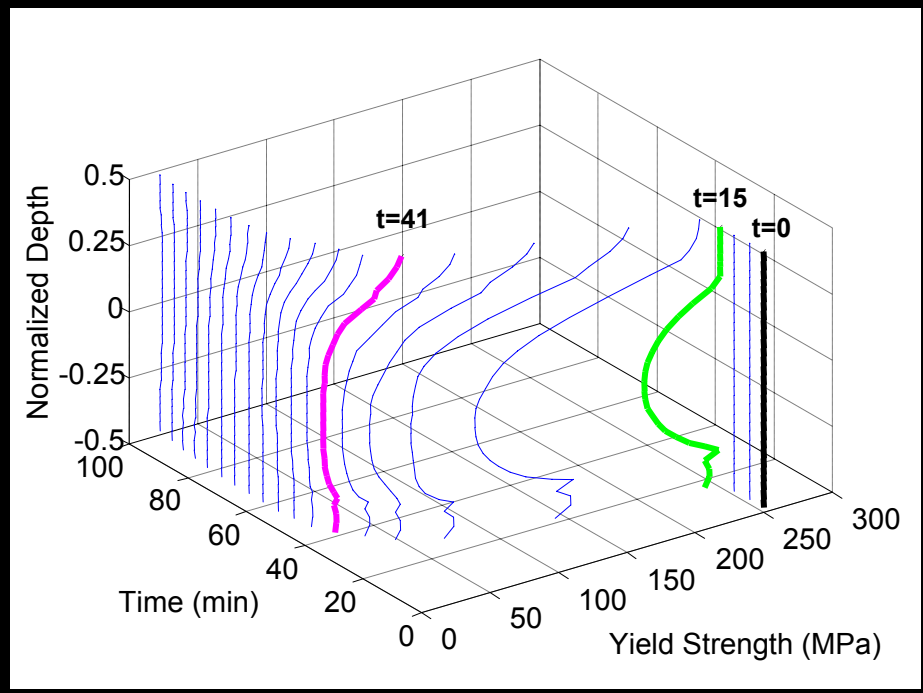

3000
2000
1000
0
-1000
-2000
-3000
P (kN)
-400 -300 -200 -100 0 100 200 300 400
M (kN-m)

Unprotected Column



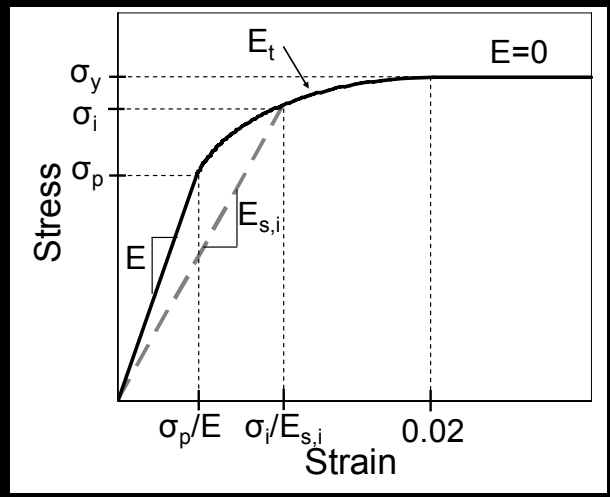






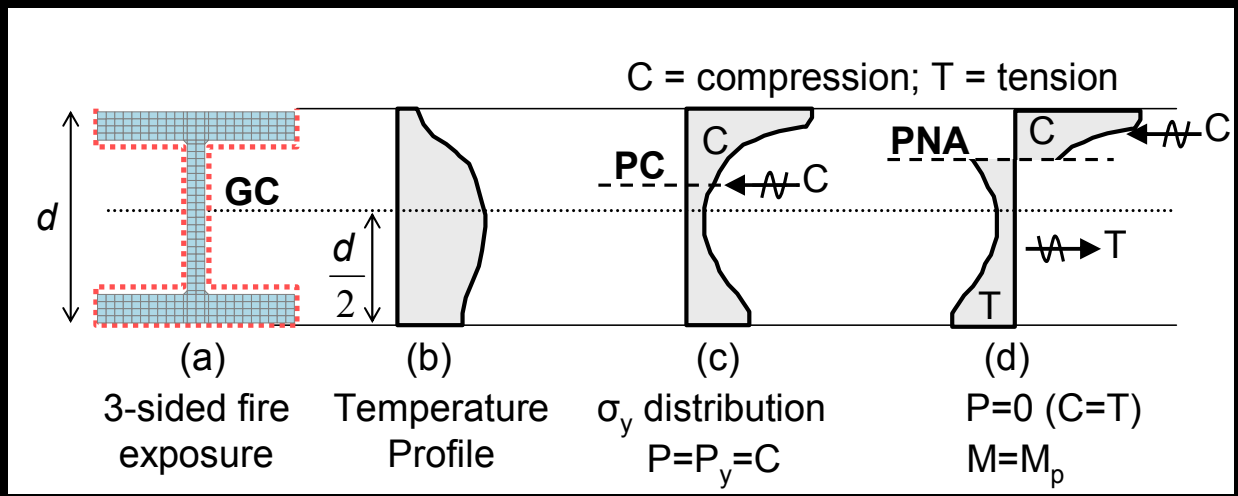
Definitions of EC, PC, PNA

Effective Centroid (EC)



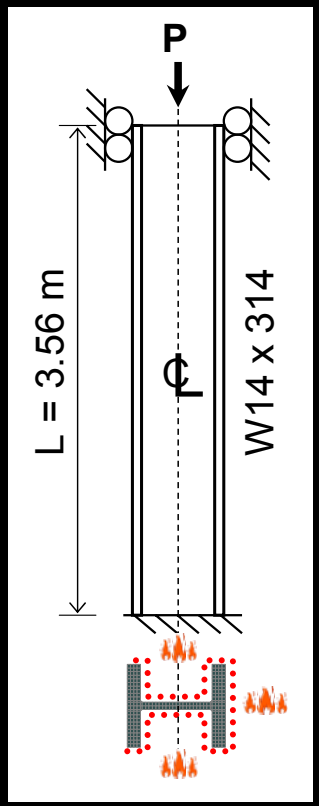
$$y_{EC} = \frac{\sum E_{s,i} y_i A_i}{\sum E_{s,i} A_i}$$

