"PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns"

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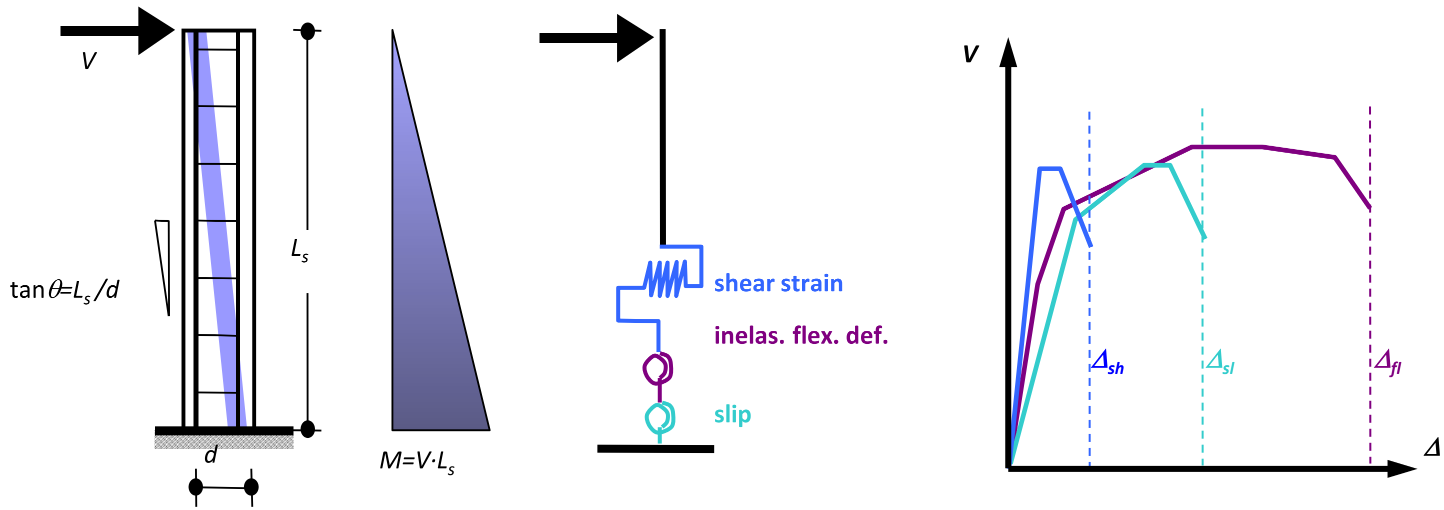
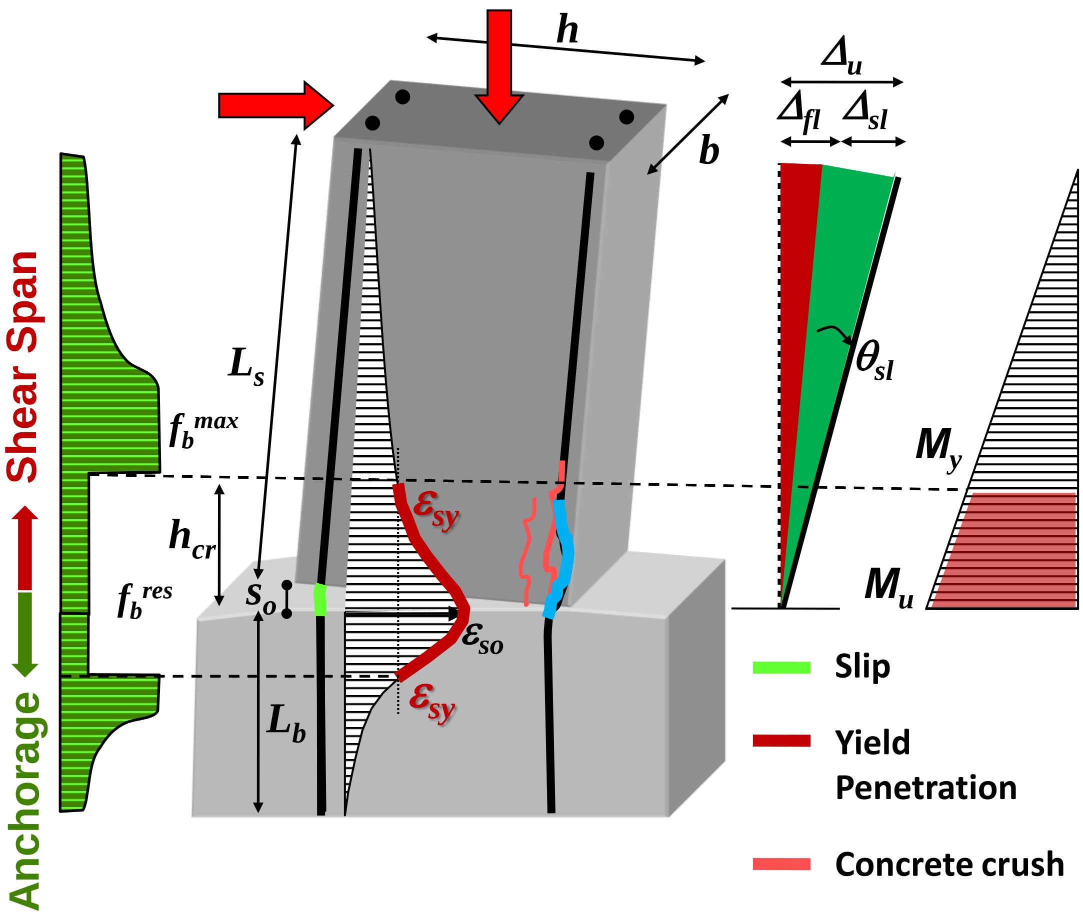
Sendai, Japan

Research Goal: Seismic Simulation of RC Columns for all possible failure modes



- **The static relationship between shear force and flexural moment** in the span of the cantilever is **identical to that occurring over the length of the actual frame member** extending from the point of contraflexure (zero moment) to the fixed end support.
- **Deformations are owing to flexure, shear action, and pull-out slip** of the reinforcement from the support or lap splice. These mechanisms of behaviour are considered to **act in series**, therefore **their effects are considered additive**, as implied by the mechanical analogue of above Figure, used in computer simulations of inelastic RC Members.

Column Rotation Due to Pull-Out of Tensile Reinforcement:



- The development of yielding flexural moment in plastic hinges of frame elements is synonymous with **yielding strain penetration in shear span and anchorage.**

- Yield penetration destroys interfacial bond between bar and concrete:

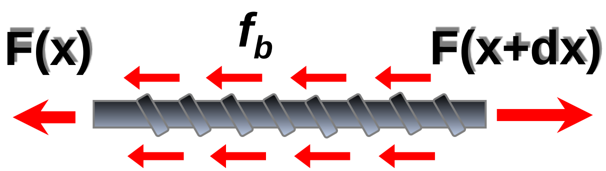
➔ **Reduction of column plastic rotation due to flexure** (reduction of strain development capacity of the reinforcement)

➔ **Increase of bar pull-out contribution in the total column rotation.**

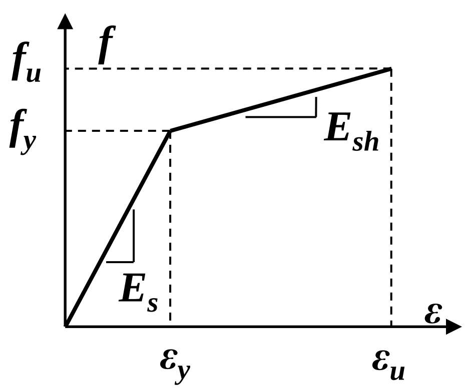
Reinforcement to Concrete Bond ⇔ Tension - Stiffening.

