"Seismic Assessment and Retrofit of Reinforced Concrete Columns using OpenSees"

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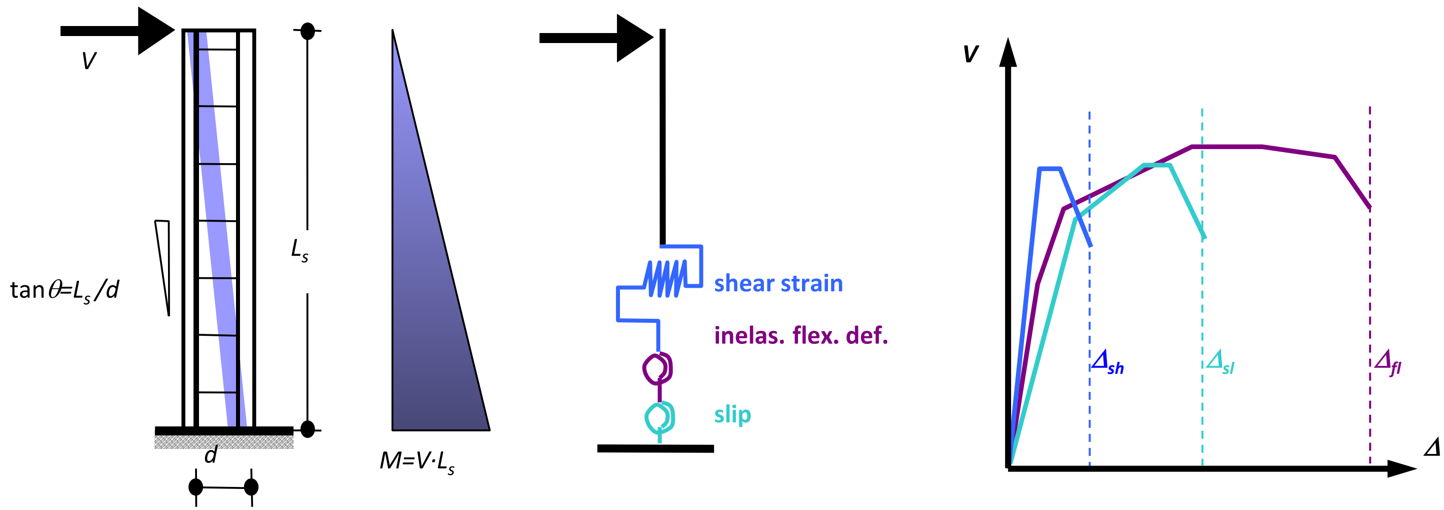
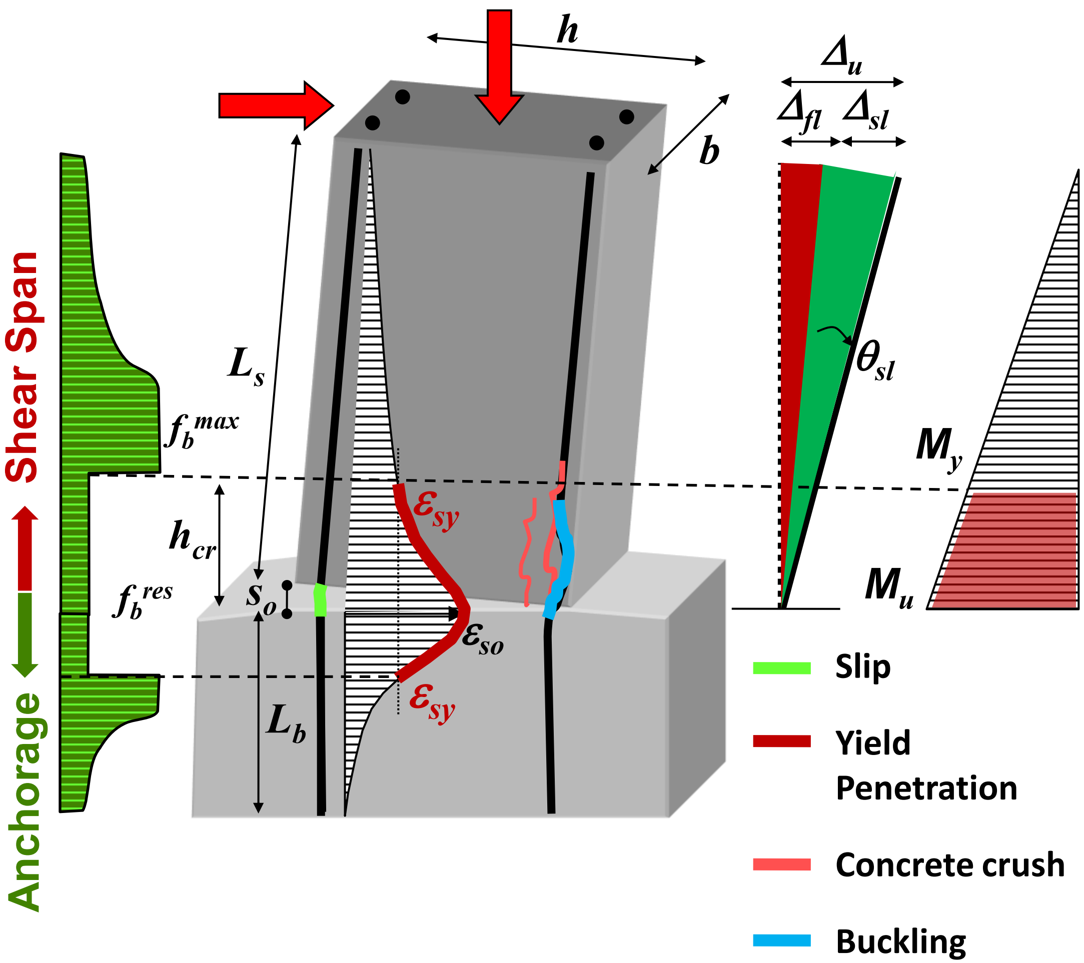
Research Goal: Seismic Simulation of RC Columns for all possible failure modes



- **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.**

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Pull-Out Slip of the Reinforcement and Plastic Hinge Length:



- 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:

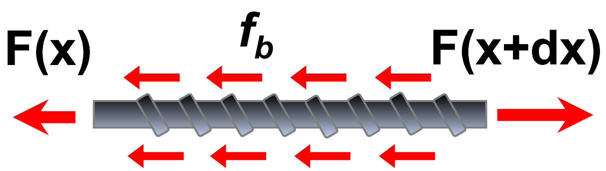
➔ Reduction of column plastic rotation due to flexure (reduction of strain development capacity of the reinforcement)

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

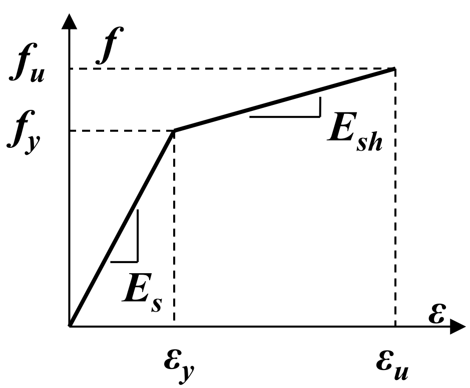
Reinforcement to Concrete Bond ⇔ Tension - Stiffening.

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

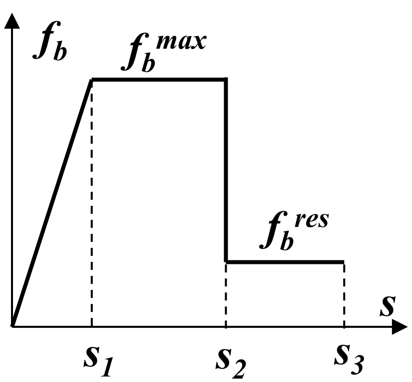
- **force equilibrium applied to an elementary bar segment of length *dx***
- **Kinematic relationship: The slip of the bar as the difference of the developed strains by the two materials (Tassios and Yannopoulos 1981, Filippou et. al. 1983):**



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



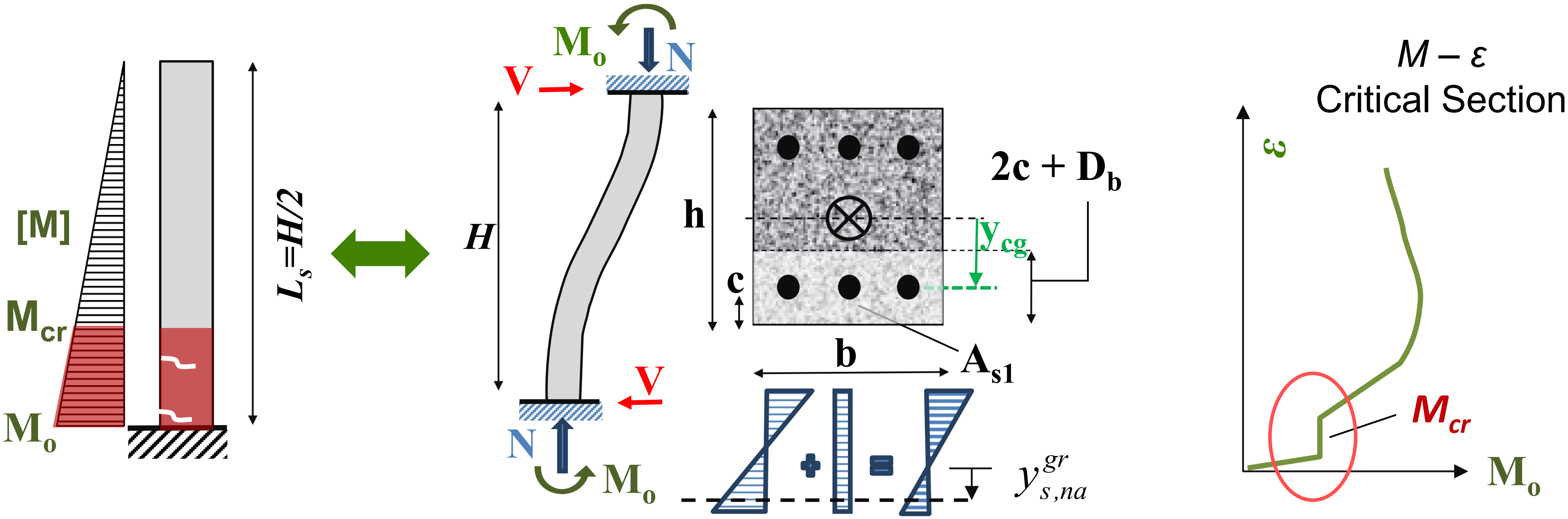
Steel reinforcing bar



local bond - slip

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

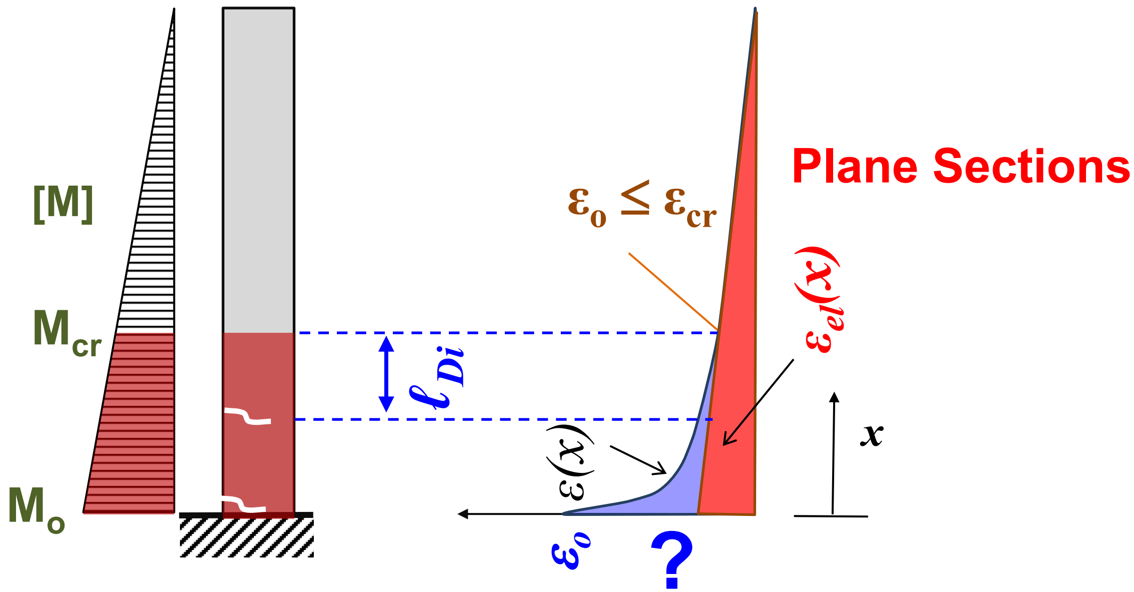
Tension – Stiffening Model: (1/3)



- The moment-shear relationship M - V in the span of a cantilever RC column under horizontal loading is identical to that occurring over the length of the actual frame member (H) extending from the inflection point at mid-height to the fixed end support (L_s=*H/2*).
- Classic Theory of Flexure: a RC element is considered cracked when $M>M_{cr}$
- Discrete Cracks
- 1st crack at the support of the column: transistion from uncracked to cracked state➔ for imperceptible moment change to M_{cr} ➔ jump in strains

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

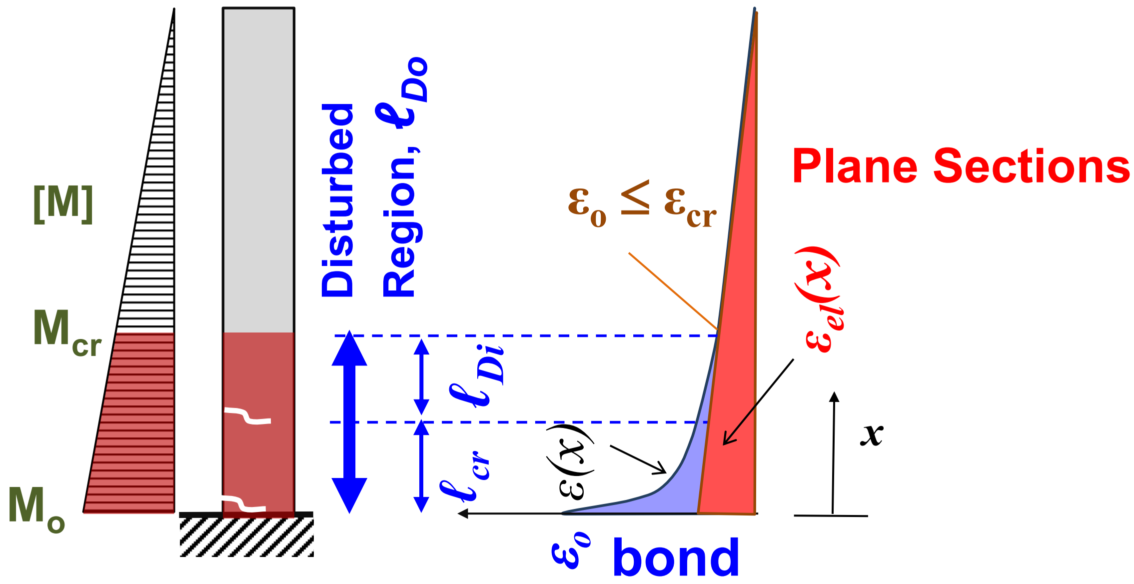
Tension – Stiffening Model: (2/3)