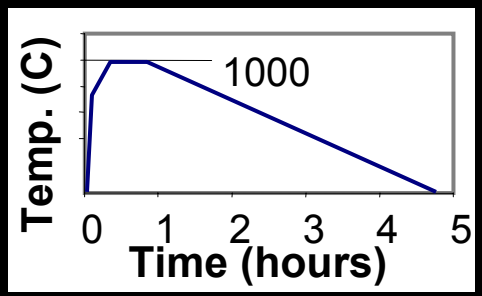
Plastic Centroid (PC) and Plastic Neutral Axis (PNA)



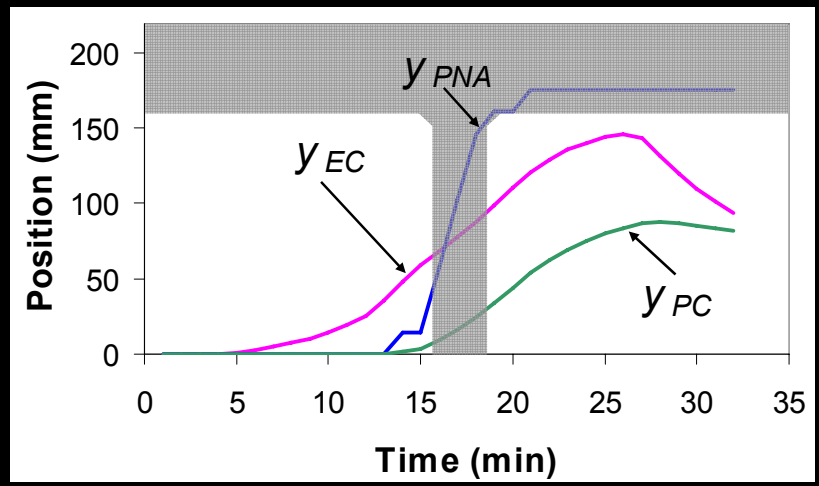
$$y_{PC} = \frac{\sum \sigma_{y,i} y_i A_i}{\sum \sigma_{y,i} A_i}$$