The basic equations that describe force transfer lengthwise from a bar to the surrounding concrete through bond:

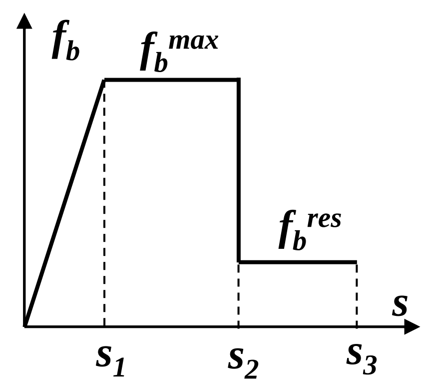
- **force equilibrium applied to an elementary bar segment of length *dx***
- **Kinematic relationship: The slip of the bar as the difference of the developed strains by the two materials (Tassios and Yannopoulos 1981, Filippou et. al. 1983):**



$$\frac{df}{dx} = -\frac{4}{D_b} f_b \quad + \quad \frac{ds}{dx} = -(\varepsilon - \varepsilon_c) \cong -\varepsilon$$



Steel reinforcing bar



local bond - slip

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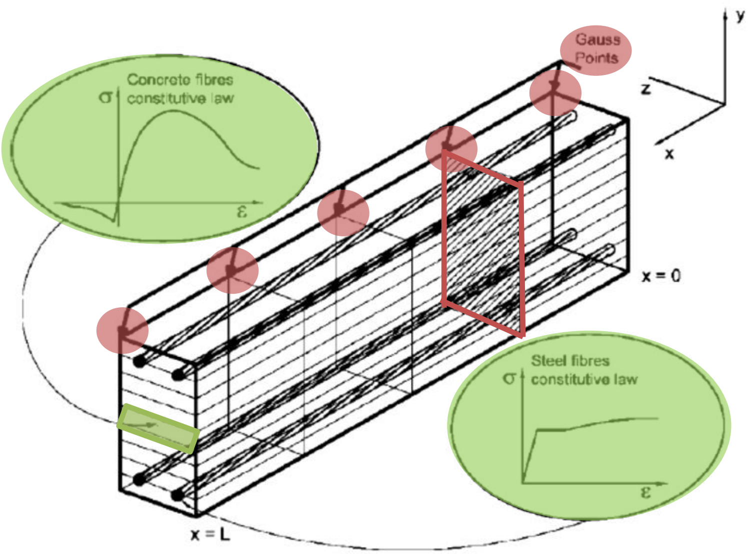
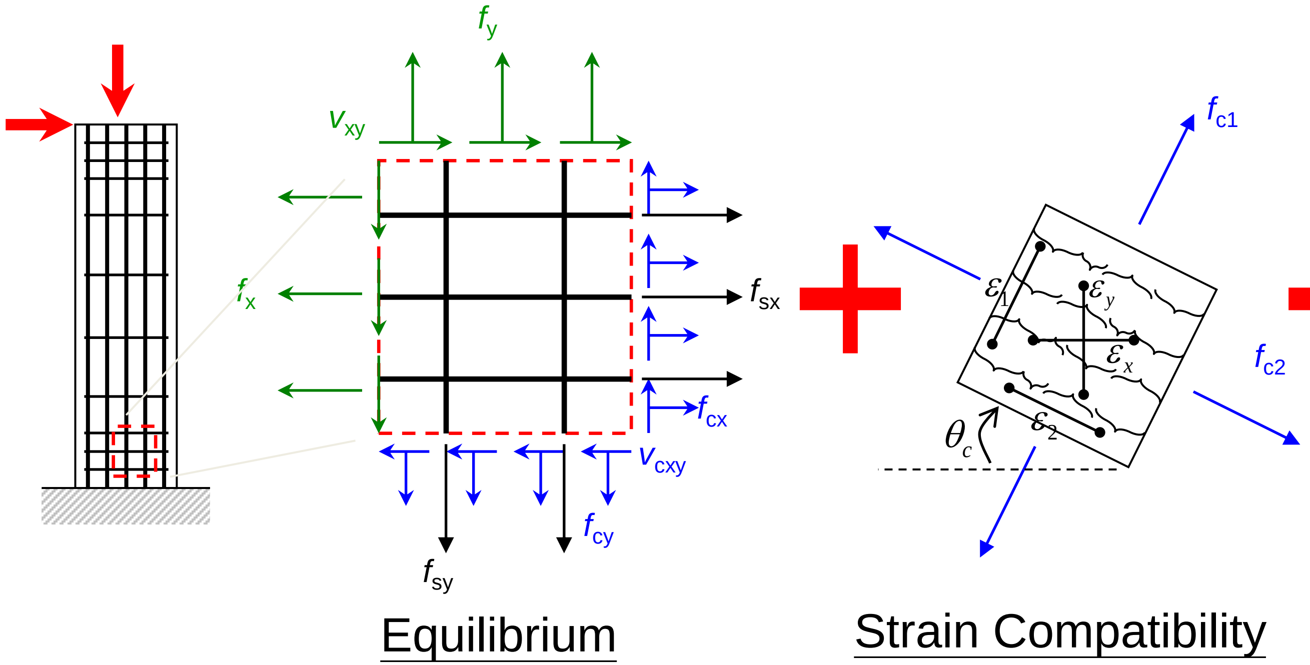
Nonlinear Analysis with fiber beam-column elements :



- The beam – column element is discretized in integration points – sections.
- It is based in the discretization of the sections of the element in layers/fibers where through appropriate constitutive laws the forces of the section are determined.
- These are distributed inelasticity models that can be force- or displacement -based.
- In order to evaluate flexural response those elements are based on Euler – Bernouli beam theory but to evaluate shear- flexure interaction they are based on Timoshenko beam theory.

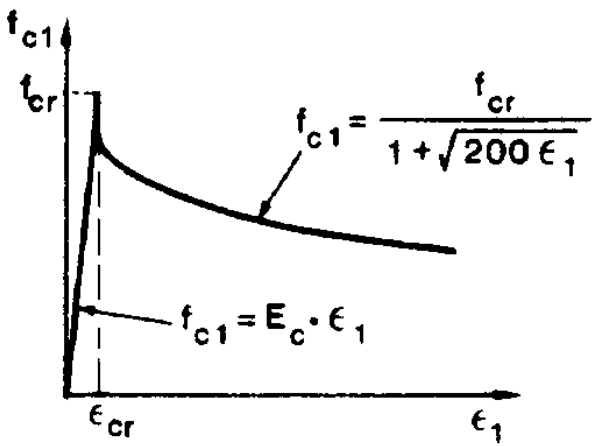
Concrete law – Modified Compression Field Theory (MCFT – Vecchio & Collins 1986):