- In the interval between cracks- where M >M_{cr} – the real bar strains deviate from those defined by flexural analysis:
  - Due to reinforcement slip, the degree of strain compatibility between steel and concrete in these locations is not well understood ("plane-sections remain plane" assumption)
  - Concrete CAN NOT be considered inert as would happen in a fully cracked tension zone.
  - It takes some distance ℓ_D from a crack location before the reinforcement may fully engage its concrete cover in tension ➔ to satisfy the conditions of strain compatibility

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Tension – Stiffening Model: (3/3)



- **The bar strain (ε) in the intervals between cracks (ℓ_{cr}) but also beyond the most distant crack (ℓ_{Di}) until the point of full compatibility of the two materials (<u>zero slip</u>):**

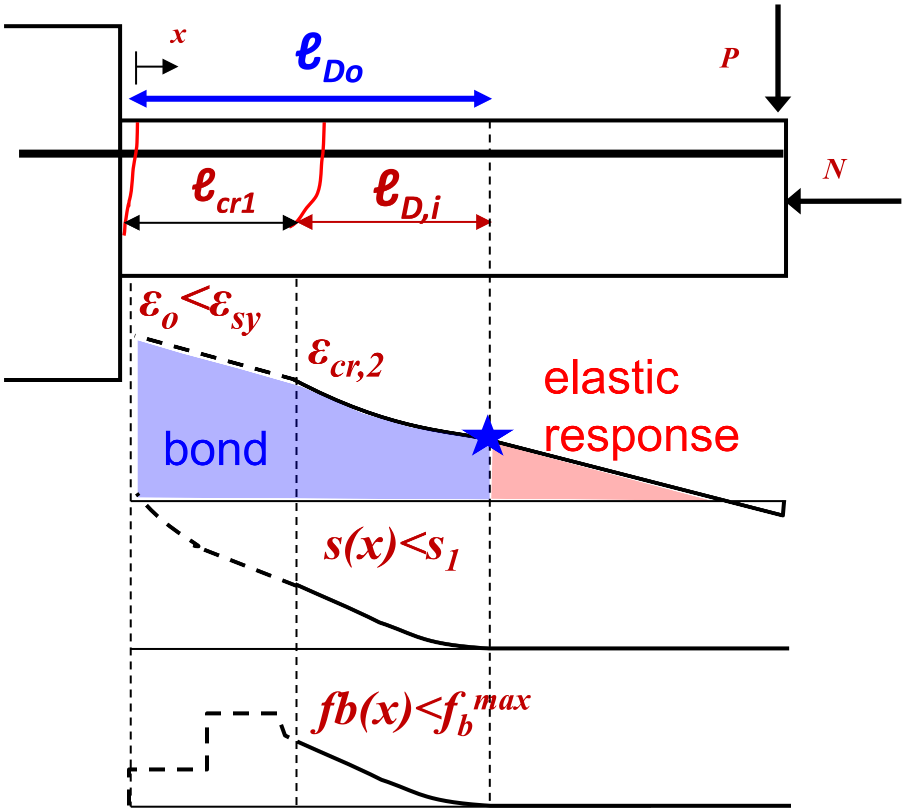
➔ **Solution of the differential equation of bond**

Disturbed Region (ℓ_{Do}) "plane-sections remain plane" assumption is not valid anymore

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Solution of differential equation of bond ➔ Distributions ε(x), s(x) & $f_b(x)$

Use of the solution of bond in the anchorage after yielding of the reinforcement (Tastani and Pantazopoulou 2013)



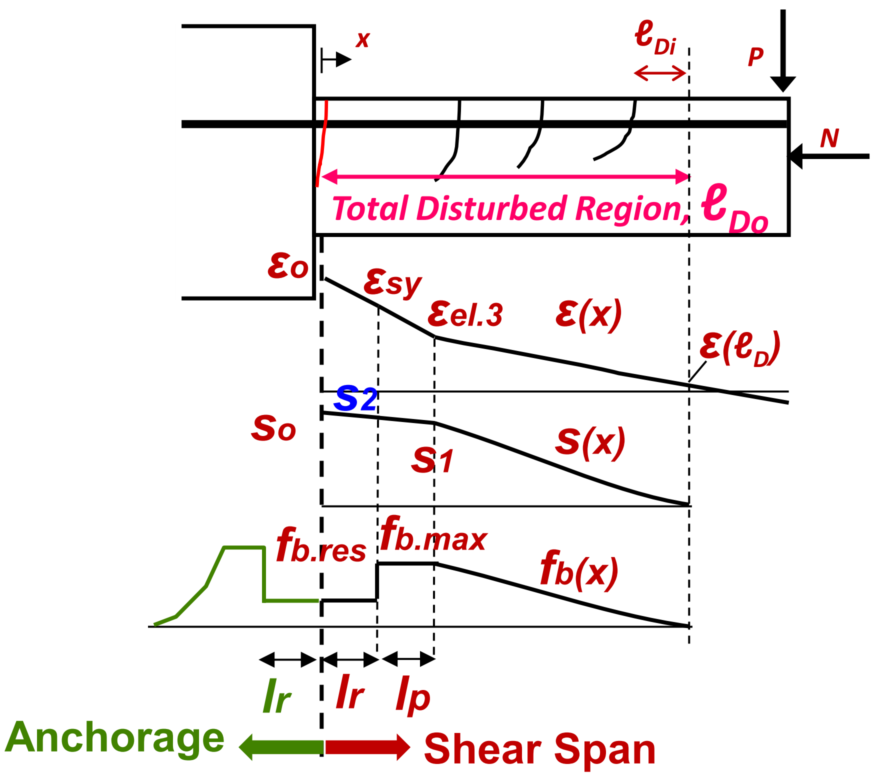
Boundary Conditions ($x = \ell_{Do}$)

- **Matching of the slopes of bar strain distributions (left due to bond and right due to elastic response)**
- **Matching of values (continuity).**
- **Compatibility of strains (zero slip).**

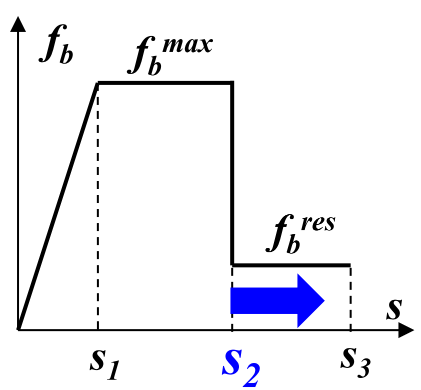
Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Plastic Hinge Length = yield penetration length

- **The plastic hinge length (ℓ_{pl}) is by definition the yield penetration length (l_r), measured from the critical section inside the shear span and inside the anchorage.**
  - **It is triggered when slip is above the limit value of s_2 in both regions**



- ℓ_{pl}: definition of the inelastic column rotation capacity



local bond slip

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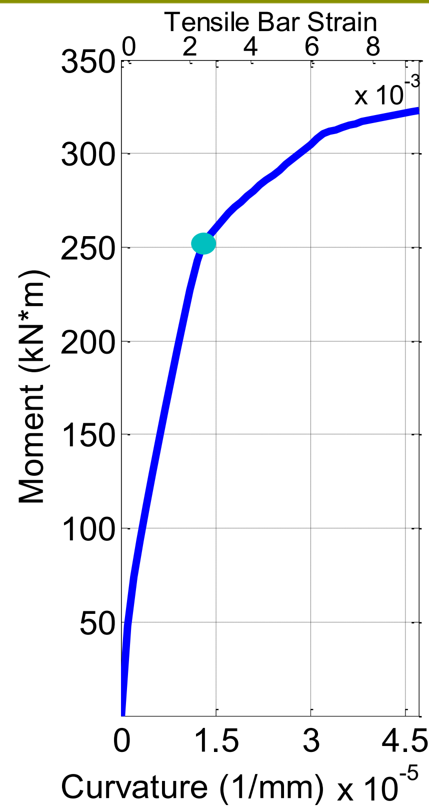
Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

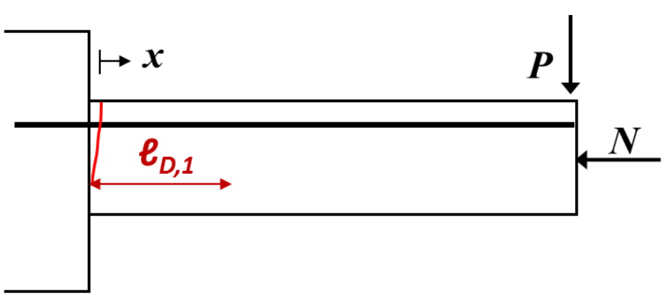
Algorithm: flexural cracks, distributions inside ℓ_D, ℓ_{pl} (1/4)

1. **Using standard section analysis with OpenSees obtain *M-ϕ* and *M-ε* diagrams (or better a unified diagram M-ϕ-ε) given *N* for the typical section of the reinforced concrete column studied.**

2. **Select value of bar strain after crack formation at the support .**

3. **Solve for the length of the disturbed region ℓ_{D1} emanating from the first crack**





$$C_1 = 0.5 \cdot e^{\omega \ell_D} \left[\varepsilon^o_{el} \cdot \left(1 - \frac{\ell_D}{L_s} + \frac{1}{\omega L_s} \right) - N/(E_c \cdot A) \right]$$

$$C_2 = 0.5 \cdot e^{-\omega \ell_D} \left[\varepsilon^o_{el} \cdot \left(1 - \frac{\ell_D}{L_s} - \frac{1}{\omega L_s} \right) - N/(E_c \cdot A) \right]$$

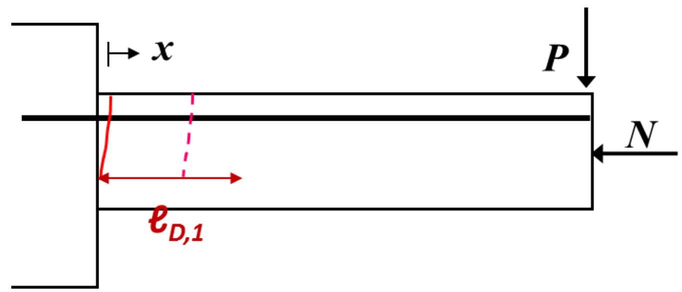
$$\varepsilon(0) = C_1 + C_2 = \varepsilon_o$$

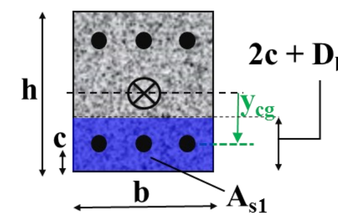
Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Algorithm: flexural cracks, distributions inside ℓ_D, ℓ_{pl} (2/4)

4. Formation of the 2nd crack

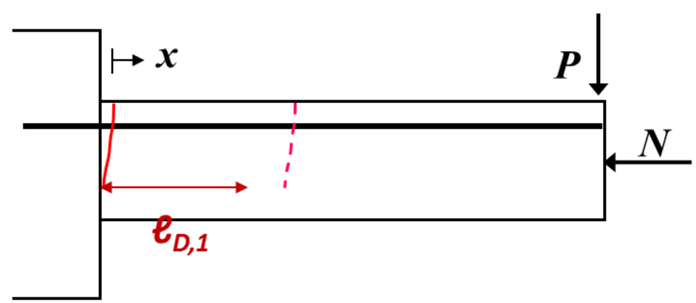
- **It is checked whether the next crack will be formed inside the disturbed region** (balance of forces due to bond and the effective concrete area in tension)





$$[(E_s \cdot A_{s1})/(f_{ct} \cdot A_{c,eff})] \cdot [\varepsilon_o - \varepsilon(x)] \geq 1$$

- **It is checked whether the next crack will be formed inside the undisturbed region.**



$$x = L_s \cdot [1 - \varepsilon_{c,cr}/\varepsilon^o_{sl} - N/(E_c A \varepsilon^o_{sl})]$$

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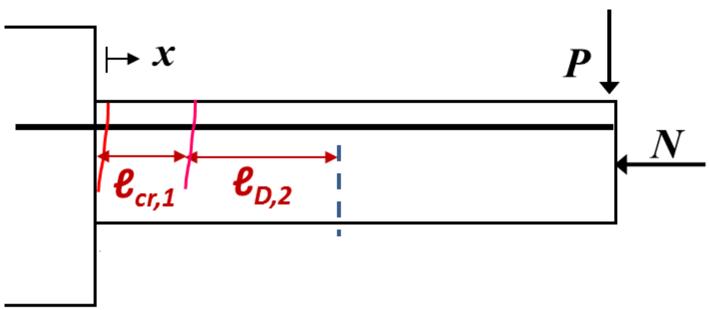
Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Algorithm: flexural cracks, distributions inside ℓ_D, ℓ_{pl} (3/4)

5. **After formation of the second crack:**
   - **The new disturbed region $\ell_{D,2}$ is defined.**
   - **The distributions inside the disturbed region ($\ell_{D,2}$) are computed**



6. **Repeat until stabilization of principal cracking ($\varepsilon_o < \varepsilon_y$)**

***Note:** condensation of cracking inside the $\ell_{cr,l}$ has not been taken into account*

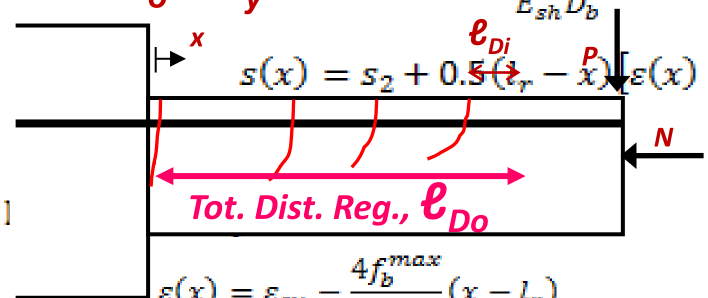
After stabilization of cracking:

Για $0 \le x \le l_r$:

$\varepsilon_o > \varepsilon_y$

$$\varepsilon(x) = \varepsilon_o - \frac{4f_b^{res}}{E_{sh}D_b}x$$

$$s(x) = s_2 + 0.5(l_r - x)[\varepsilon(x) + \varepsilon_{sy}]$$



Για l

$$\varepsilon(x) = \varepsilon_{sy} - \frac{4f_b^{max}}{E_s D_b}(x - l_r)$$

$$s(x) = s_1 + 0.5(l_r + l_p - x)[\varepsilon(x) + \varepsilon_{sl}^3]$$

The total disturbed region (ℓ_{Do}): Extending from the support to the end of the disturbed region of the last crack