Movement of EC, PC, PNA

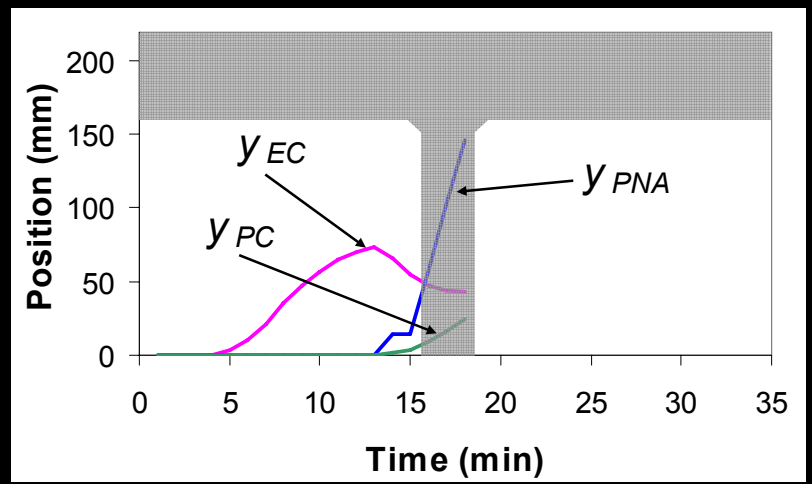




P = 25% of initial P_y

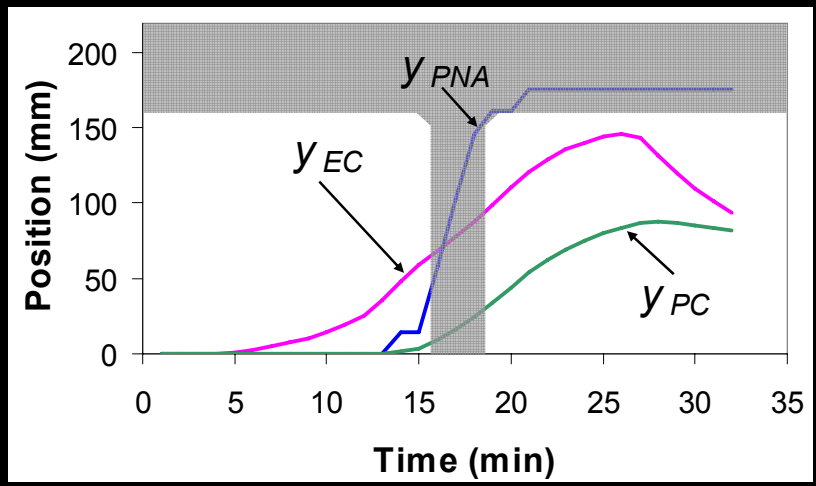


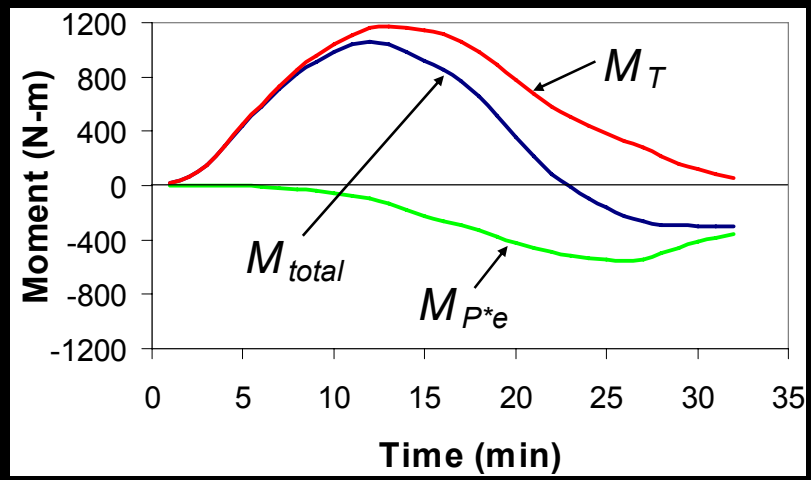
P = 75% of initial P_y



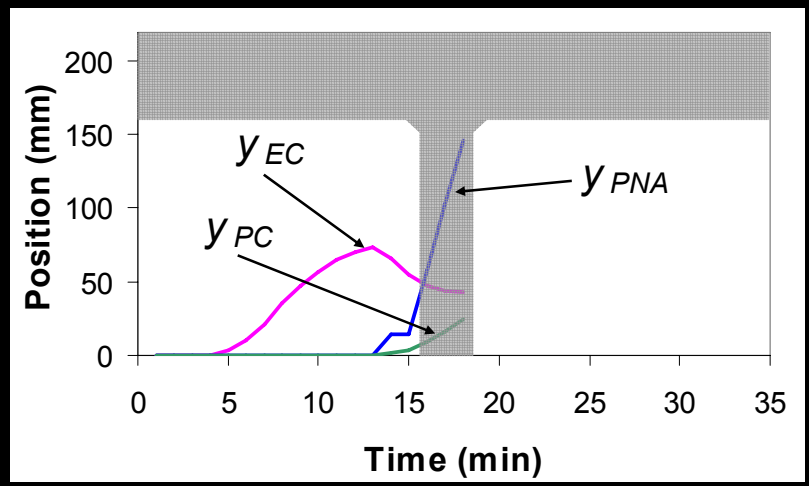
Mechanics: EC, PC, PNA

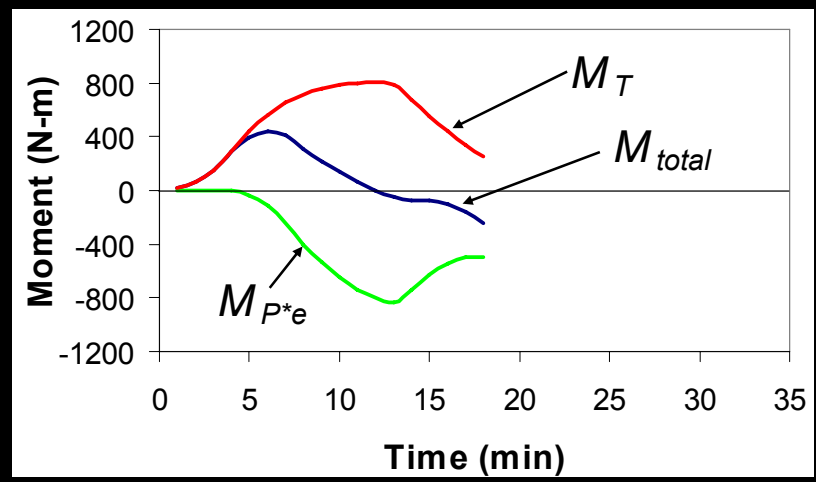