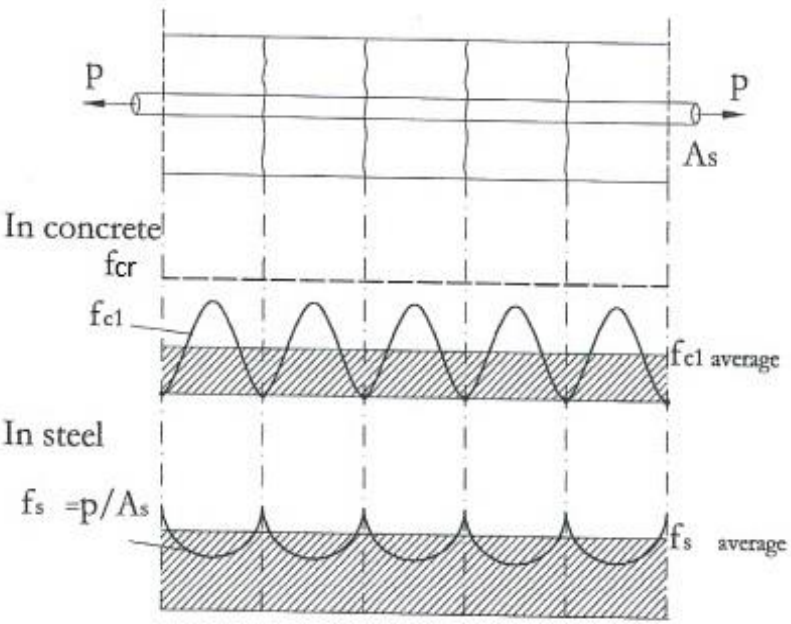


$$
\begin{cases}
f_{c1} = \dfrac{f_{cr}}{1+\sqrt{200\varepsilon_1}} \\
f_{c2} = f_{c2,\max} \cdot \left[2\left(\dfrac{\varepsilon_2}{\varepsilon_c^{'}}\right) - \left(\dfrac{\varepsilon_2}{\varepsilon_c^{'}}\right)^2 \right] \\
f_{sx} = E_s \cdot \varepsilon_x \le f_{y,x} \\
f_{sy} = E_s \cdot \varepsilon_y \le f_{y,y}
\end{cases}
$$

Constitutive Law

Bond –Modified Compression Field Theory (MCFT – Vecchio & Collins 1986):

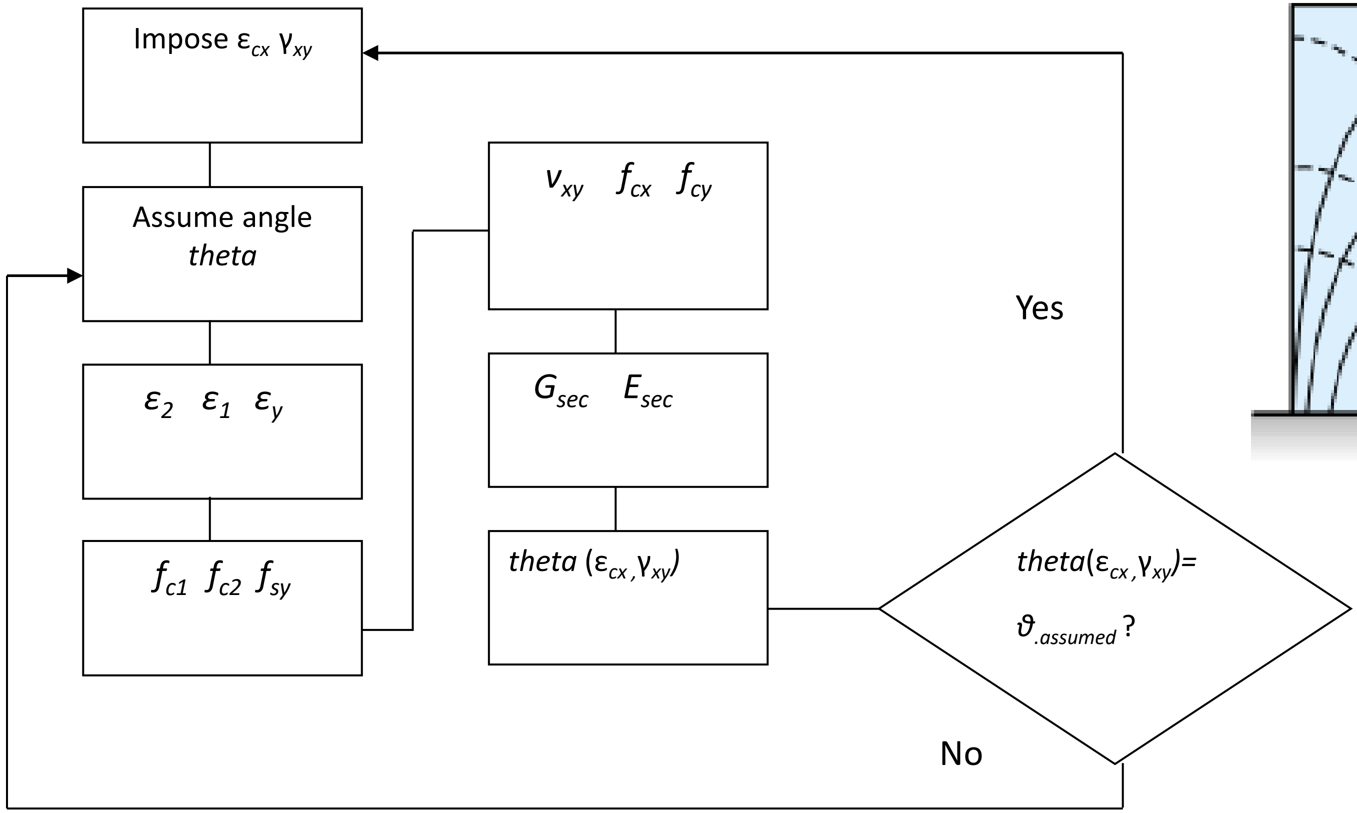


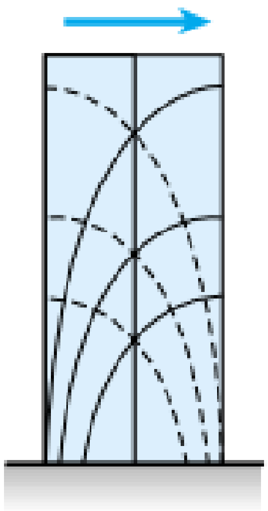


•Due to the influence of bond, tensile stresses can develop in the concrete between cracks. To model this phenomenon, which is referred to in the literature as "tension stiffening", the concrete tensile stress is assumed to decay from the tensile strength as principal strain increases.

• It is assumed that the average tensile concrete stress, $f_{c1\ average}$ is transmitted across cracks. This implies that stress in the reinforcement increases in proximity of cracks but it is limited by yielding value.

Fiber Stresses – Iterative procedure based on MCFT:





Root search based on numerical method Regula Falsi

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Section State Determination:

Section Forces

$$f_s(x) = \int B_s^T(y) \cdot \sigma(x,y) dA$$

$$f_s(x) = \begin{Bmatrix} N \\ M \\ V \end{Bmatrix} \qquad \sigma(x,y) = \begin{Bmatrix} \sigma_x \\ \tau_{xy} \end{Bmatrix}$$

$$B_s(y) = \begin{bmatrix} 1 & -y & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Section Stiffness

$$k_s = \begin{bmatrix} \frac{\partial f_{s1}}{\partial e_1} & \frac{\partial f_{s1}}{\partial e_2} & \frac{\partial f_{s1}}{\partial e_3} \\ \frac{\partial f_{s2}}{\partial e_1} & \frac{\partial f_{s2}}{\partial e_2} & \frac{\partial f_{s2}}{\partial e_3} \\ \frac{\partial f_{s3}}{\partial e_1} & \frac{\partial f_{s3}}{\partial e_2} & \frac{\partial f_{s3}}{\partial e_3} \end{bmatrix}$$

$$\sigma(x,y) = \begin{Bmatrix} \sigma_x \\ \tau_{xy} \end{Bmatrix}$$

$$\varepsilon(x,y) = \begin{Bmatrix} \varepsilon_x \\ \gamma_{xy} \end{Bmatrix}$$

$$\frac{d\sigma(x,y)}{d\varepsilon(x,y)} = \begin{bmatrix} E_m & 0 \\ 0 & G_m \end{bmatrix}$$

$$k_s = \frac{\partial f_s}{\partial e} = \int B_s^T(y) \cdot \frac{d\sigma(x,y)}{\partial \varepsilon(x,y)} \cdot \frac{\partial \varepsilon(x,y)}{\partial e} dA = \int B_s^T(y) \cdot \frac{d\sigma(x,y)}{d\varepsilon(x,y)} B_s(y) dA$$