$f_b(x) = f_b^{max}$

Για $l_r + l_p \le x \le l_D$:

$$\varepsilon(x) = C_1 \cdot e^{-\omega(x - l_p - l_r)} + C_2 \cdot e^{\omega(x - l_p - l_r)}$$

$$s(x) = \frac{1}{\omega}\left(C_1 \cdot e^{-\omega(x - l_p - l_r)} - C_2 \cdot e^{\omega(x - l_p - l_r)}\right) + C$$

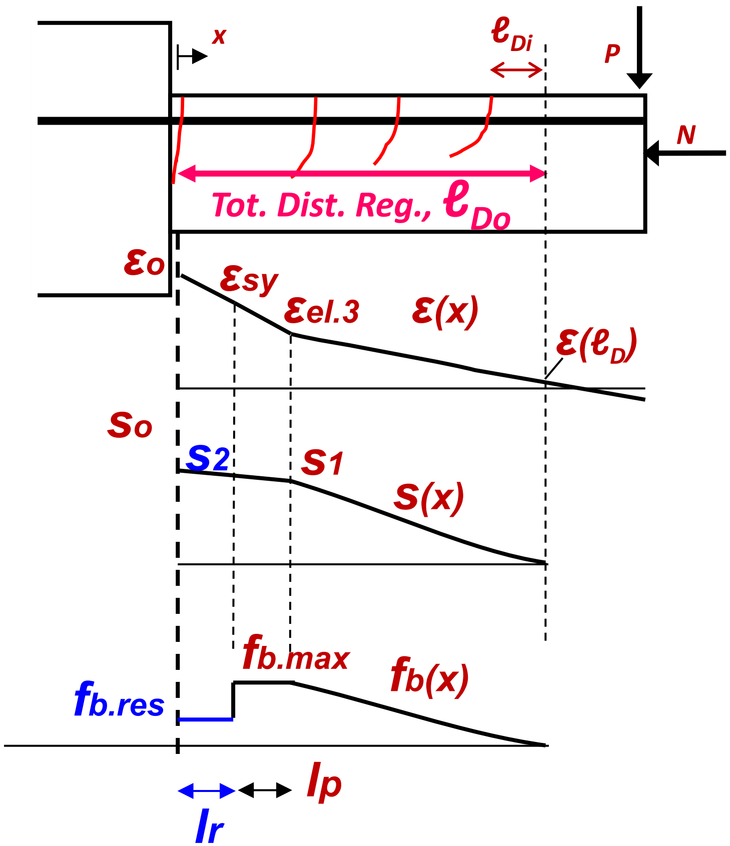
$$f_b(x) = \frac{f_b^{max}}{s_1} \cdot s(x)$$

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Algorithm: flexural cracks, distributions inside ℓ_D , ℓ_{pl} (4/4)

7. **Termination: when the bar strain at the support becomes equal to the strain corresponding to ultimate moment**
(Moment– Strain diagram)

- **Bar strain, slip and bond distribution inside ℓ_{Do}**
- **The plastic hinge length ℓ_{pl}: the yield penetration length of reinforcement l_r** (corresponds to the residual bond strength , f_b^{res}) **inside ℓ_{Do}**



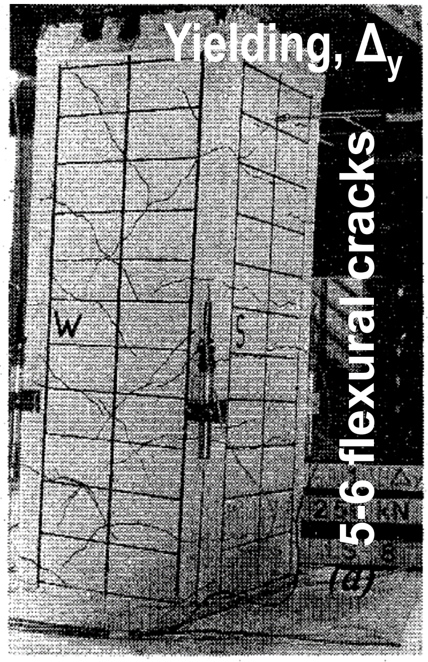
Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

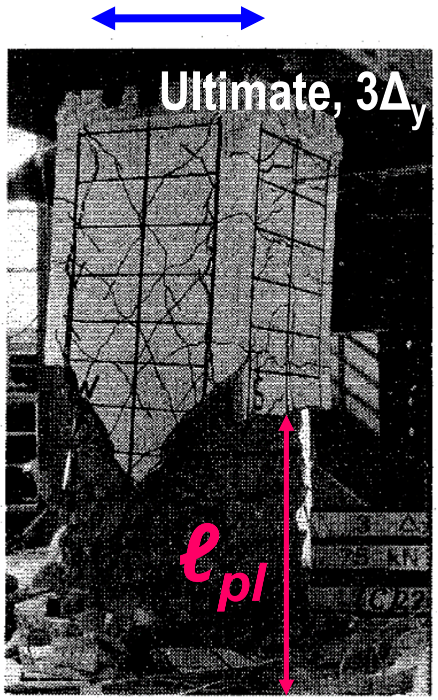
Numerical Results:

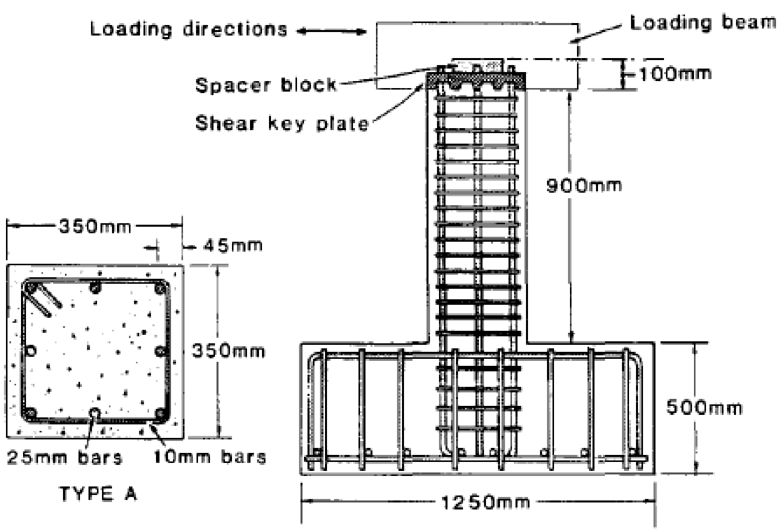
Saatcioglu and Ozcebe, 1989:

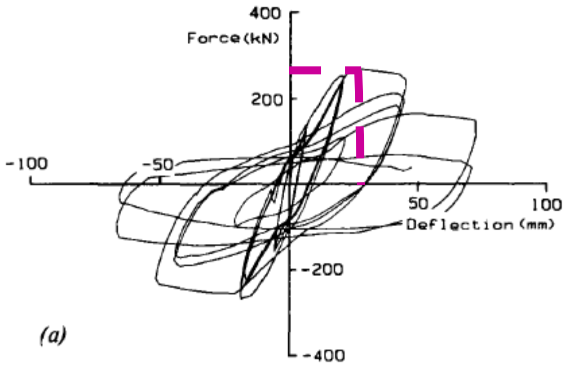
- Square column(350 mm)
- Shear span *Ls*=1000 mm
- Long. Reinf. 8Φ25, stirrups Φ10/75
- Concrete 34.8 MPa, Steel *fy*=430MPa

Loading Direction S-N





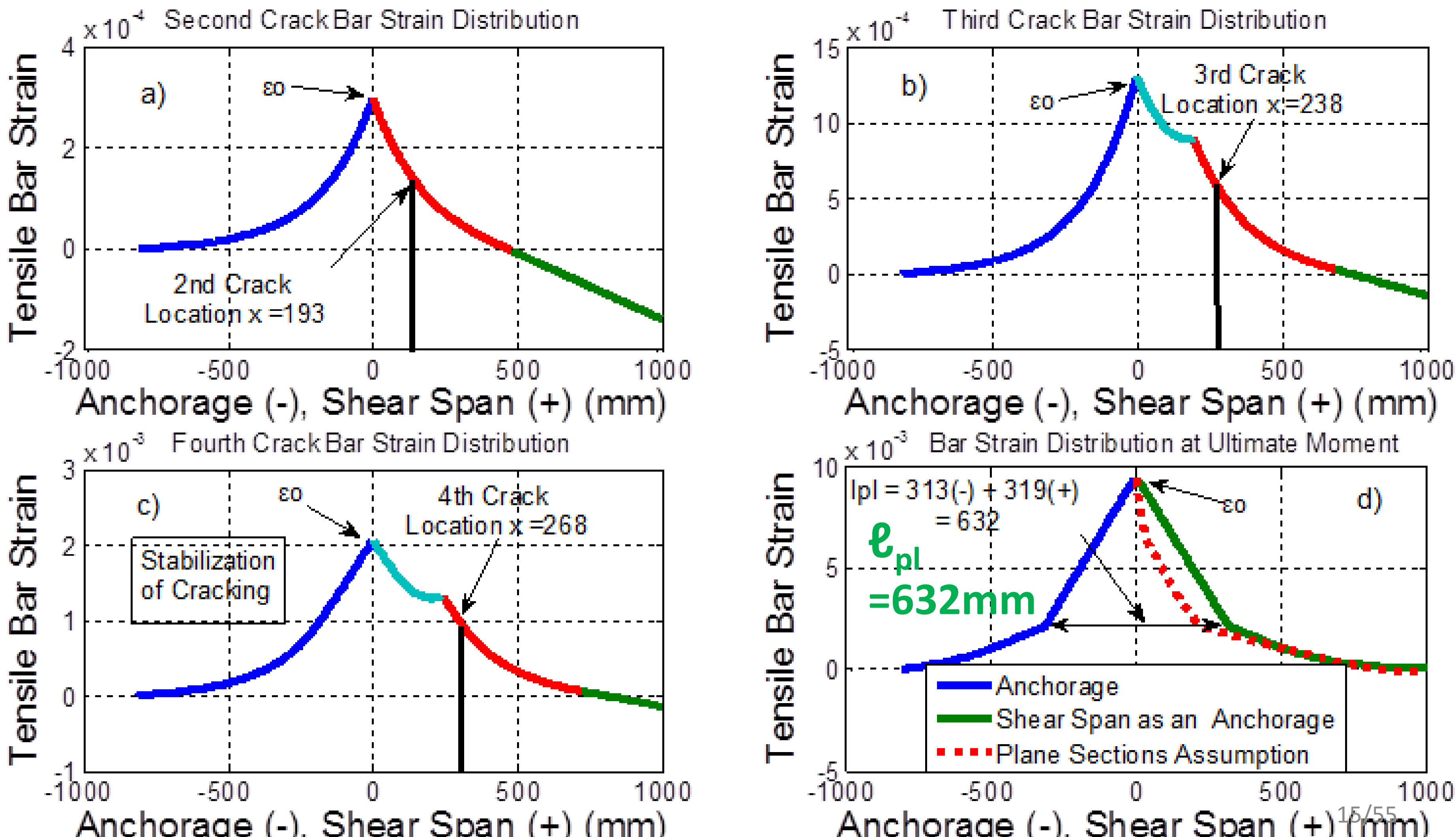




θ_u = 0.035 rad

Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Numerical Results:



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Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

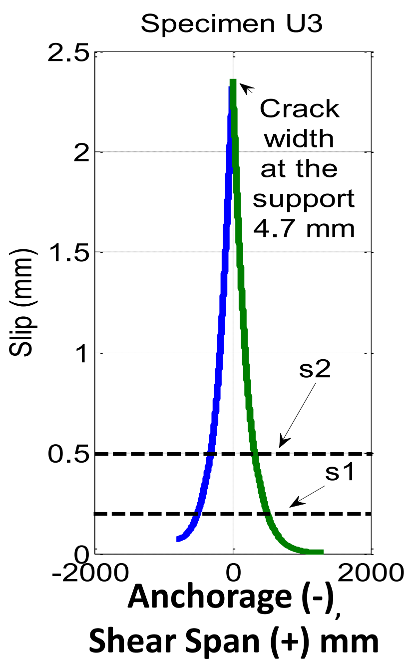
Plastic Hinge Length - Correlation with Empirical Expressions:

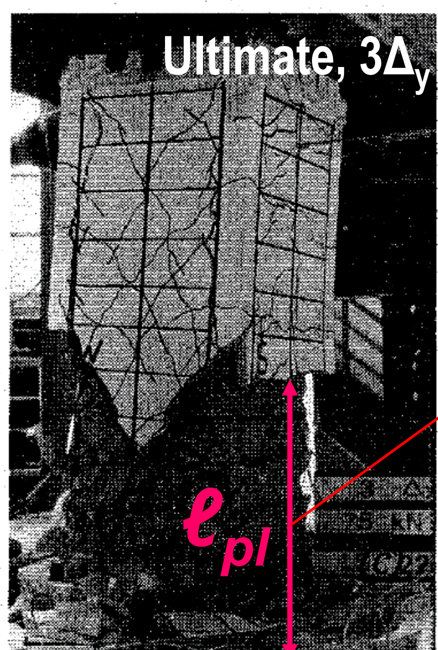
- **Empirical Definition** $\ell_{pl} = 0.5d$
- **Classic Definition** $\ell_{pl} = (M_u - M_y) \cdot L_s / M_u + c$
- **Priestley et. al. 1996** $\ell_{pl} = 0.08L_s + 0.022D_b f_y$
- **Eurocode 8 – Part III, 2005** $\ell_{pl} = 0.1L_s + 0.17h + 0.24D_b f_y / f_c^{0.5}$