P = 25% of initial P_y



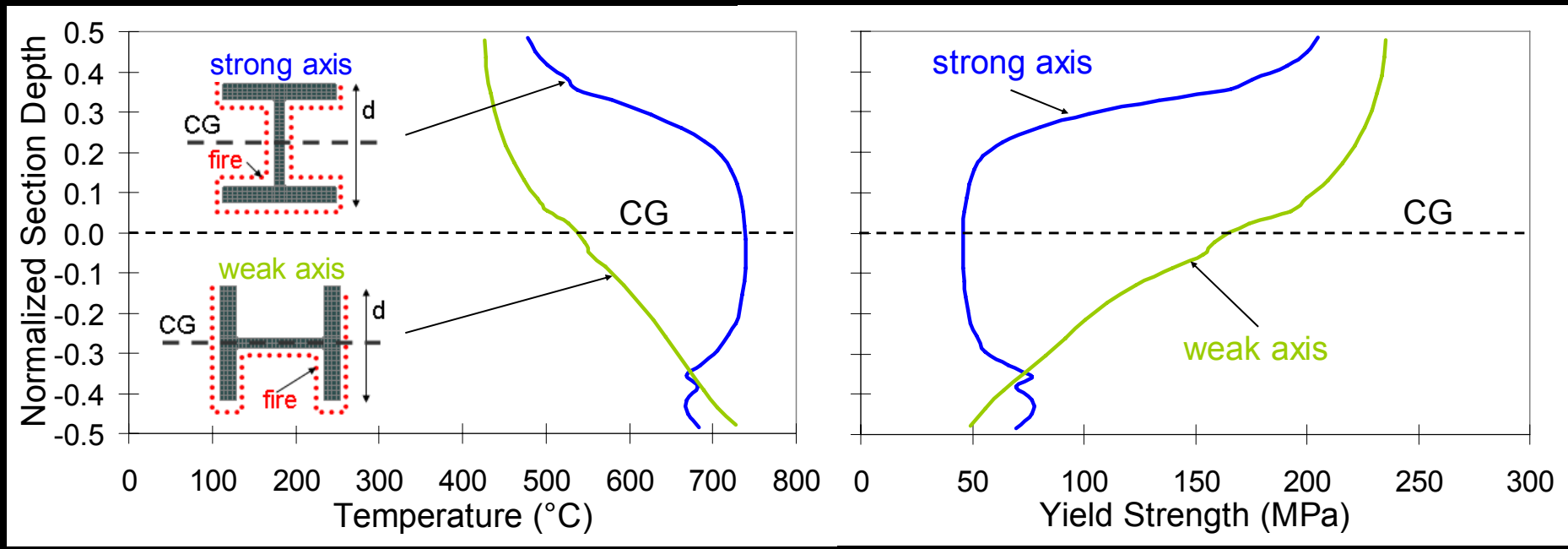


P = 75% of initial P_y

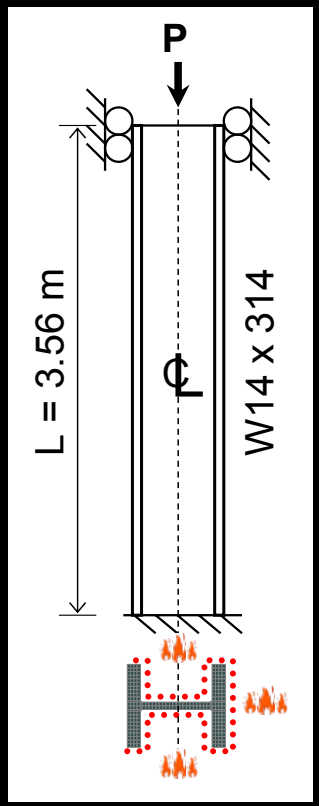




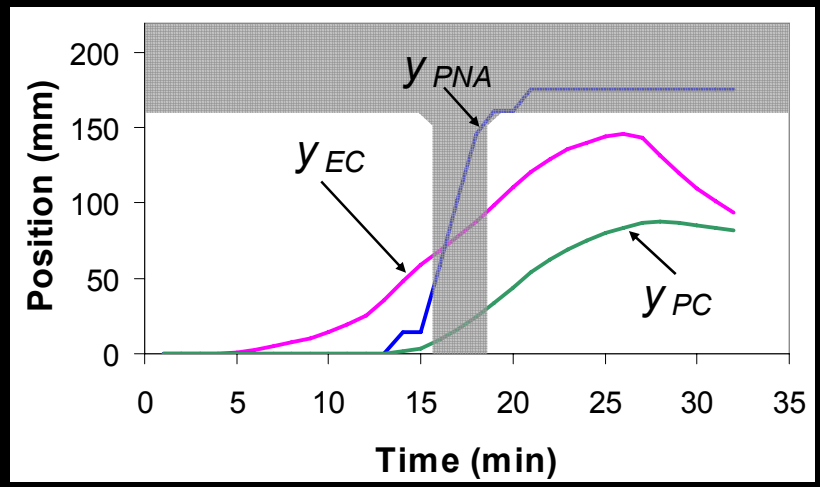
Movement of EC, PC, PNA

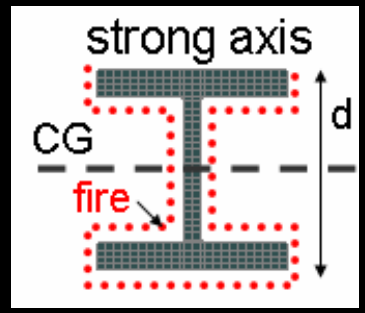


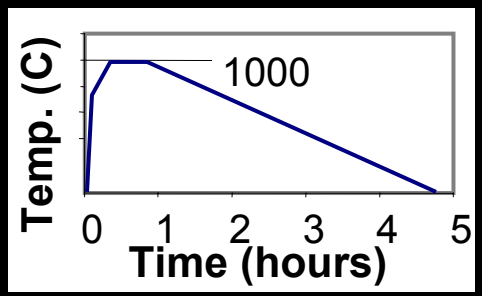