$$N = \int \sigma_x dA = \text{Axial Force}$$

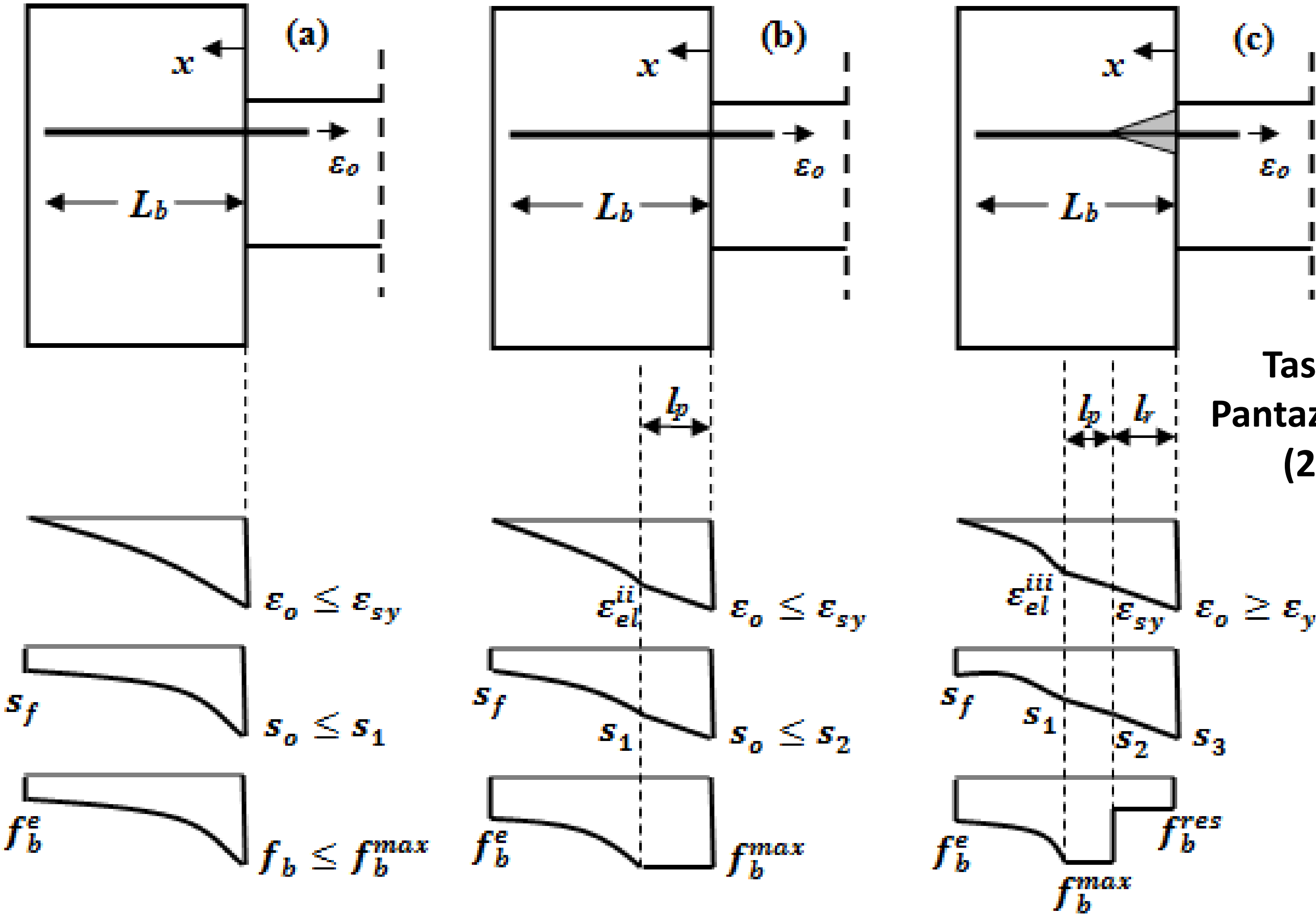
$$V = \int \tau_{xy} dA = \text{Shear Force}$$

$$M = -\int y\sigma_x dA = \text{Moment}$$

$$N = \sum_{i=1}^{n.layer} \sigma_x^i A^i \text{ and } V = \sum_{i=1}^{n.layer} \tau_{xy}^i A_s^i \text{ and } M = -\sum_{i=1}^{n.layer} \sigma_x^i y^i A^i$$

Note: Parabolic Shear Strain Distribution along Section height with maximum value (***γ_{xy}***) at the neutral axis.

Strain, Slip and Bond Distributions in the Anchorage Length:



Tastani & Pantazopoulou (2013)

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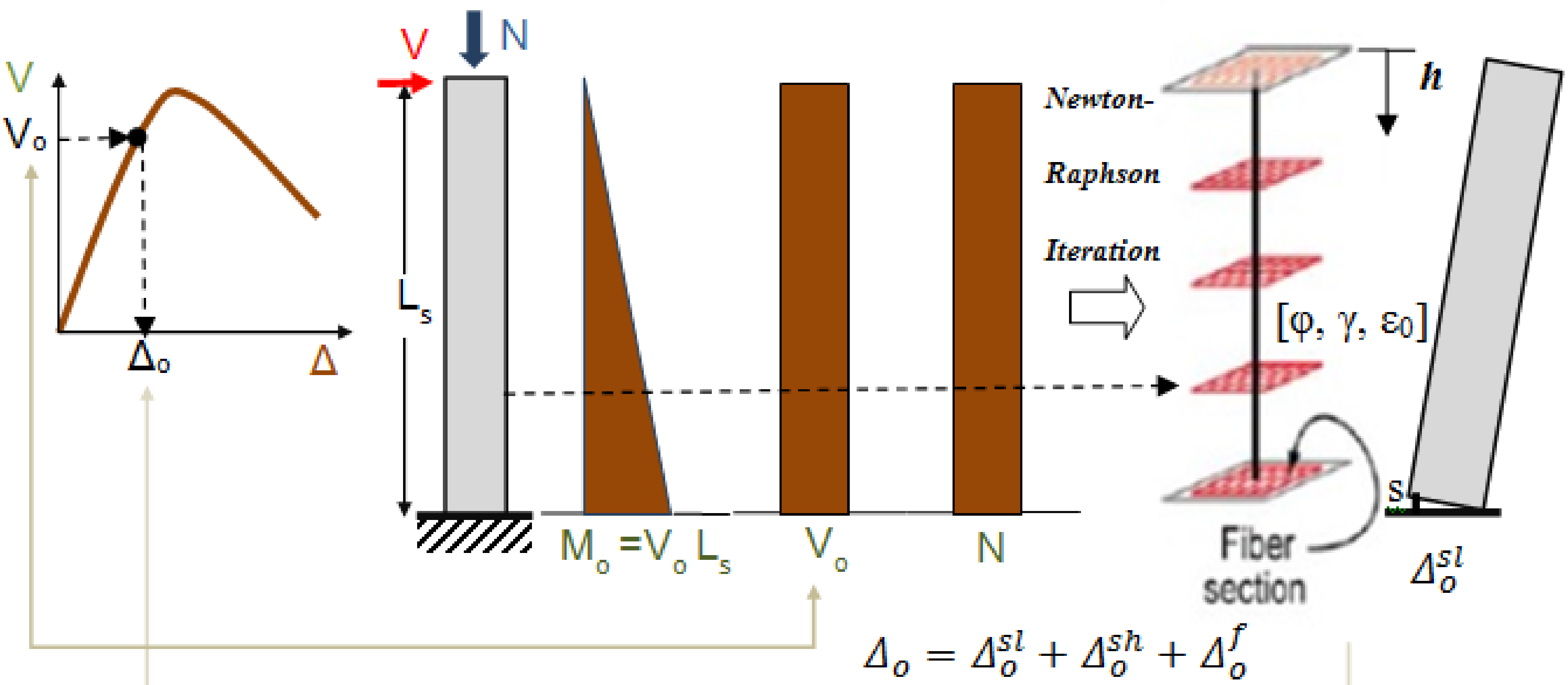
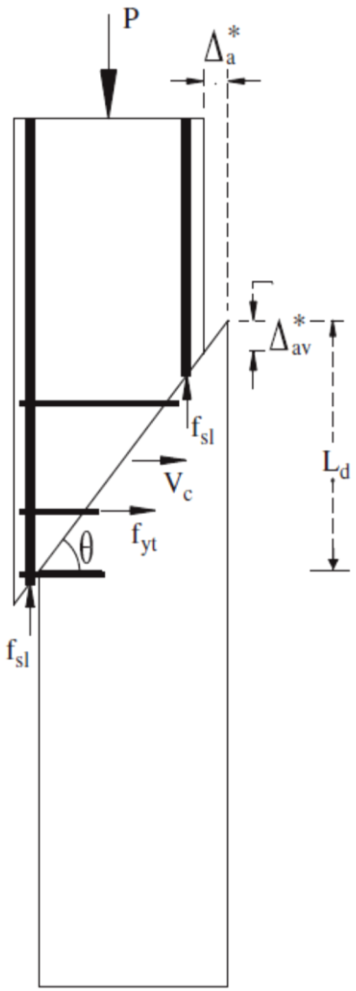
Capacity Curve of Shear-Critical RC Column - Phaethon:



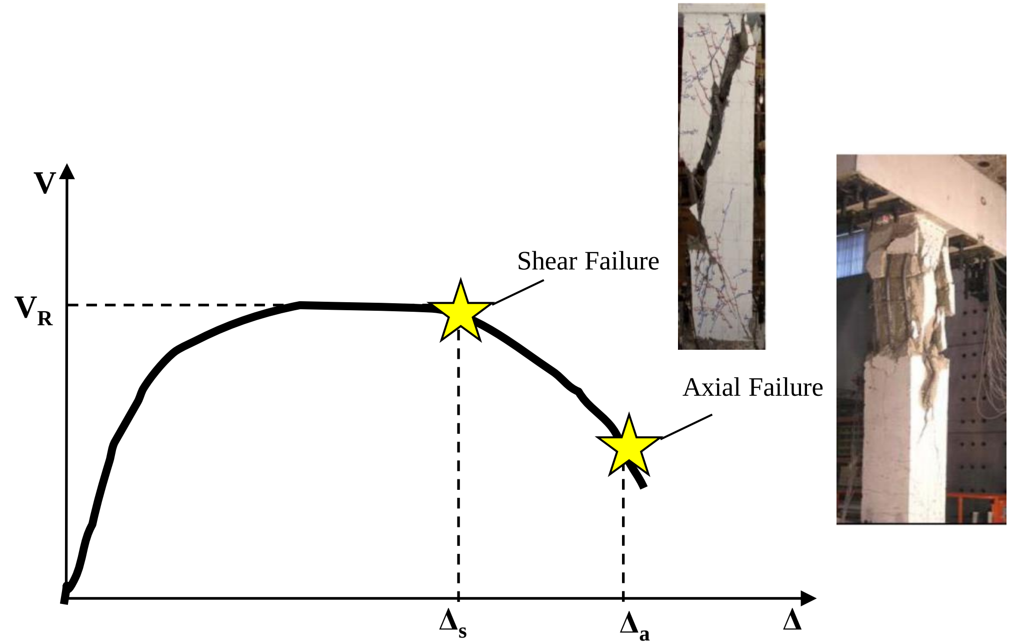
$$\Delta_o^{sh} = \int_0^{L_s} \gamma(h) \cdot dh \qquad \Delta_o^{f} = \int_0^{L_s} \varphi(h) \cdot h \cdot dh \qquad \Delta_o^{sl} = \frac{s}{(d - 0.4c_x)} \cdot L_s$$

Drift at Axial Failure (Elwood and Moehle, 2005):

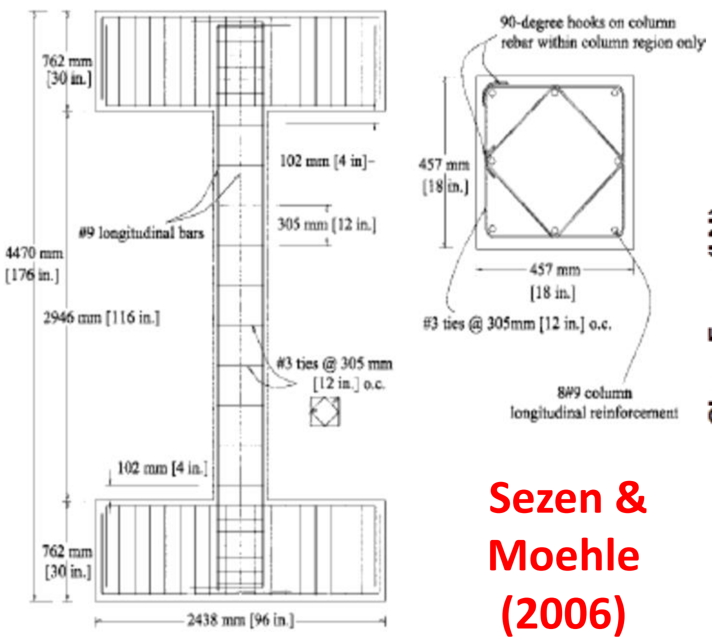


- **Elwood and Moehle (2005)**

$$\left(\frac{\Delta}{L}\right)_{axial} = \frac{4}{100}\frac{1+(\tan 65^o)^2}{\left[\tan 65^o + P\cdot\left(\frac{s}{A_{st}\cdot f_{yt}\cdot d_c.\tan 65^o}\right)\right]}$$

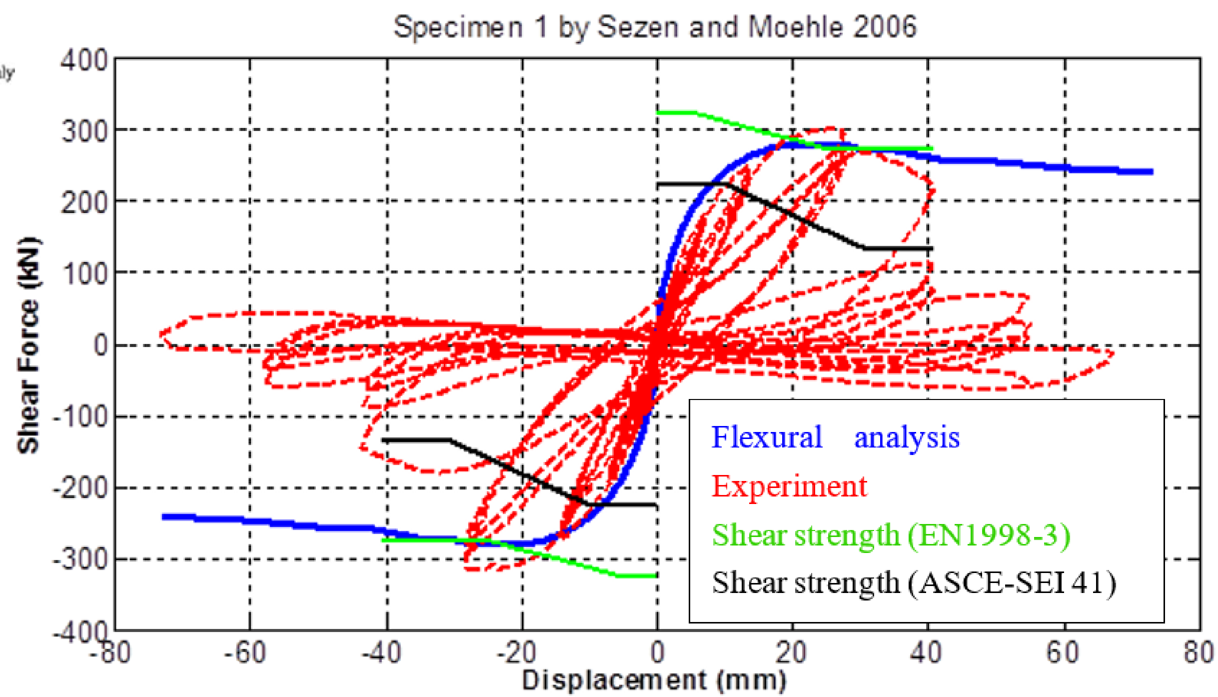


Correlation with Experimental Results - Specimen 1 (Sezen & Moehle, 2006):