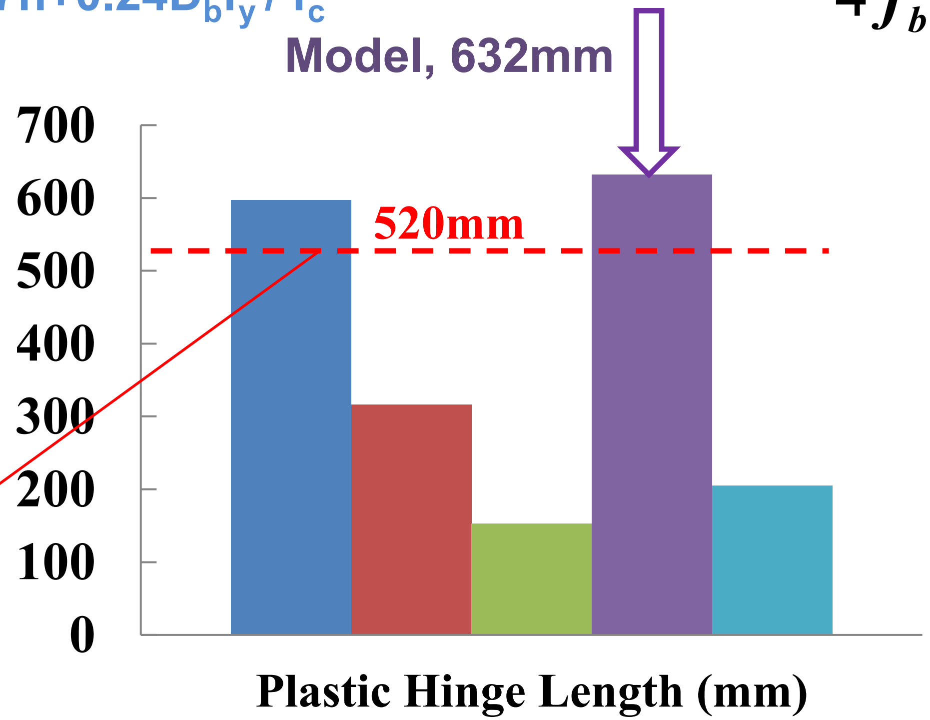
$$\theta^{slip}_{y\,or\,u} = \underbrace{\left.\frac{s^{span}_{y\,or\,u}}{d-0.4c_x}\right|_{x=0}}_{shear\ span} + \underbrace{\left.\frac{s^{anch}_{y\,or\,u}}{d-0.4c_x}\right|_{x=0}}_{anchorage}$$

$\theta u = 0.033$ rad

$$l_r = (\varepsilon_o - \varepsilon_{sy}) \cdot \frac{E_{sh} D_b}{4 f_b^{res}}$$







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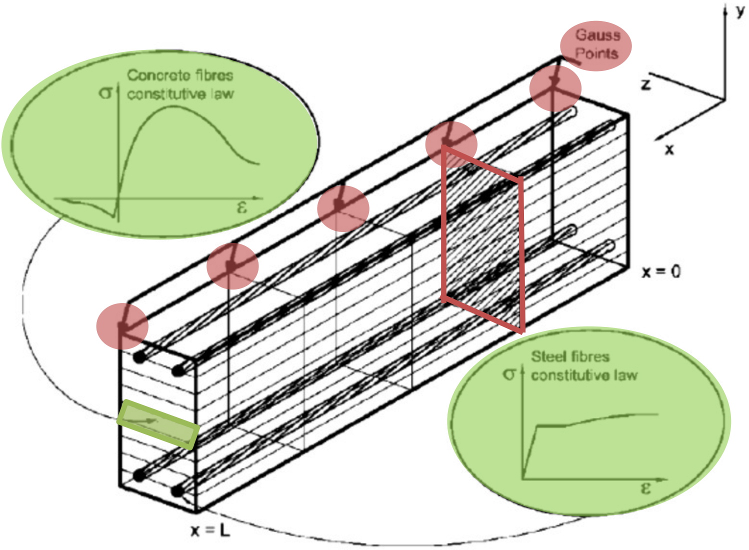
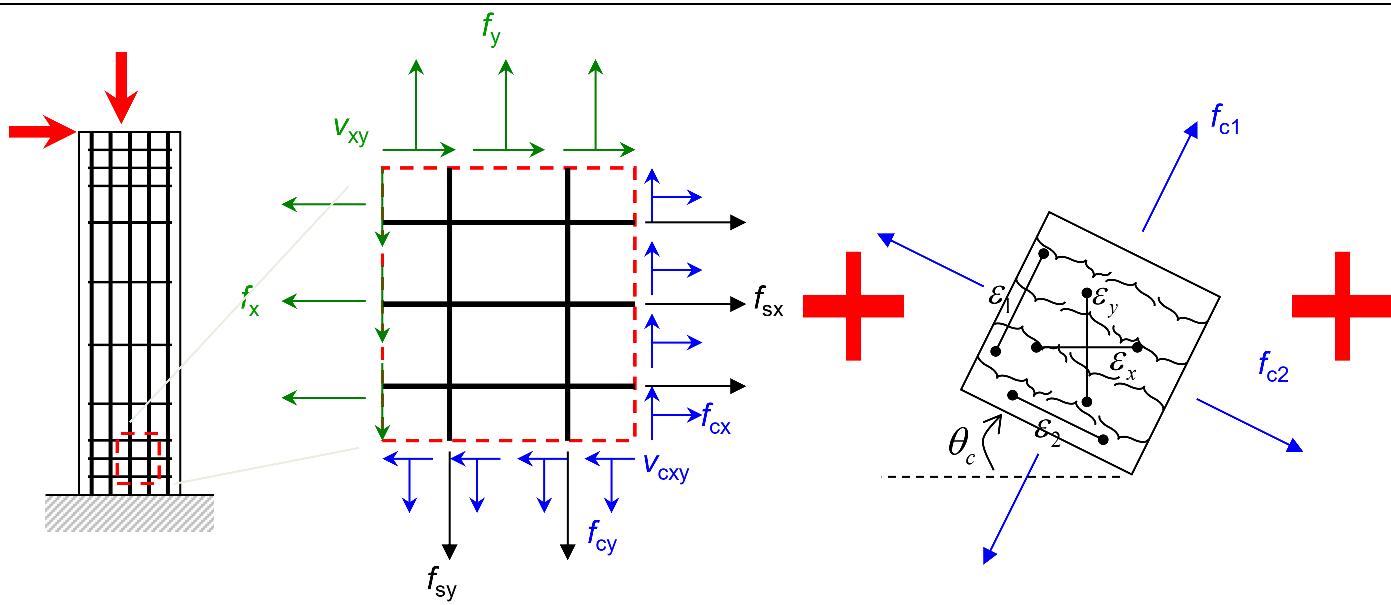
Nonlinear Analysis with fiber beam-column elements - Flexure vs. Shear :



- 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.

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

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



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

Equilibrium + Strain Compatibility + Constitutive Law

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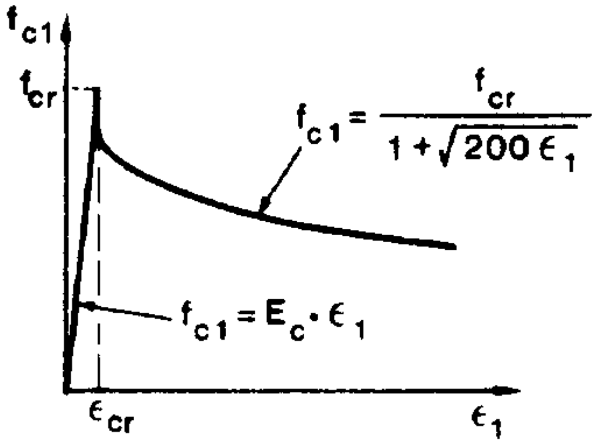
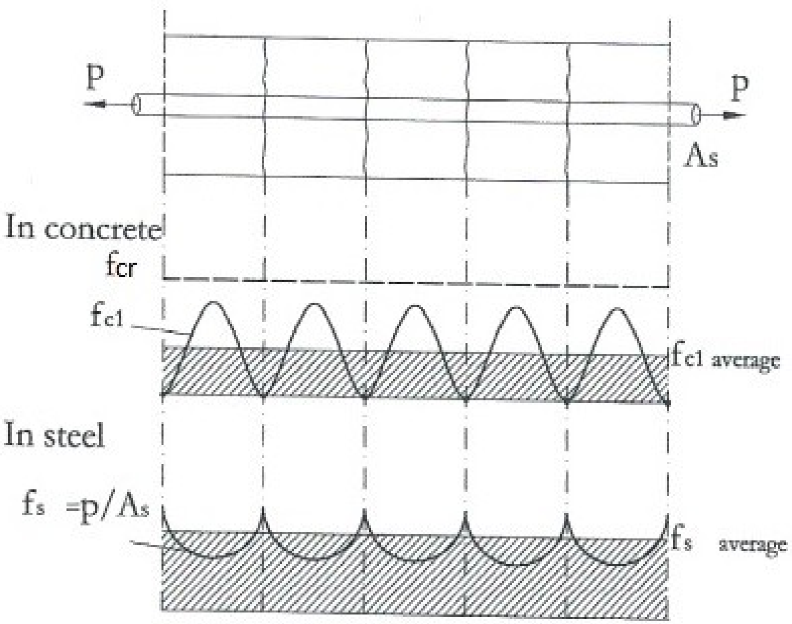
Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

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



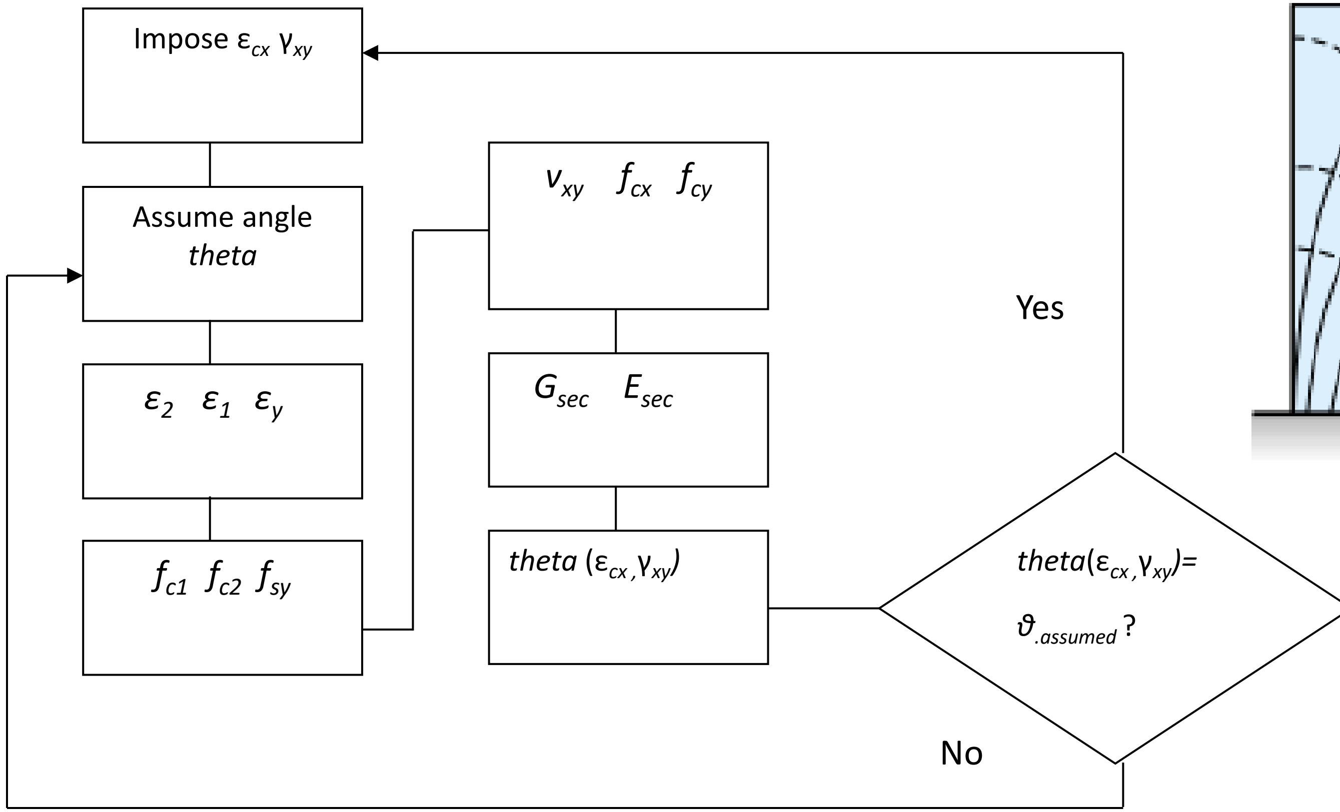


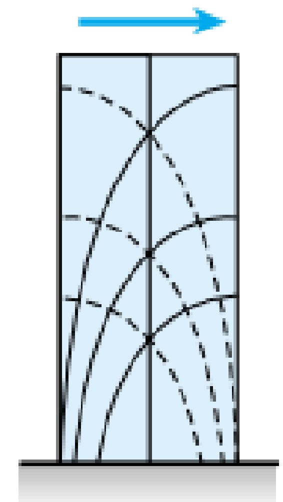
•Due to the influence of bond, tensile stresses can develop in the concrete between cracks. To model this phenomenon, which is referred to in the literature as "tension stiffening", the concrete tensile stress is assumed to decay from the tensile strength as principal strain increases.

• 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.

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

Fiber Stresses – Iterative procedure based on MCFT:





Root search based on numerical method Regula Falsi

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

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

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

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

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

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

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

$$N = \int \sigma_x dA = Axial\ Force$$

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

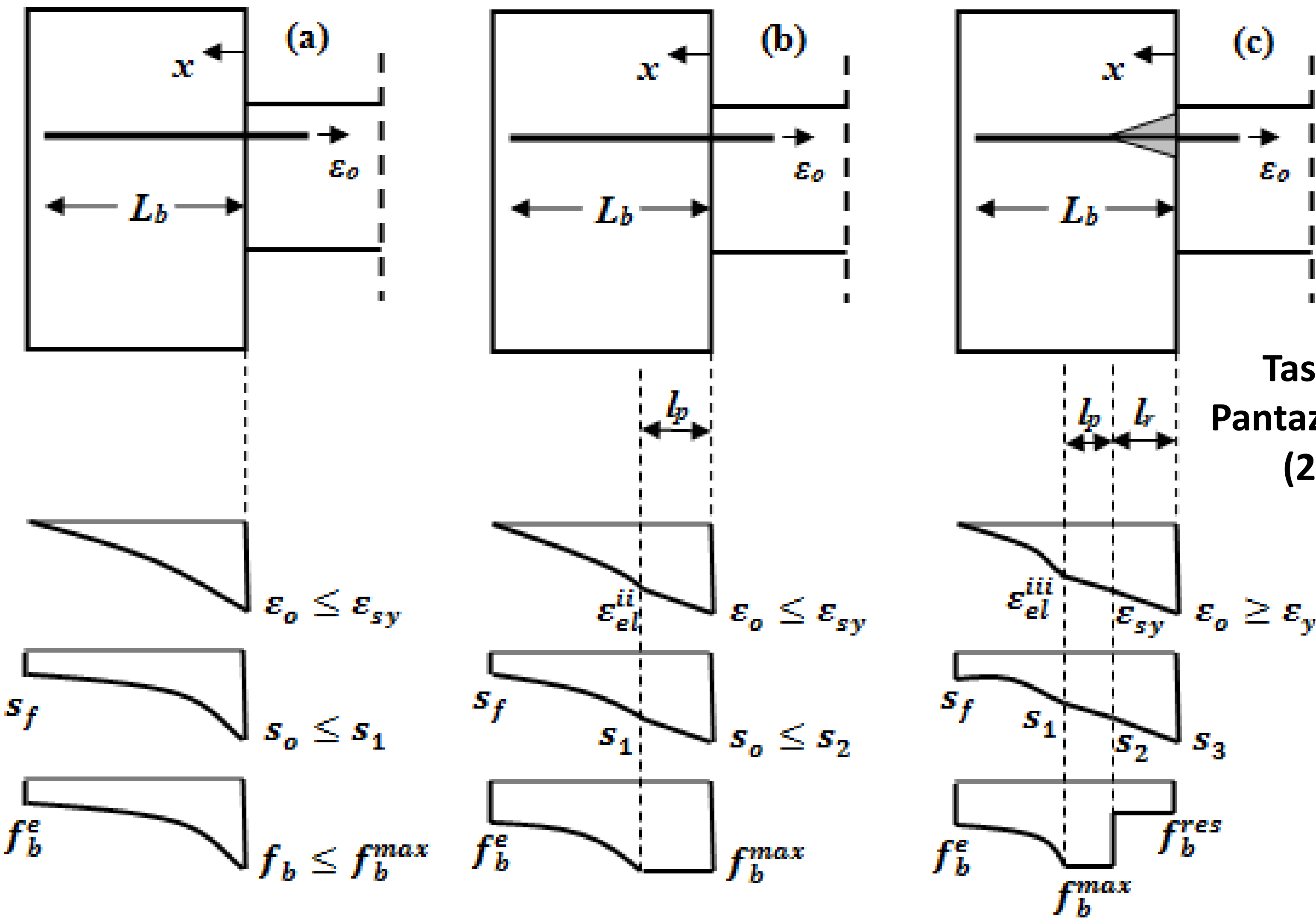
$$M = -\int y\sigma_x dA = Moment$$

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

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

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

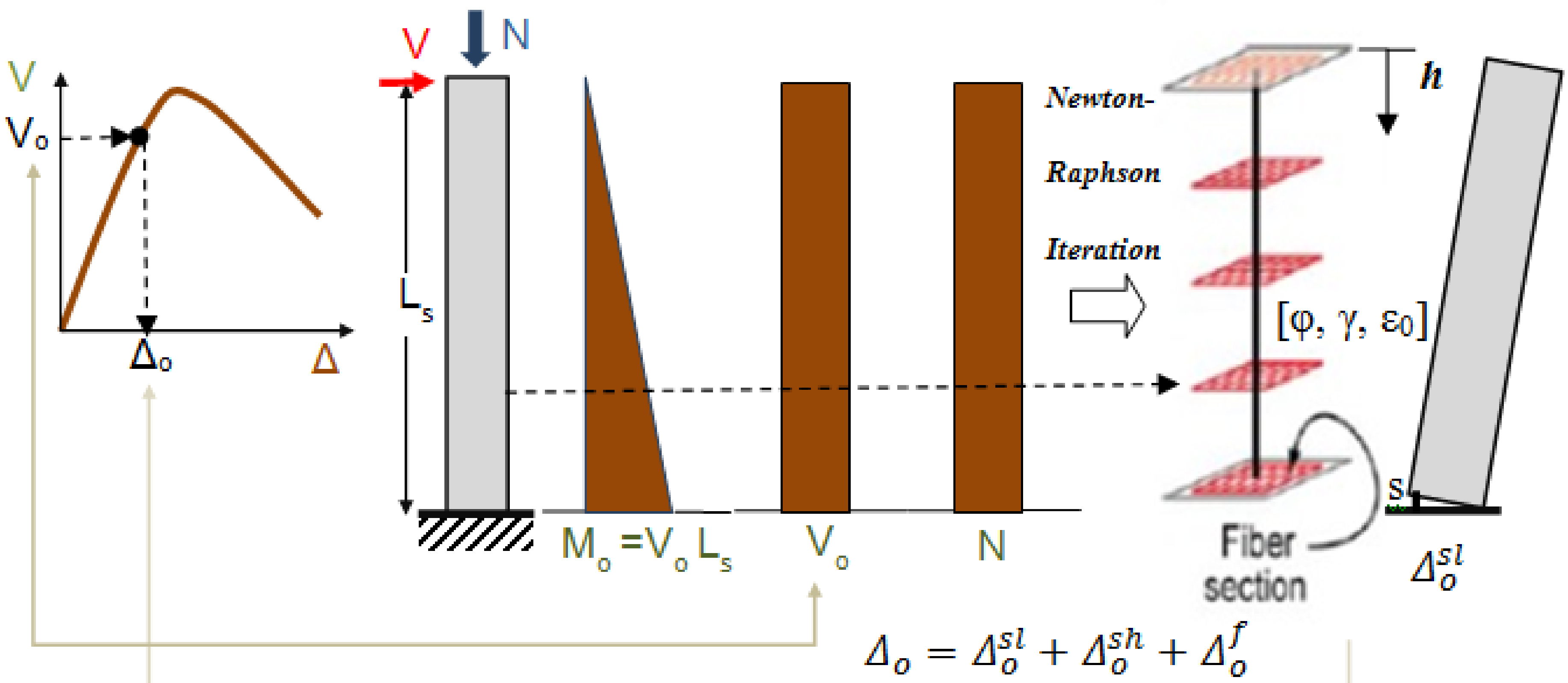
Strain, Slip and Bond Distributions in the Anchorage Length:



Tastani & Pantazopoulou (2013)

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

Capacity Curve of Shear-Critical RC Column - Phaethon:

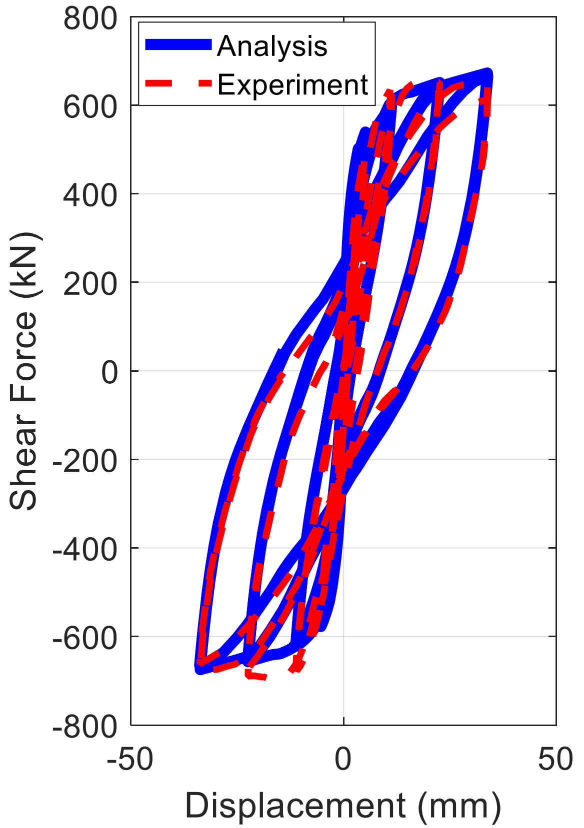


$$\Delta_o = \Delta_o^{sl} + \Delta_o^{sh} + \Delta_o^{f}$$

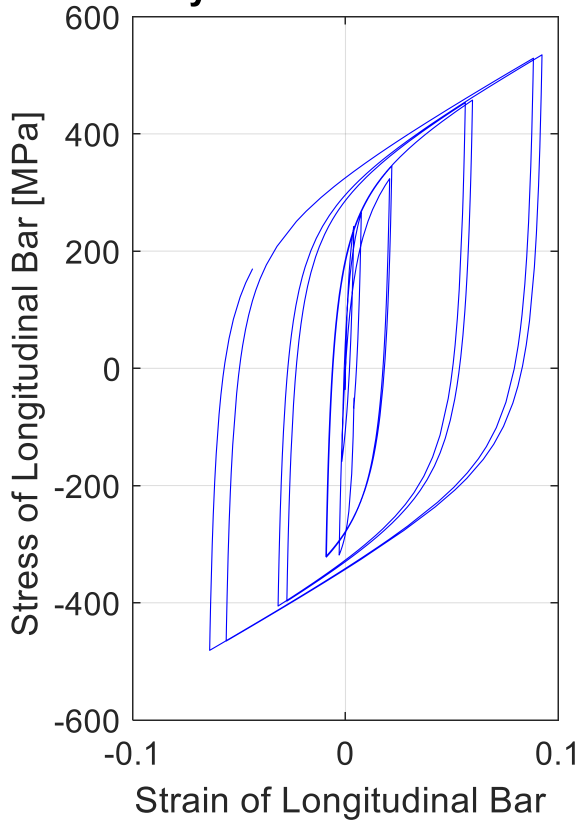
$$\Delta_o^{sh} = \int_0^{L_s} \gamma(h) \cdot dh \qquad \Delta_o^{f} = \int_0^{L_s} \varphi(h) \cdot h \cdot dh \qquad \Delta_o^{sl} = \frac{s}{(d - 0.4c_x)} \cdot L_s$$

Drift at Axial Failure – RC Column with Flexural Response :

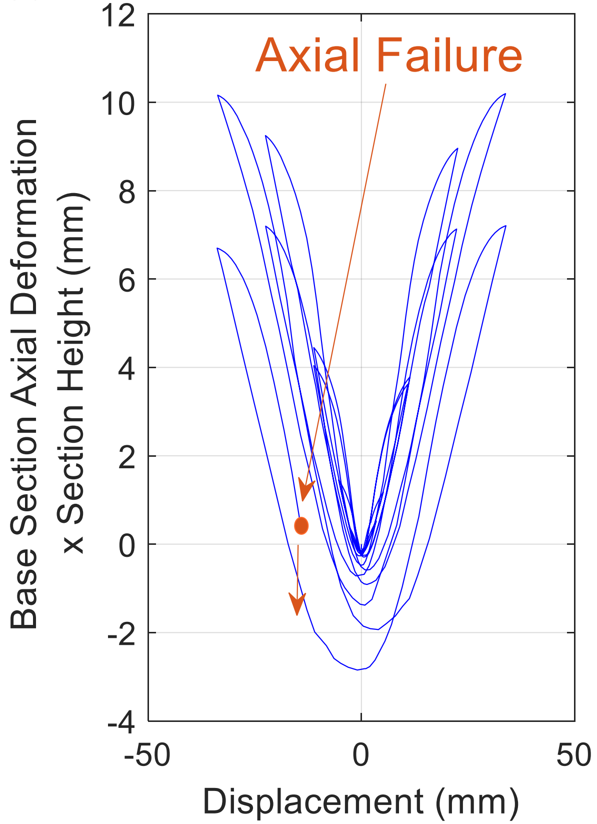
Force-Displacement for RC Column 1 of Berry and Eberhard Database



Stress-Strain relation for Longitudinal Bar for RC Column 1 of Berry and Eberhard Database

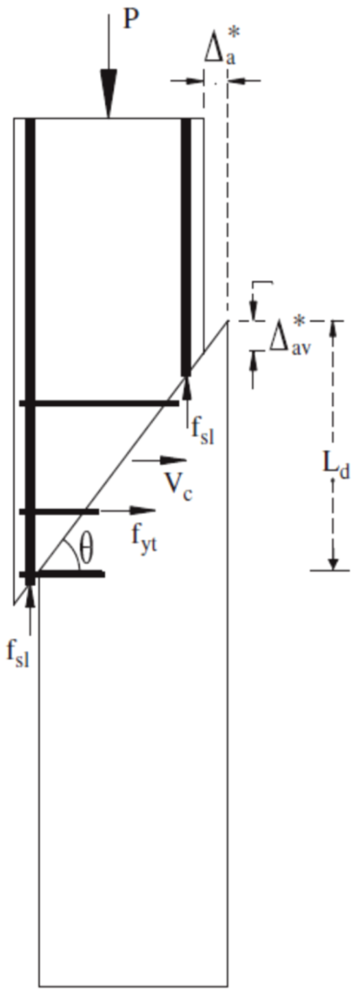


Cantilever Column Model Axial Elongation versus Lateral Displacement



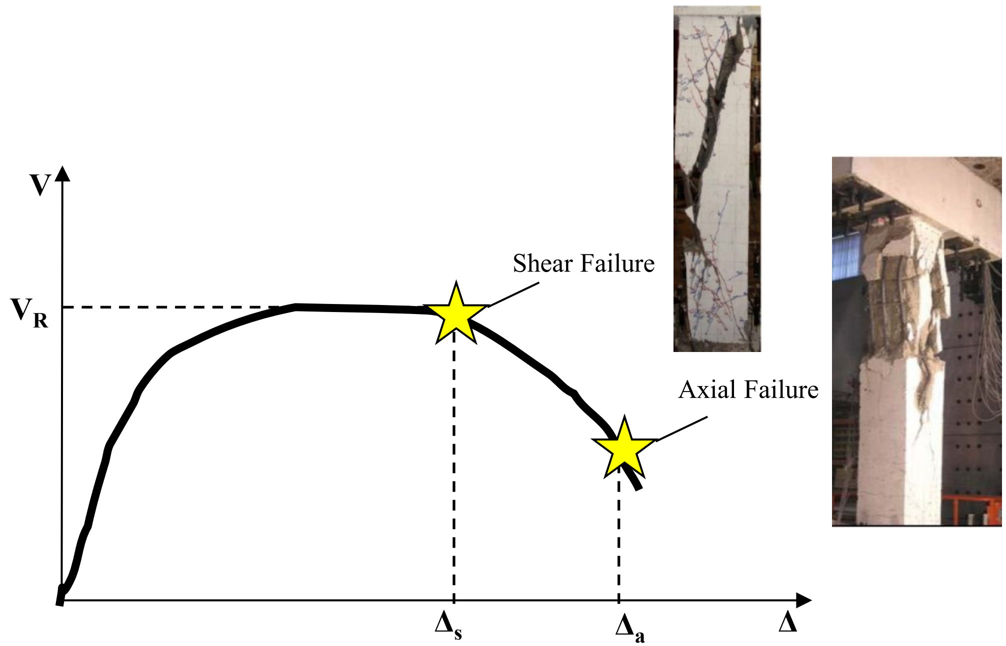
Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

Drift at Axial Failure - Shear-Critical RC Column (Elwood and Moehle, 2005):