Movement of EC, PC, PNA

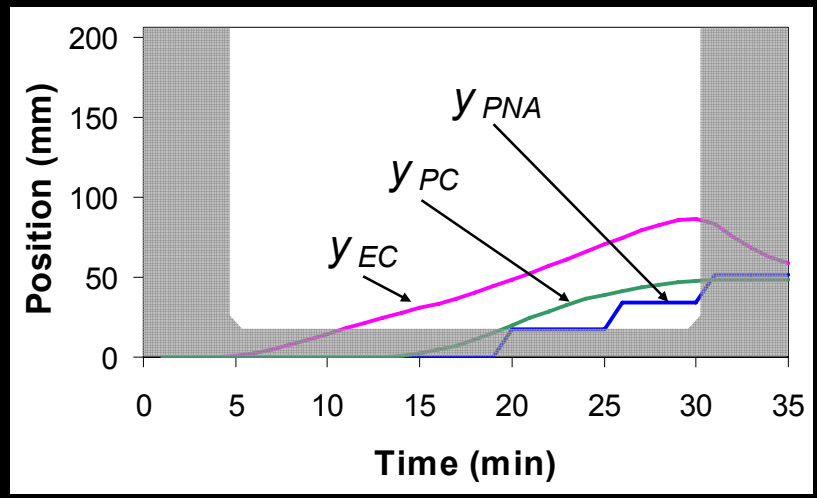


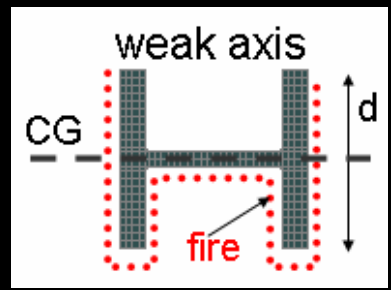
P = 25% of initial P_y





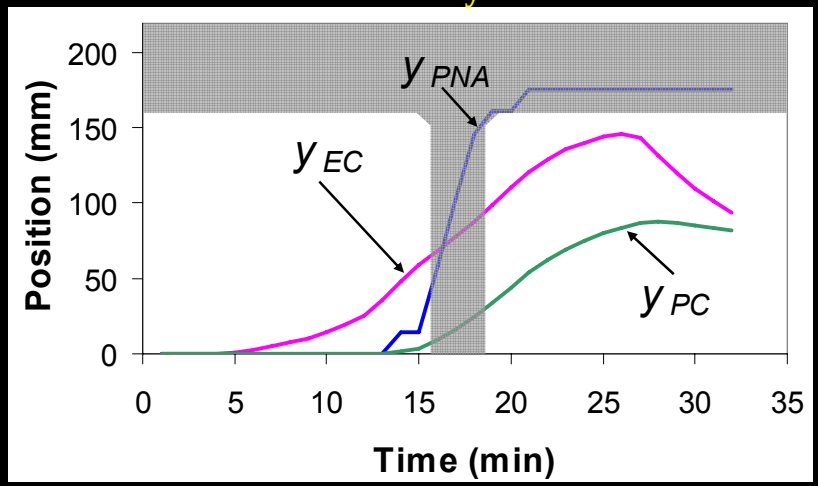


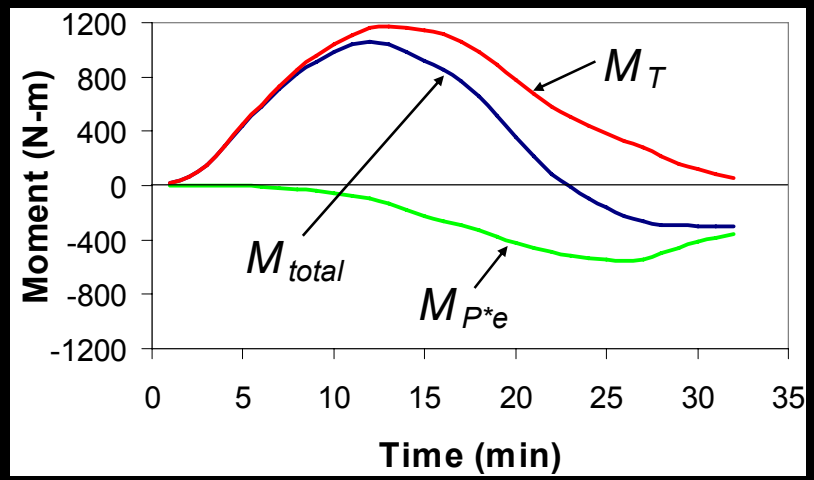


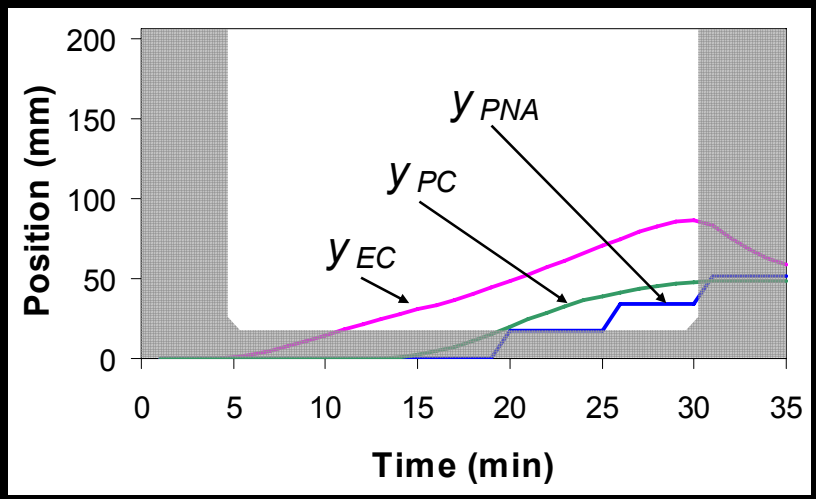


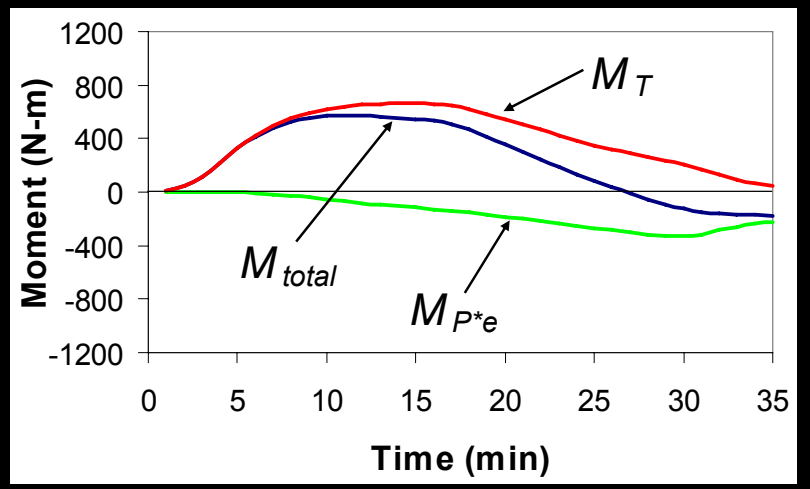