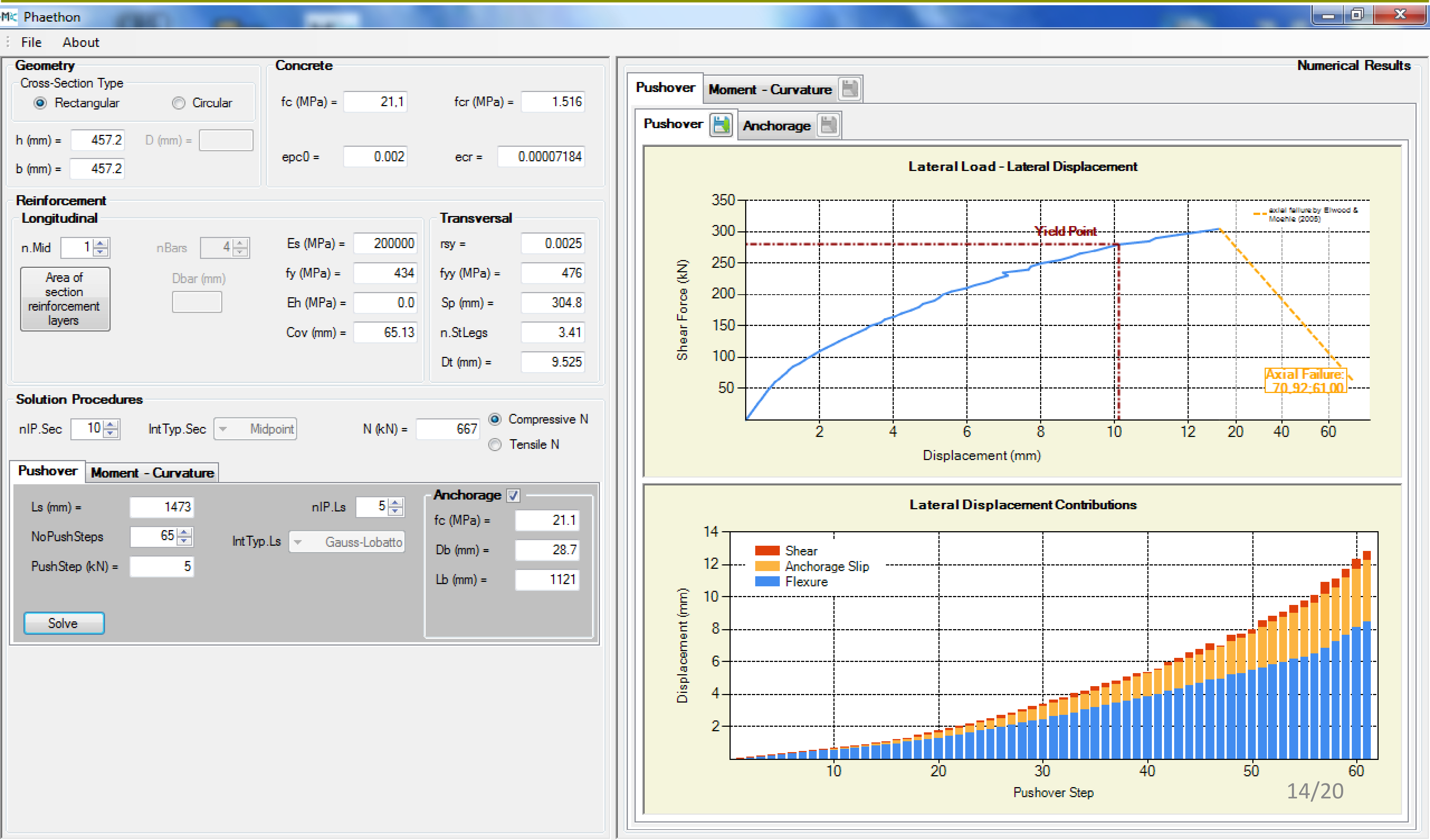


Sezen & Moehle (2006)

Cantilever Column



Correlation with Experimental Results – Phaethon - Specimen 1:



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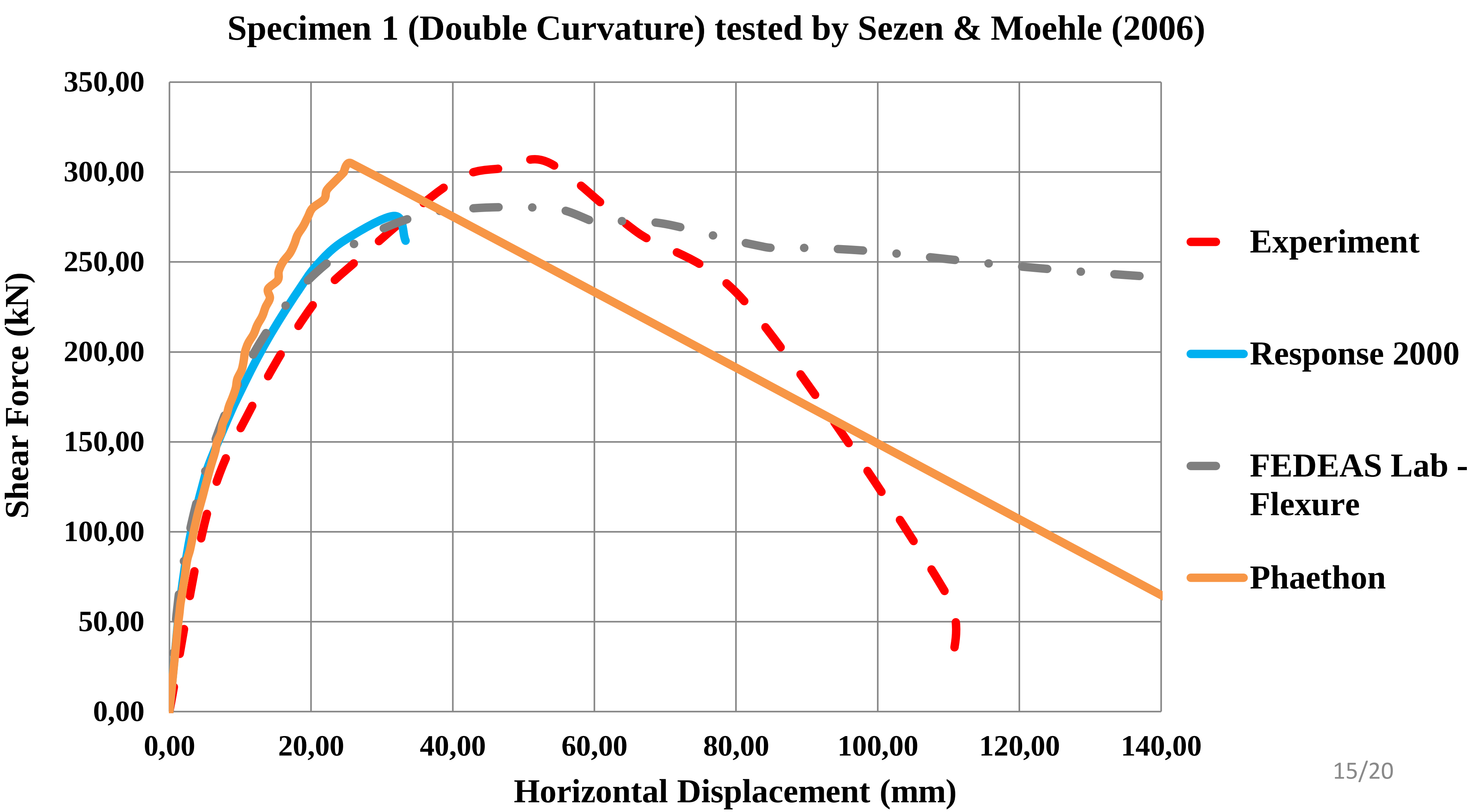
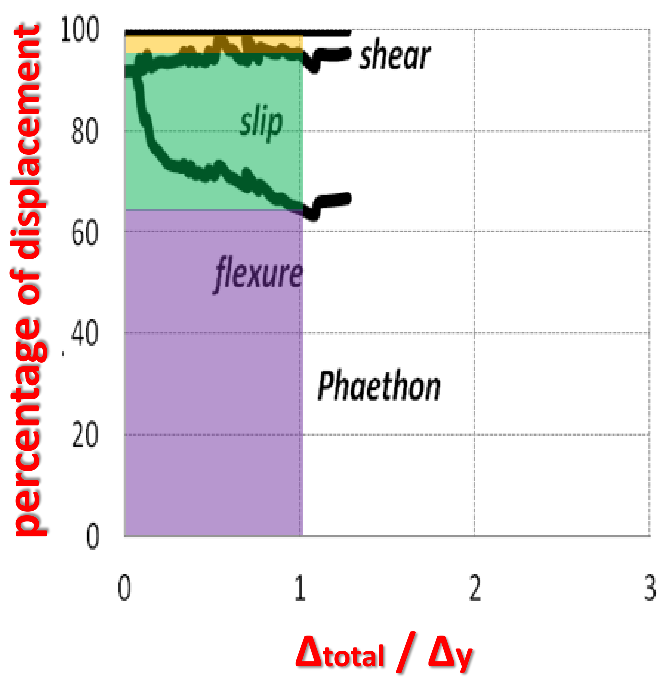
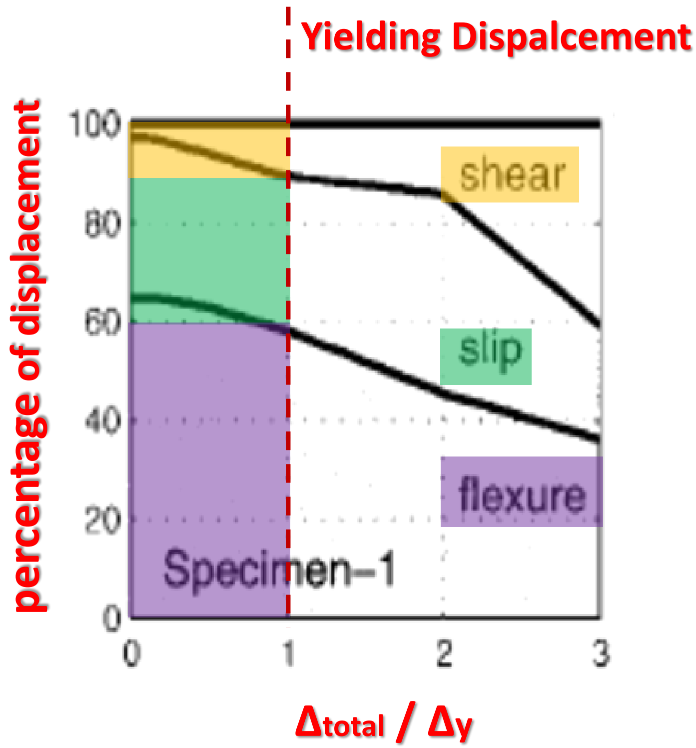
Correation with Experimental Results – Phaethon - Specimen 1:



Correlation with Experimental Results- Phaethon - Specimen 1:

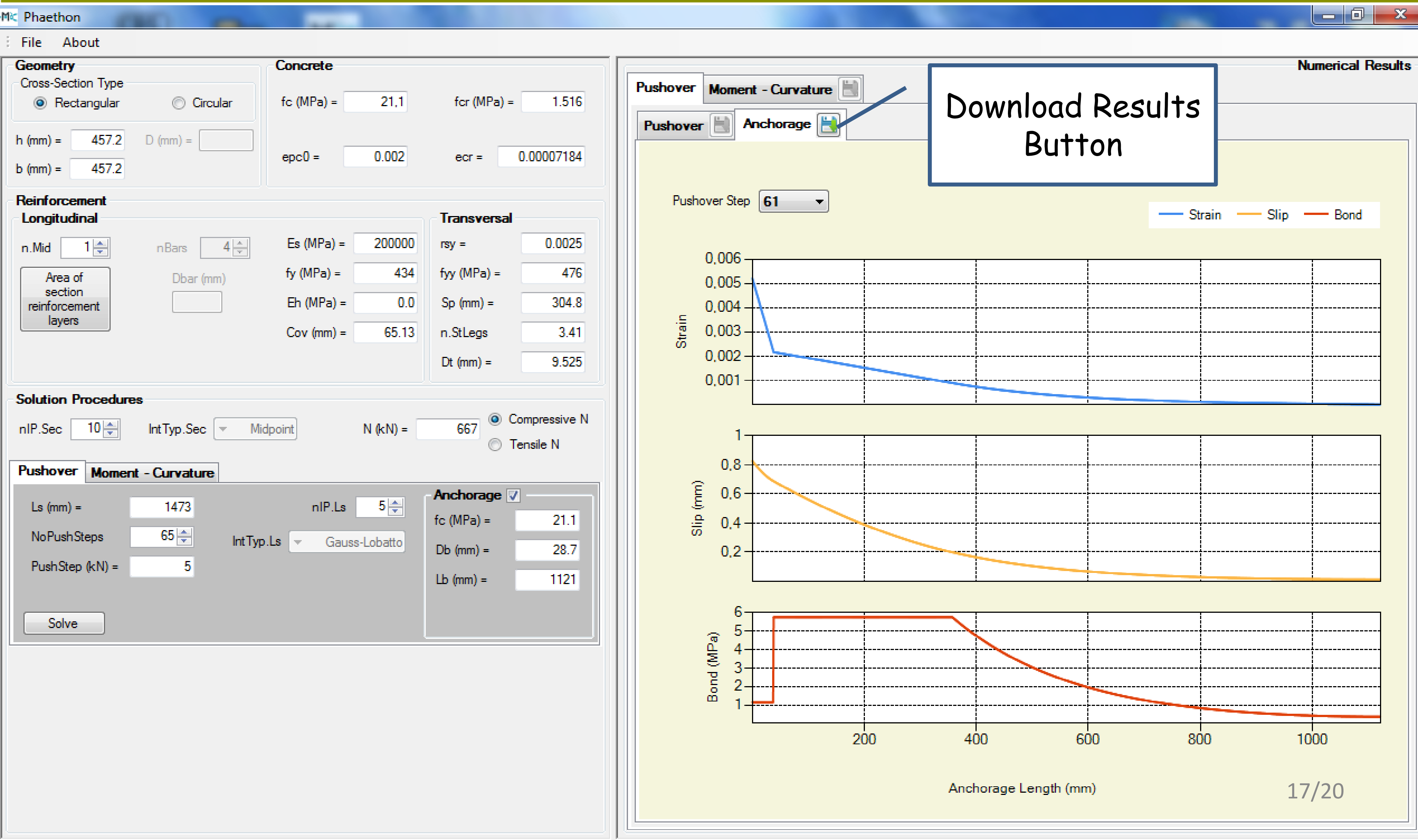


Numerical Results



Experimental Results

Phaethon – Anchorage – Specimen 1 (Sezen & Moehle, 2006):