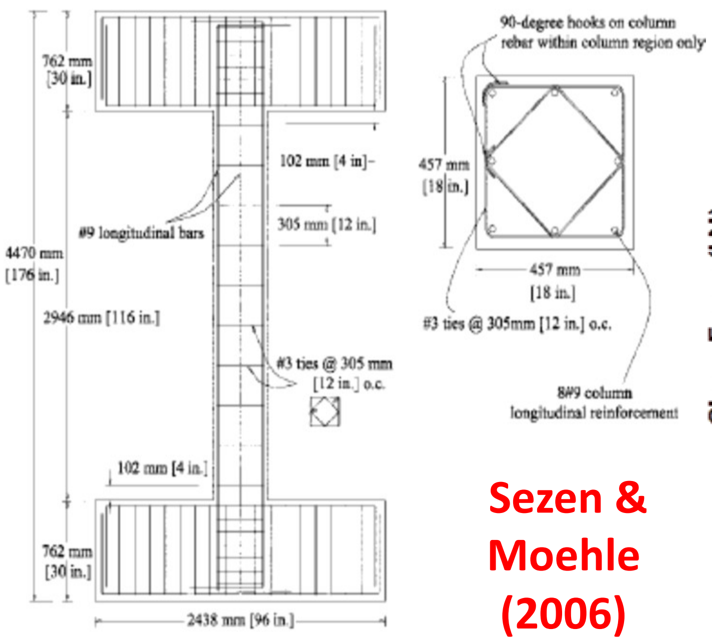
- **Elwood and Moehle (2005)**

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



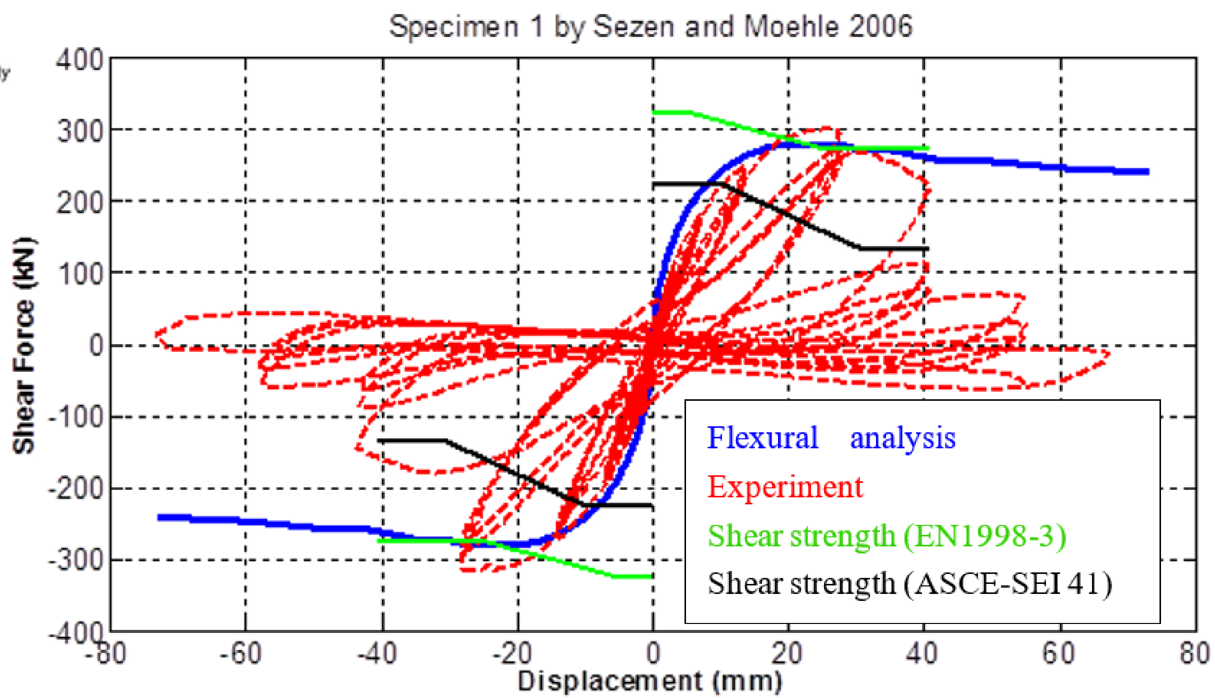
Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

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



Sezen & Moehle (2006)

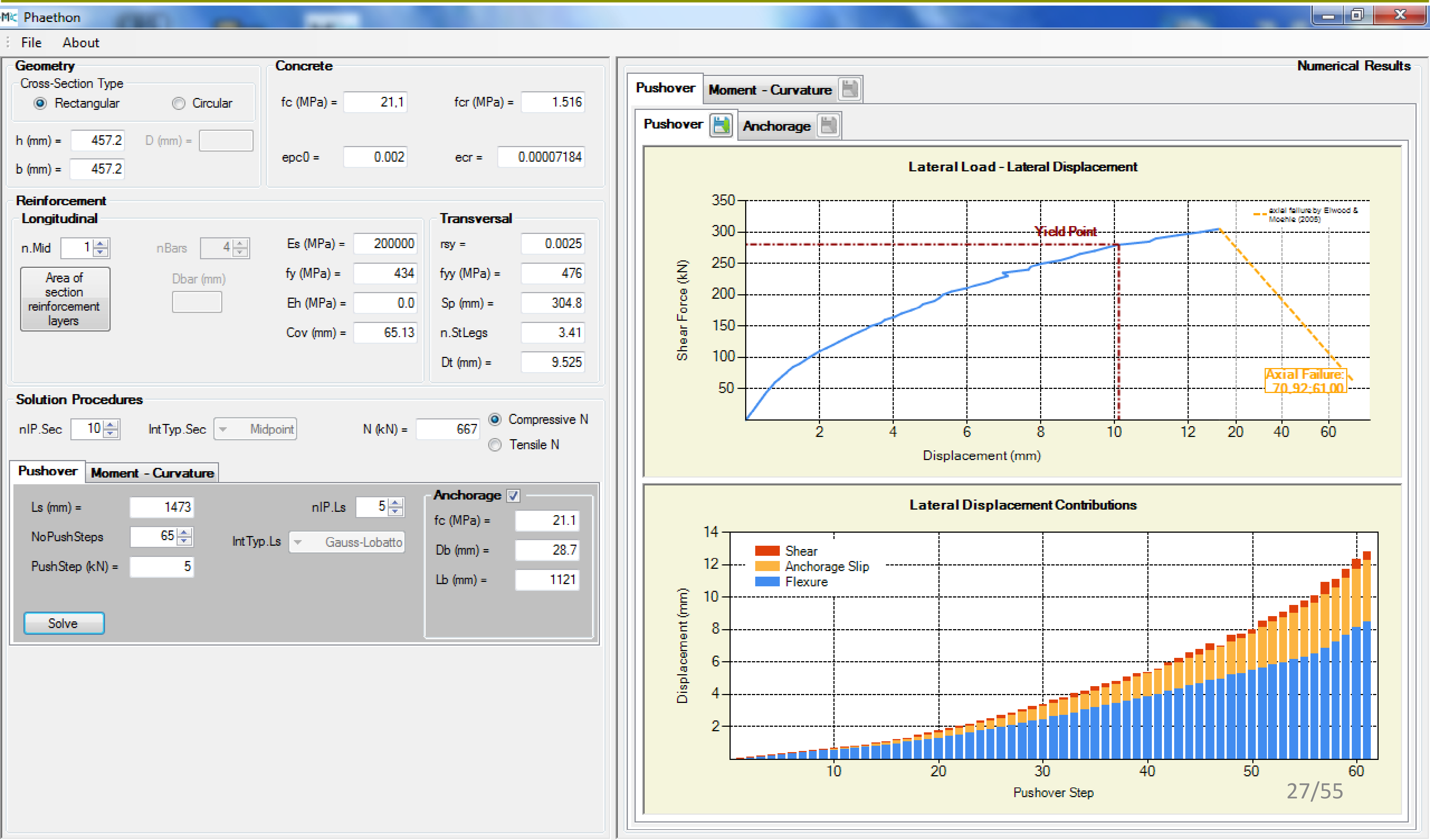
Cantilever Column



University of Cyprus

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

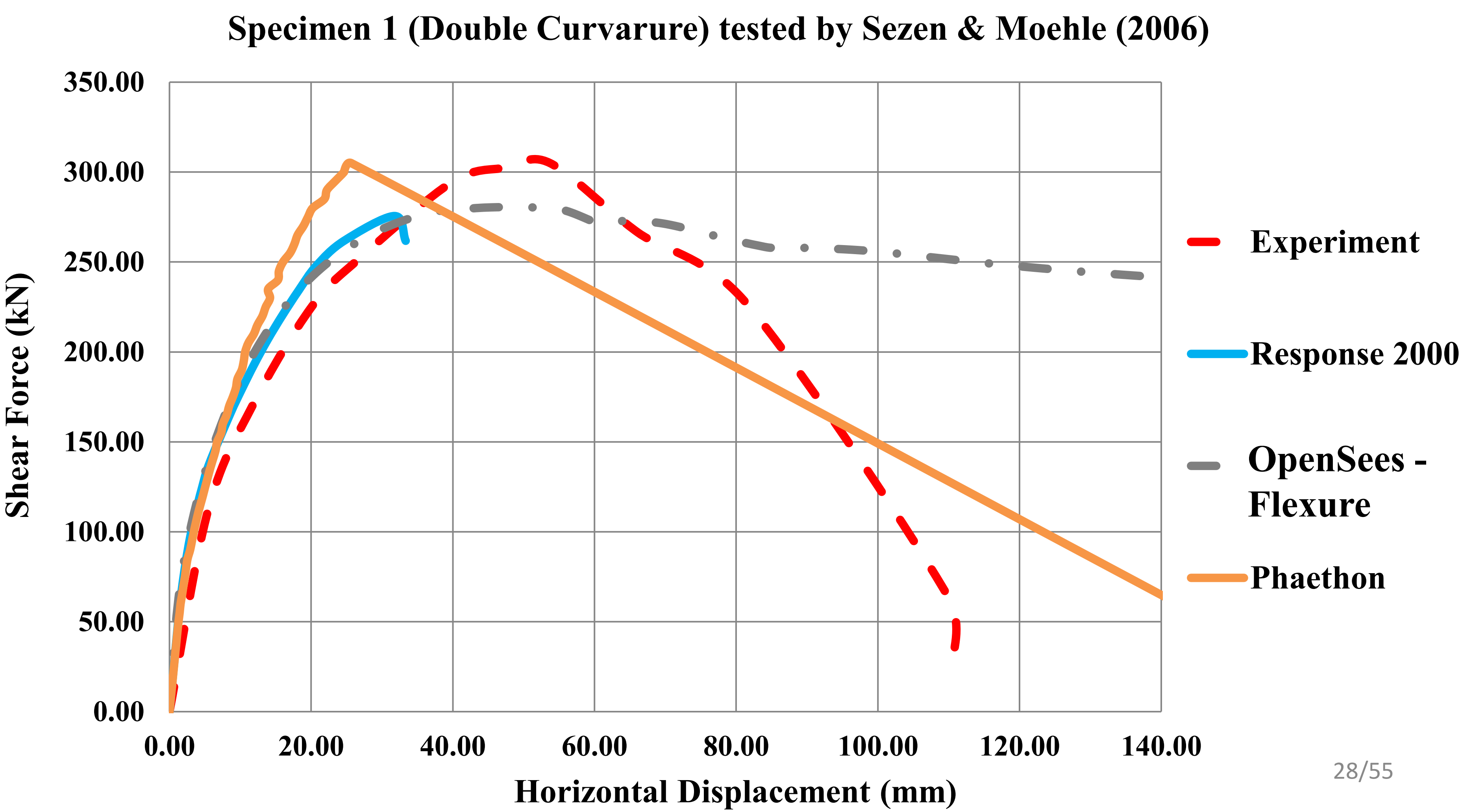
Correlation with Experimental Results – Phaethon - Specimen 1:



University of Cyprus

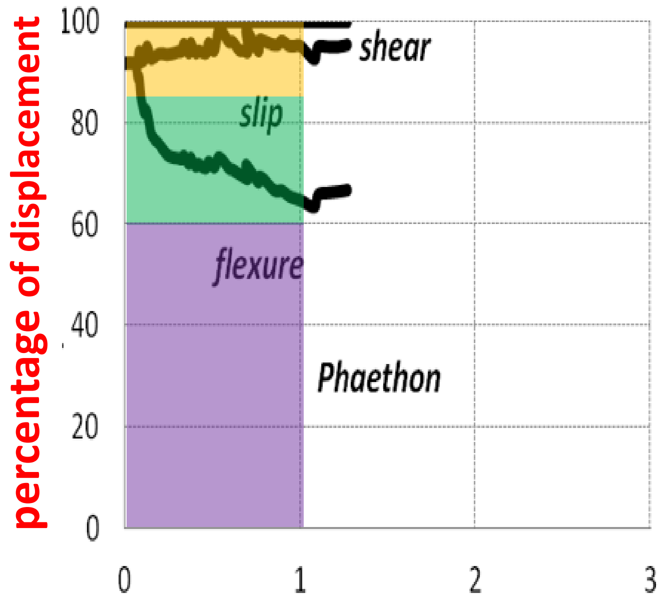
Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

Correation with Experimental Results – Phaethon - Specimen 1:



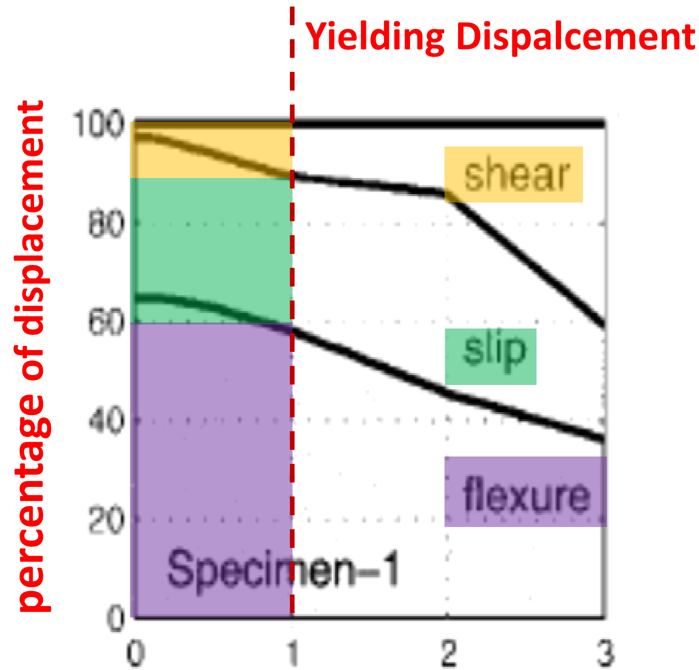
Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

Correlation with Experimental Results- Phaethon - Specimen 1:



Δtotal / Δy

Numerical Results



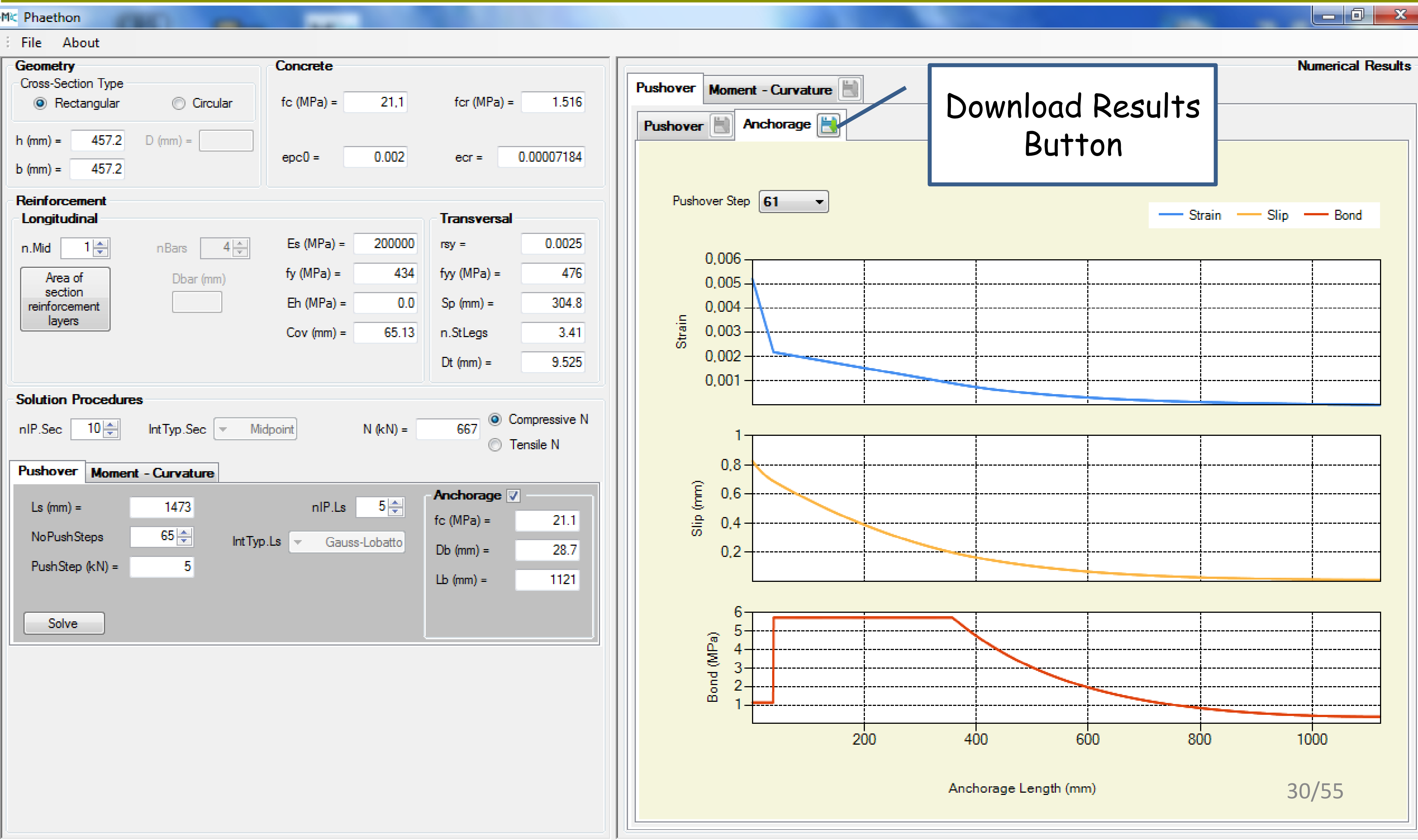
Δtotal / Δy

Experimental Results

University of Cyprus

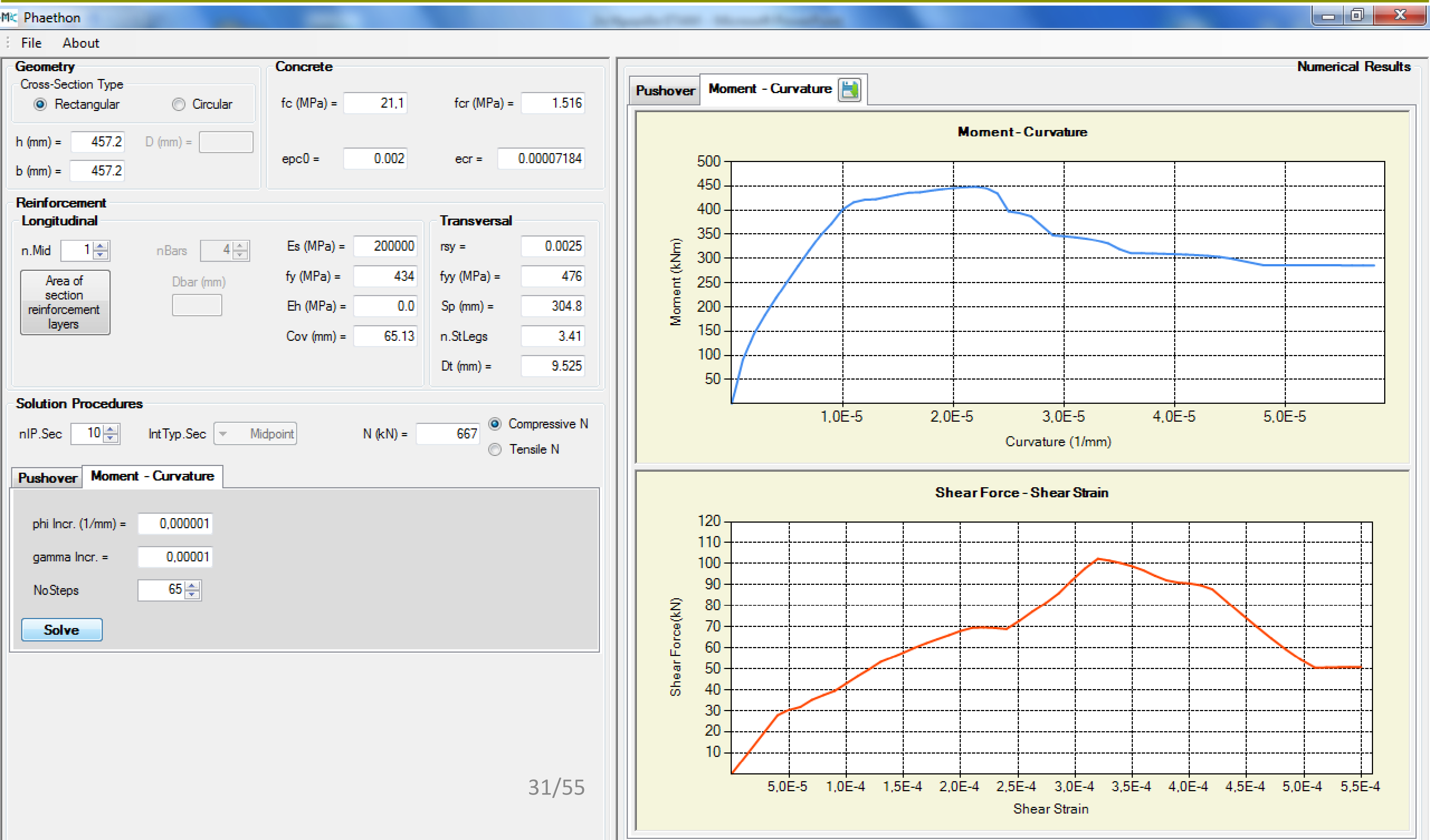
Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

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



Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

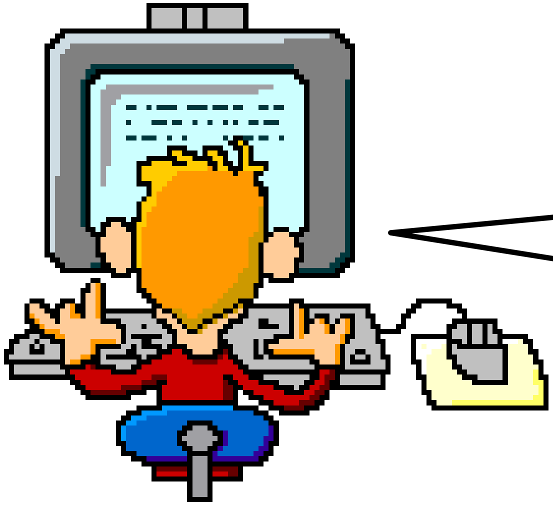
Sectional Analysis: Moment – Curvature & Shear Force – Shear Strain (Specimen 1)



END OF FIRST PART – SEISMIC ASSESSMENT OF RC COLUMNS:

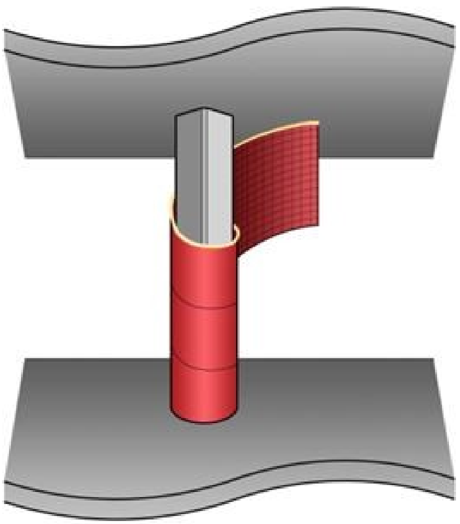
You can download Phaethon Windows software from the following link:

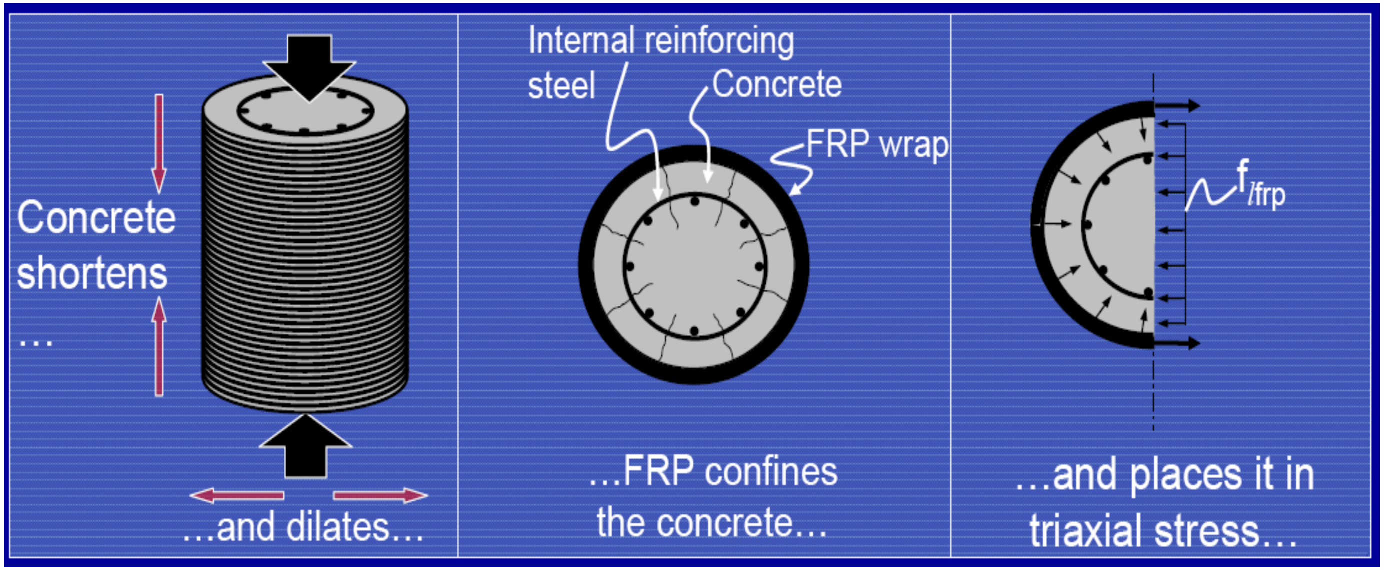
www.bigeconomy.gr/en/phaethon-en/



ANY QUESTIONS ?

Seismic Retrofit of Substandard RC Columns with FRP Jacket:





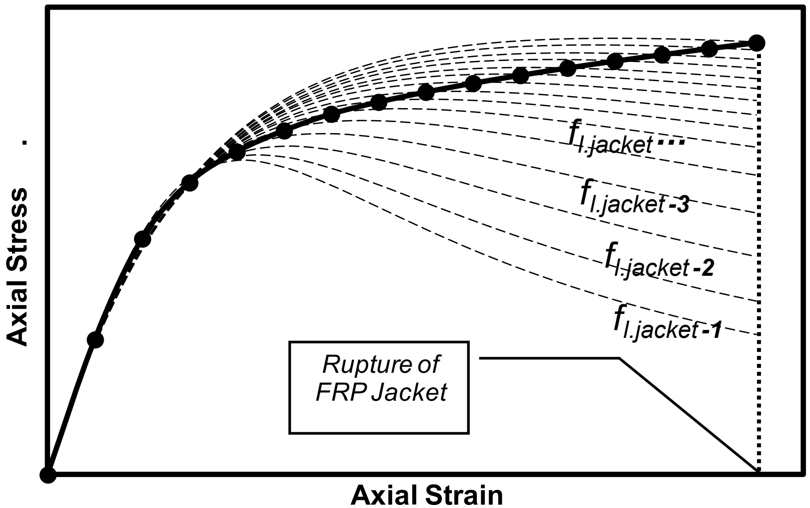
FRP Jackets have been found to be beneficial for the :

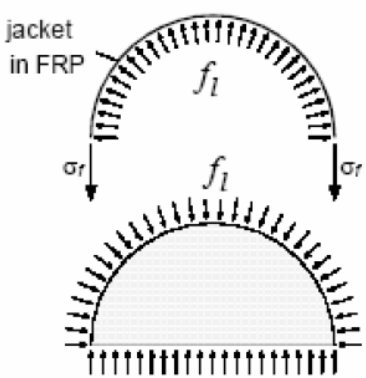
- ***Compressive Strength***
- ***Shear Strength***
- ***Flexural Strength***
- ***Displacement ductility of RC columns.***

University of Cyprus

Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

FRP and Steel Confined Concrete:





Steel ties

$$f_l = \frac{1}{2} k_e \, \rho_{st} \, f_y \qquad \rho_{st} = \frac{4 A_{st}}{s \, d_s}$$