Mechanics: EC, PC, PNA

P = 25% of initial P_y

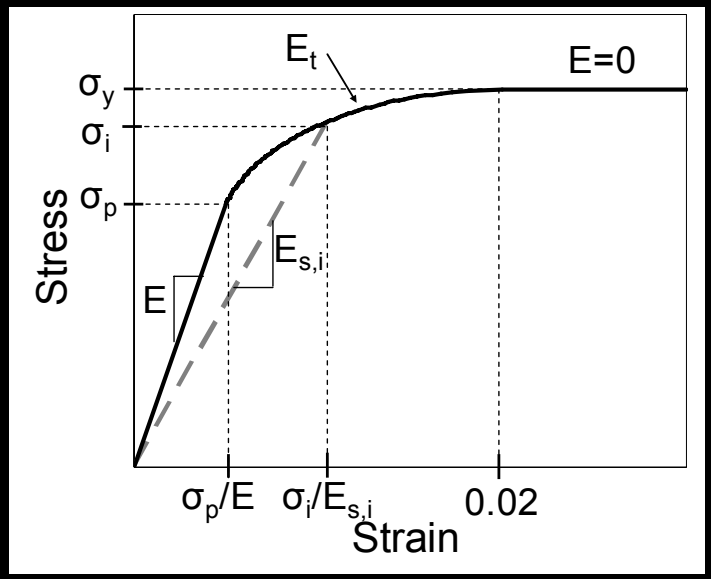




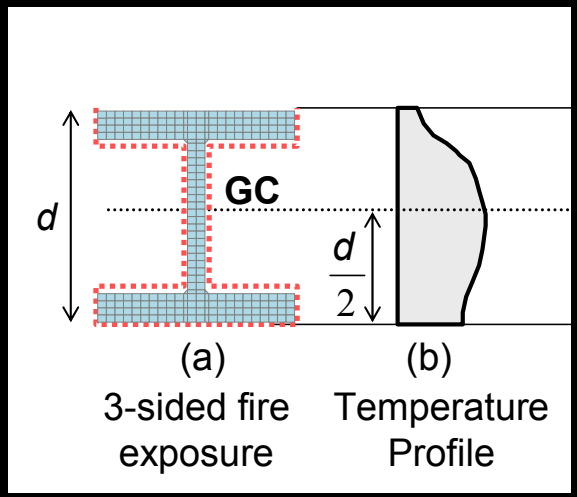




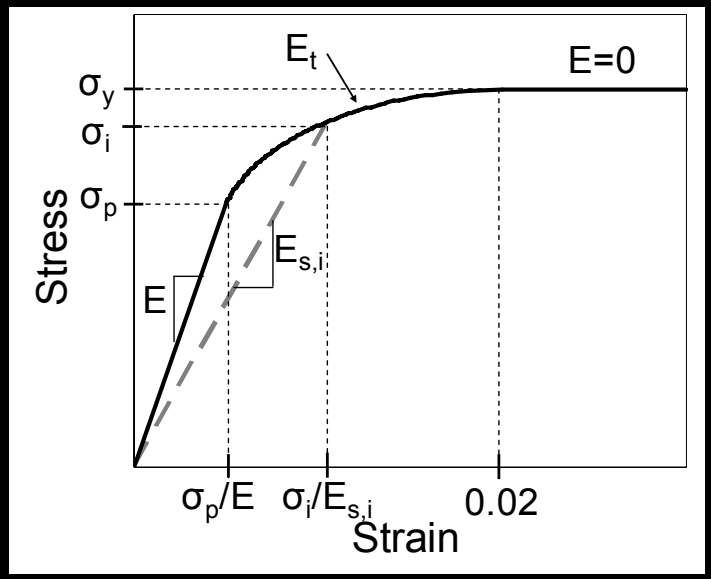
Effective Centroid



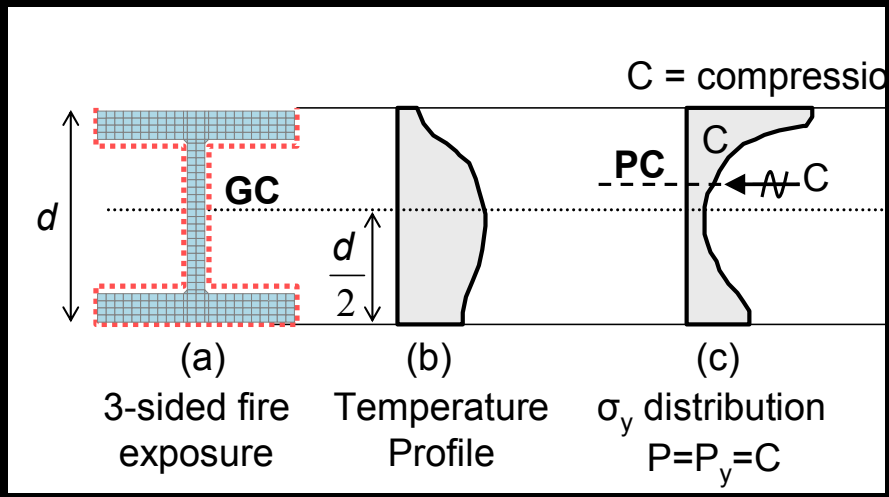
$$y_{EC} = \frac{\sum E_{s,i} y_i A_i}{\sum E_{s,i} A_i}$$