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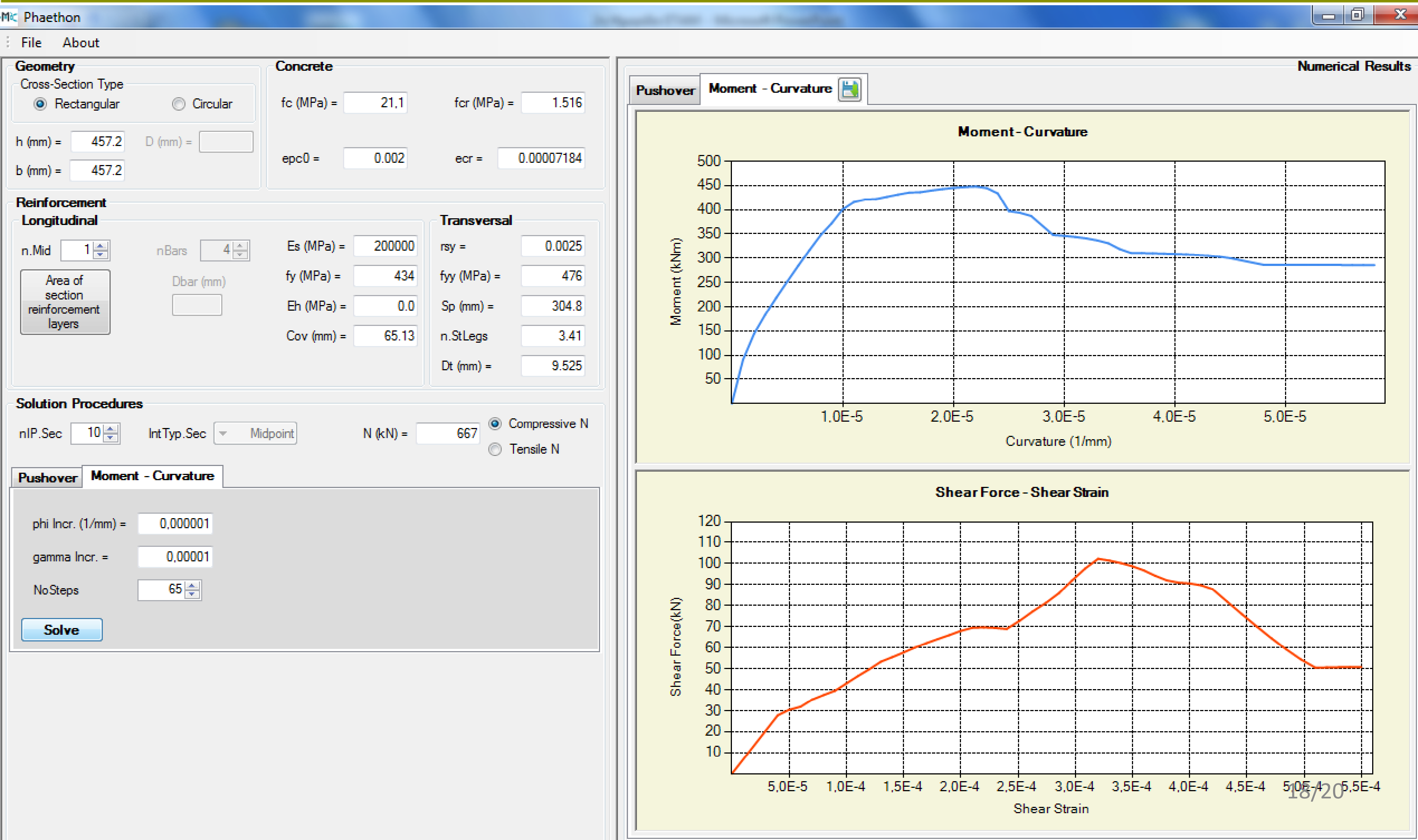
Sectional Analysis: Moment – Curvature & Shear Force – Shear Strain (Specimen 1)



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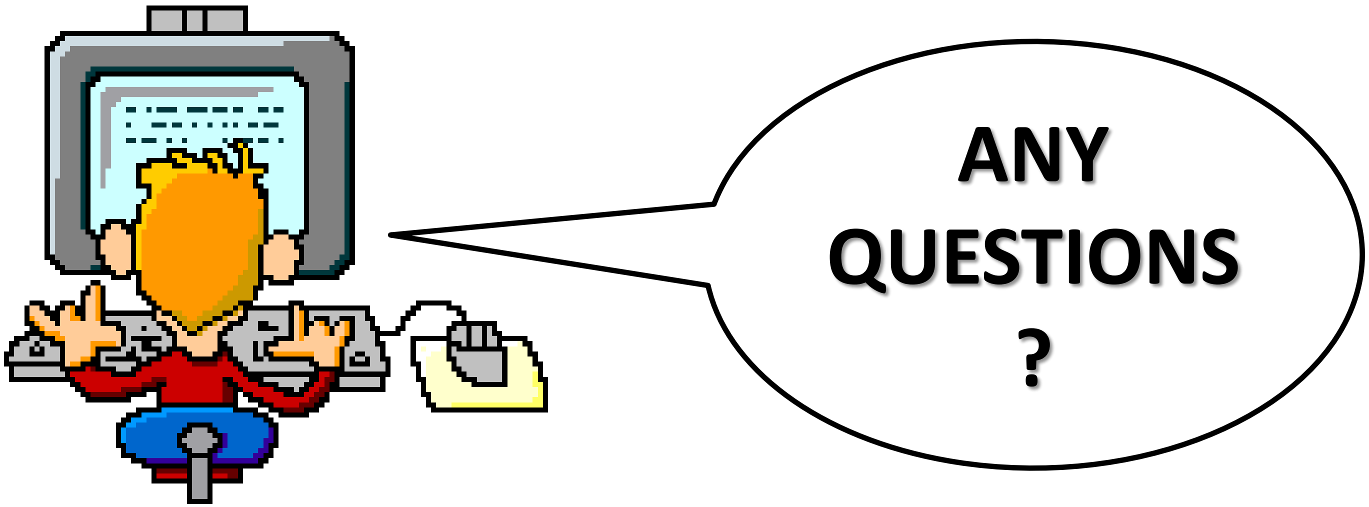
Conclusions:

- A **Windows-based software** was developed for fiber-based, distributed nonlinearity analysis of prismatic frame elements undergoing lateral sway such as would occur during an earthquake.
- The formulation was extended to fiber-type analysis with distributed nonlinearity also considering the **exact Timoshenko beam theory** whereby shear deformations are explicitly considered in the state determination.
- **Moment, shear and axial load interaction** were considered in calculating the resistance curve for a number of different column cases that underwent flexure shear or purely shear dominated mode of failure, and the **distinct contributions of the many contributing sources of column deformation (curvature, shear angle, axial elongation, pullout rotation)** were illustrated through the developed algorithm.
- **Good correlation with experimental results from the literature.**

THANK YOU FOR YOUR ATTENTION!



ACKNOWLEDGEMENTS

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