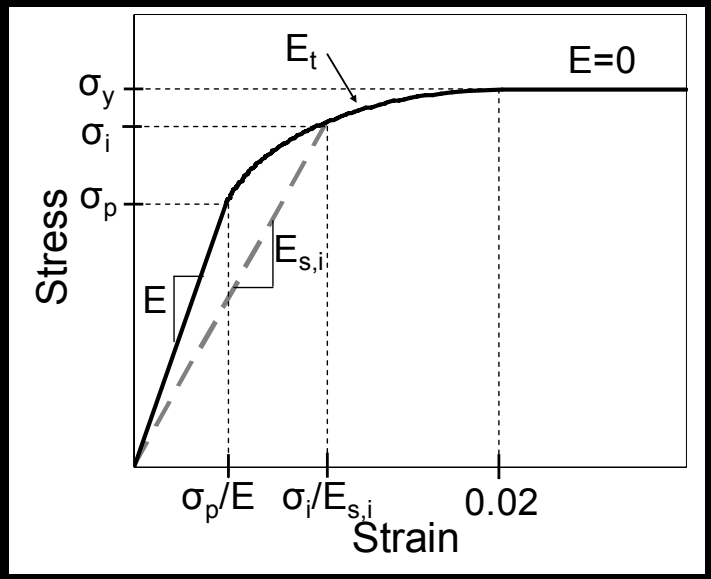
Effective Centroid



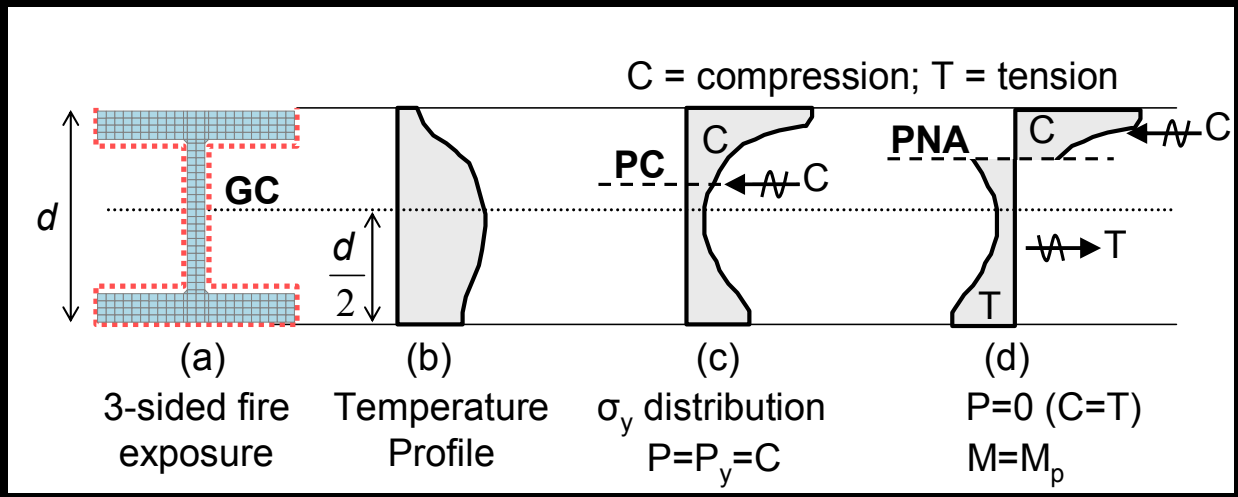
$$y_{EC} = \frac{\sum E_{s,i} y_i A_i}{\sum E_{s,i} A_i}$$



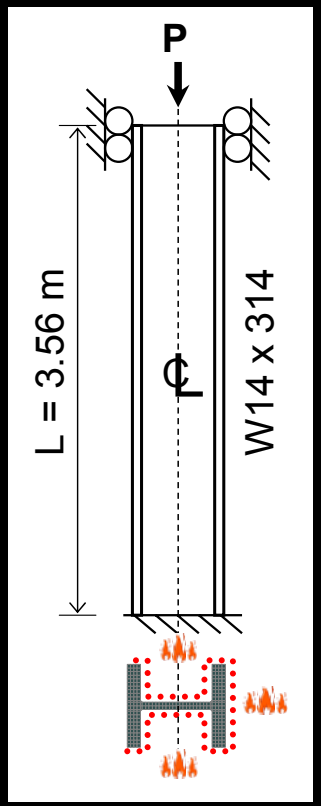
Effective Centroid

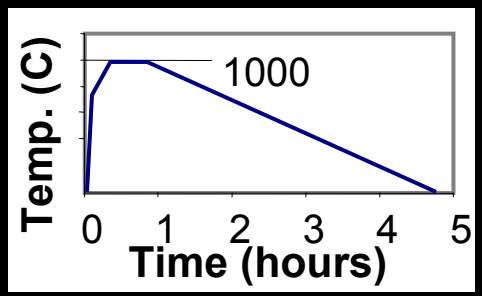


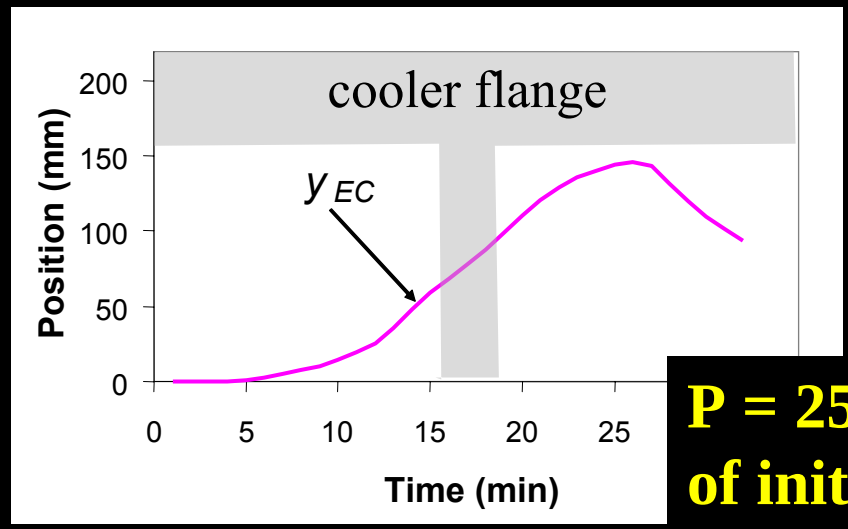
$$y_{EC} = \frac{\sum E_{s,i} y_i A_i}{\sum E_{s,i} A_i}$$



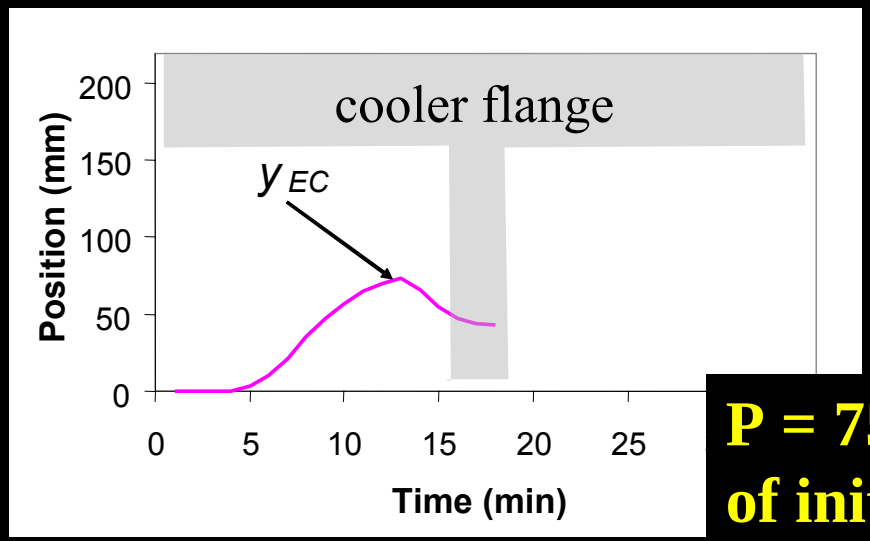
Movement of Effective Centroid







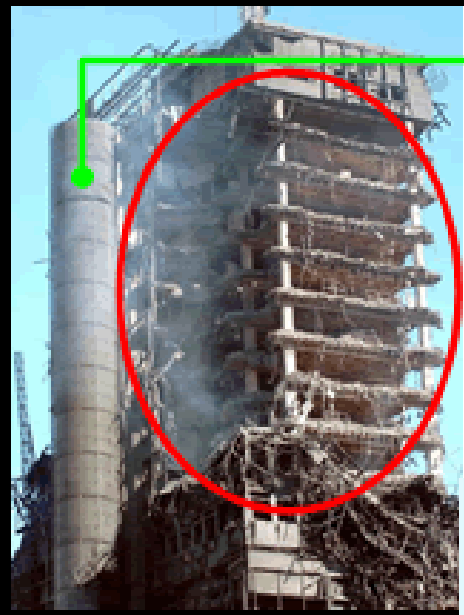
P = 25% of initial P_y



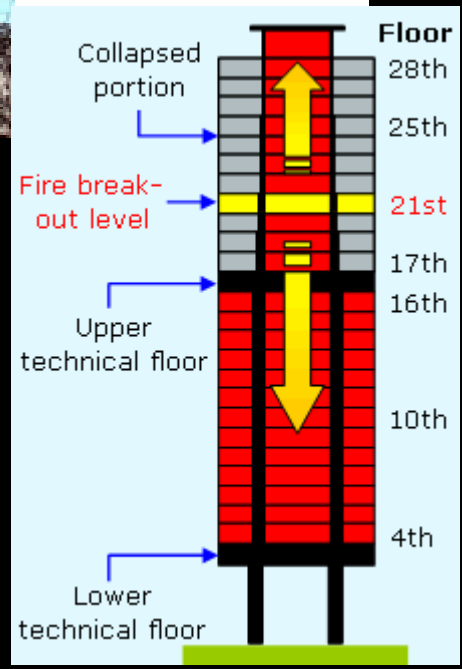
P = 75% of initial P_y

Background

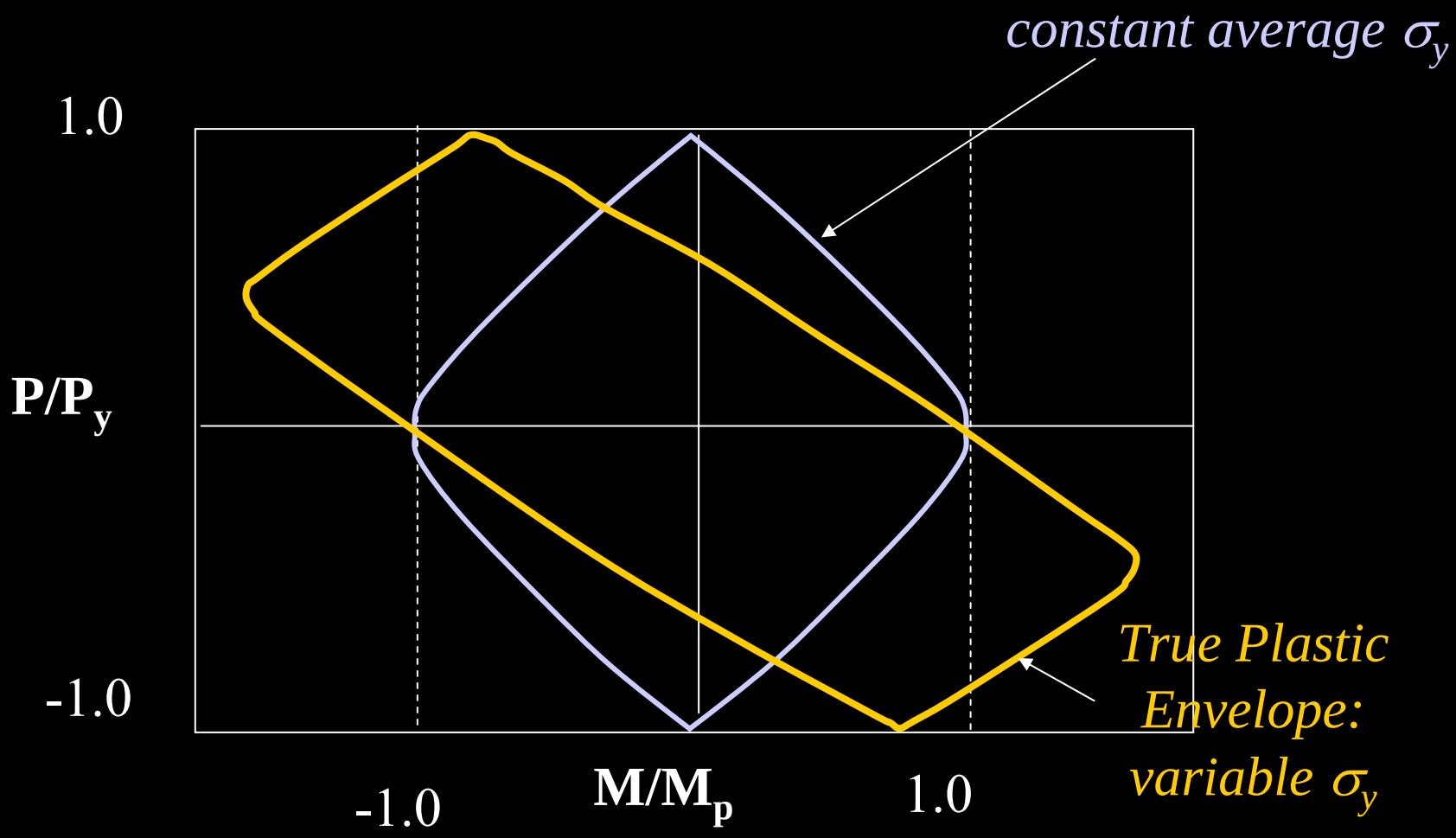
WTC
NYC 2001



Windsor Tower
Madrid 2005



Predicting the Capacity



Predicting the Capacity