FRP

$$f_l = \frac{1}{2} \rho_f E_f \varepsilon_f \qquad \rho_f = \frac{4 t_f}{d}$$

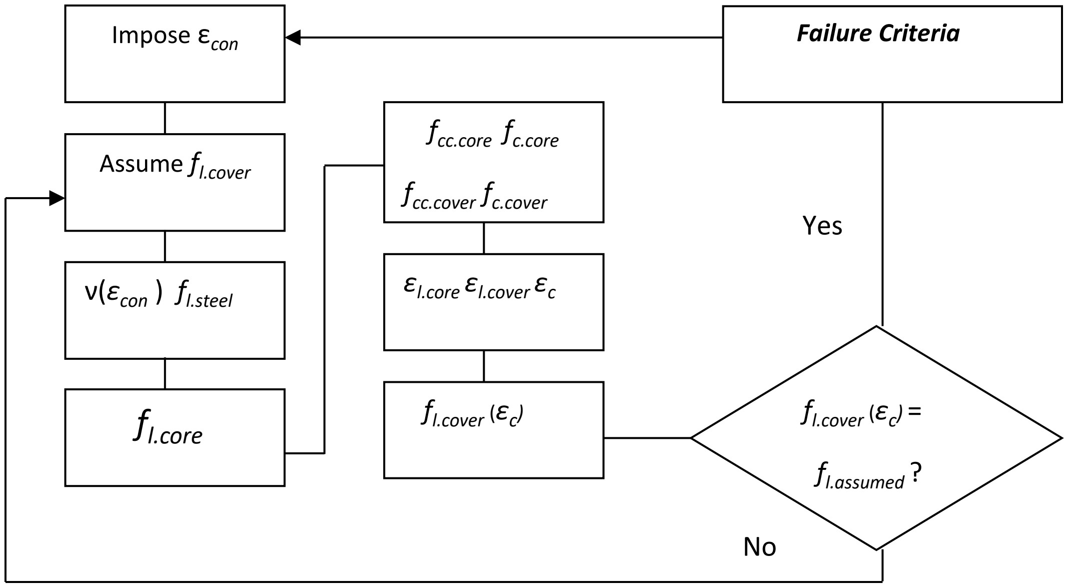
• **For low strain values, the stress state in the transverse steel reinforcement is very small and the concrete is basically unconfined. In this range, steel and FRP jacketing behave similarly. That is, the inward pressure as a reaction to the expansion of concrete increases continuously.**

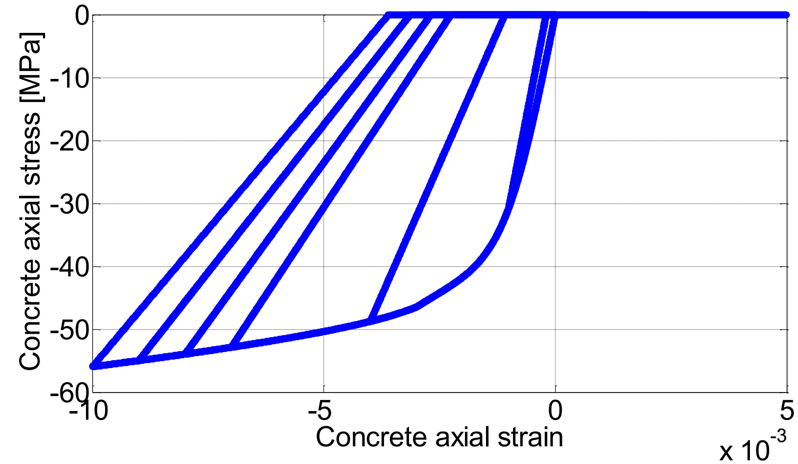
• **Therefore, speaking in terms of variable confining pressures corresponding to the axial strain level in the section and active triaxial models defining axial stress-strain curves for concrete subject to constant lateral pressure, it can be stated that the stress-strain curve describing the stress state of the section has to cross all active confinement curves up to a confined-concrete axial stress-strain curve that is associated with a lateral pressure magnitude equal to the tensile strength of the FRP jacket plus the yielding strength of ties.**

University of Cyprus

Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., “Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete”, *ACI Structural Journal*, Vol. 109, No. 4, July 2012, pp. 569-578.

Constitutive Law for FRP and Steel Confined Concrete :





- **After imposing an axial strain on the section, a pressure coming from the FRP jacket is assumed. Then, the Poisson’s coefficient until yielding of steel stirrups and the pressure coming from the steel ties, is calculated based on the Braga model (2006). The confining pressure in the concrete core is simply the summation of the lateral pressures contributed by the two confining systems (FRP and Steel). The Spoelstra and Monti (1999) model beyond this point is basically used to define the remainder of the parameters declared above, applying that model on the concrete core and concrete cover of the circular section.**

University of Cyprus

Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

"FRPConfinedConcrete" Uniaxial Material in OpenSees:

•uniaxialMaterial FRPConfinedConcrete *$tag $fpc1 $fpc2 $epsc0 $D $c $Ej $Sj $tj $eju $S $fyl $fyh $dlong $dtrans $Es $vo $k $useBuck*

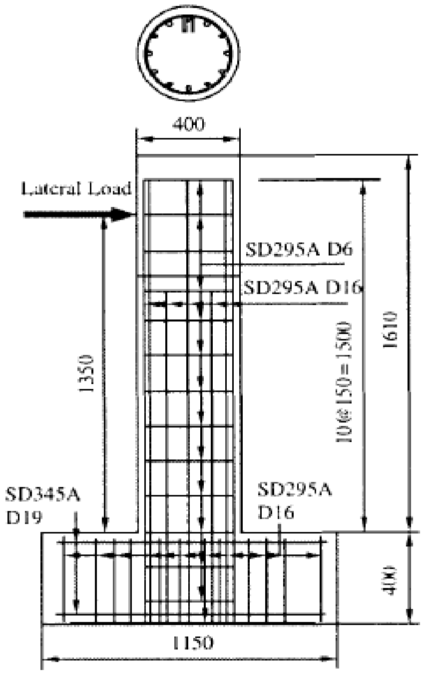
1	*tag*	*Material Tag*
2	*fpc1*	*Concrete Core Compressive Strength*
3	*fpc2*	*Concrete Cover Compressive Strength*
4	*epsc0*	*Strain Corresponding to Unconfined Concrete Strength*
5	*D*	*Diameter of the Circular Section*
6	*c*	*Dimension of Concrete Cover*
7	*Ej*	*Elastic Modulus of the Jacket*
8	*Sj*	*Clear Spacing of the FRP Strips - zero if it's continuous*
9	*tj*	*Total Thickness of the FRP Jacket*
10	*eju*	*Rupture Strain of the Jacket*
11	*S*	*Spacing of the Stirrups*
12	*fyl*	*Yielding Strength of Longitudinal Steel Bars*
13	*fyh*	*Yielding Strength of the Hoops*
14	*dlong*	*Diameter of the Longitudinal bars*
15	*dtrans*	*Diameter of the Stirrups*
16	*Es*	*Steel's Elastic Modulus*
17	*vo*	*Initial Poisson's Coefficient for Concrete*
18	*k*	*Reduction Factor (0.5-0.8) for the Rupture Strain of the FRP*
19	*useBuck*	*FRP jacket failure criterion due to buckling of longitudinal compressive steel bars (0 = not include it, 1= to include it)*

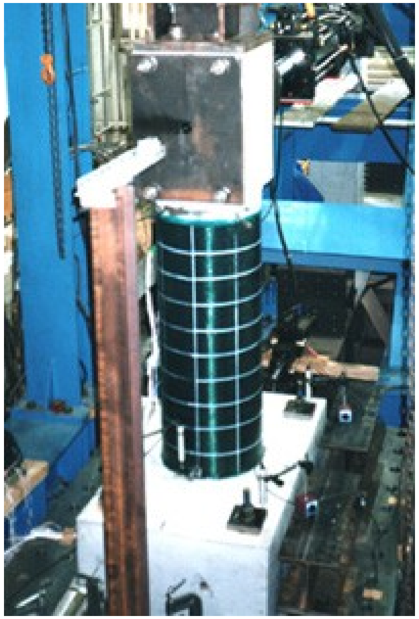
Units (N,mm,MPa)

University of Cyprus

Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Experiments by Gallardo-Zafra R. & K. Kawashima (2009) :





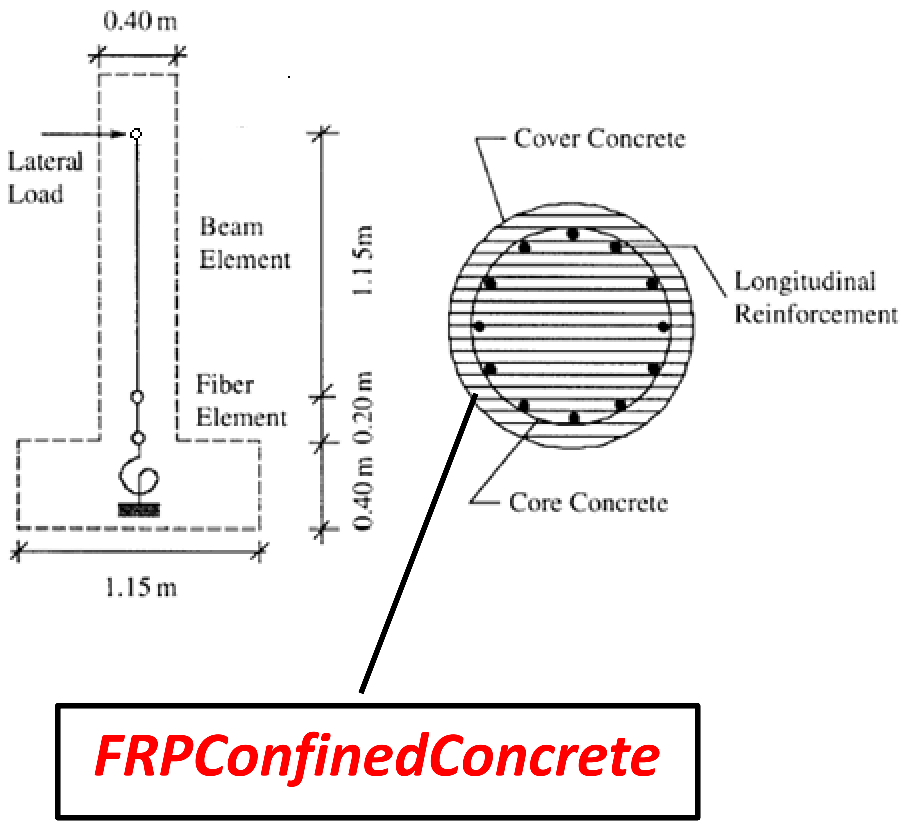
•The experimental study under consideration contains a series of cyclic loading tests that was conducted on six reinforced concrete column specimens 400 mm in diameter and 1.350 mm in effective height.

•The specimens were grouped into A and B series where each series consisted of three specimens each; one was as-built while the second and the third were wrapped laterally by CFRP with a single layer and with two layers, respectively.

• The specimens were laterally confined by 6mm deformed bars having yield strength of 363 MPa (SD295) with 135o bent hooks. The tie reinforcement spacing was 150 mm for the A-series and 300 mm for the B-series.

Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Numerical Simulation of Bridge Piers Using Opensees:



- The cantilever column **was modeled by a linear beam element** with the stiffness corresponding to flexural yielding **and a fiber element used to capture the flexural hysteretic behaviour at the plastic hinge.**

- The **length of the fiber element** was assumed to be **half of the column's diameter.**

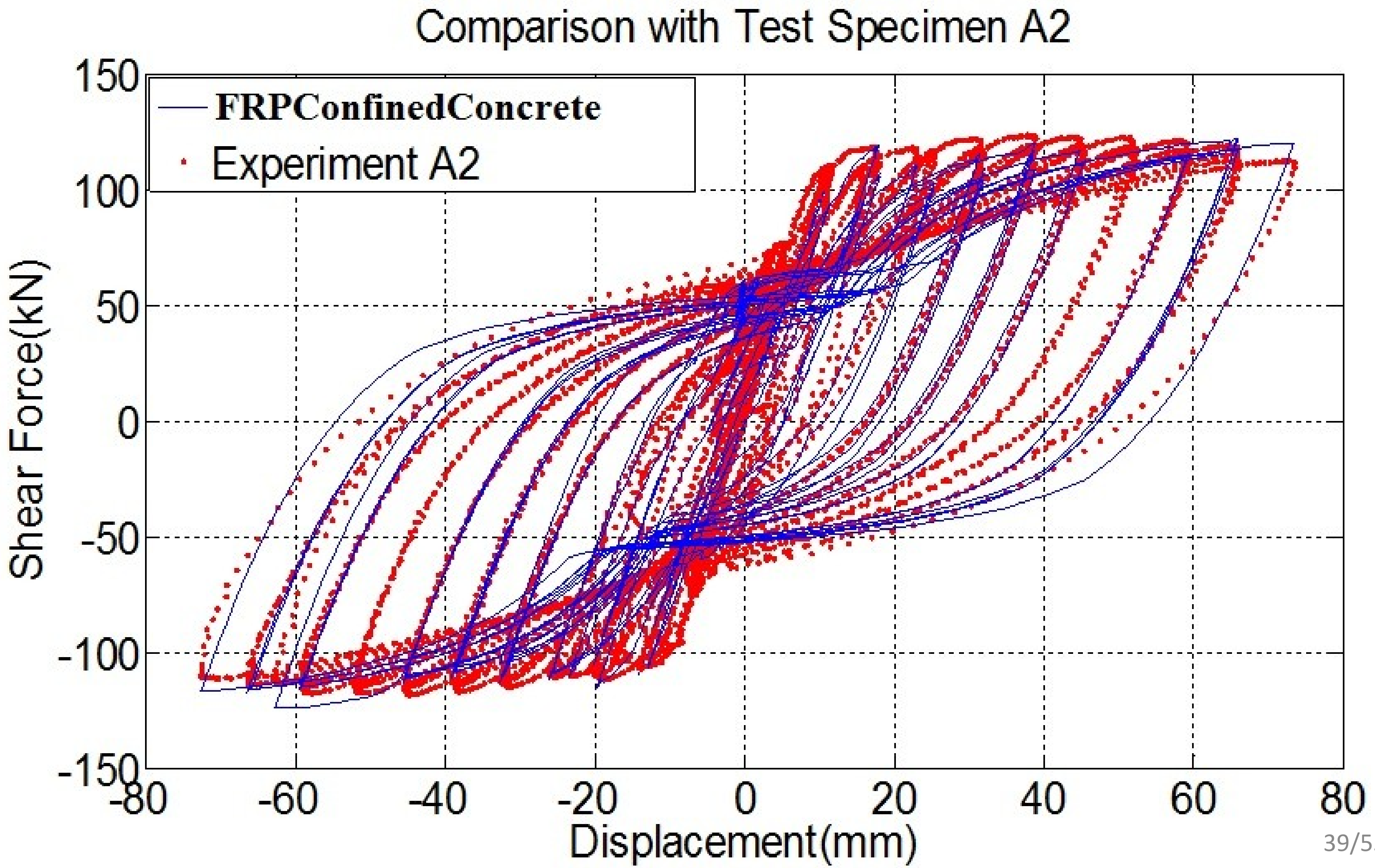
- **A rotational spring at the bottom of the column represents the longitudinal bar pullout from the footing.** Its property was based on moment-rotation curve obtained from the experiment at small amplitude loading and was assumed to have an elastic stiffness.

- **No P-Δ effect was considered in the performed analyses**

University of Cyprus

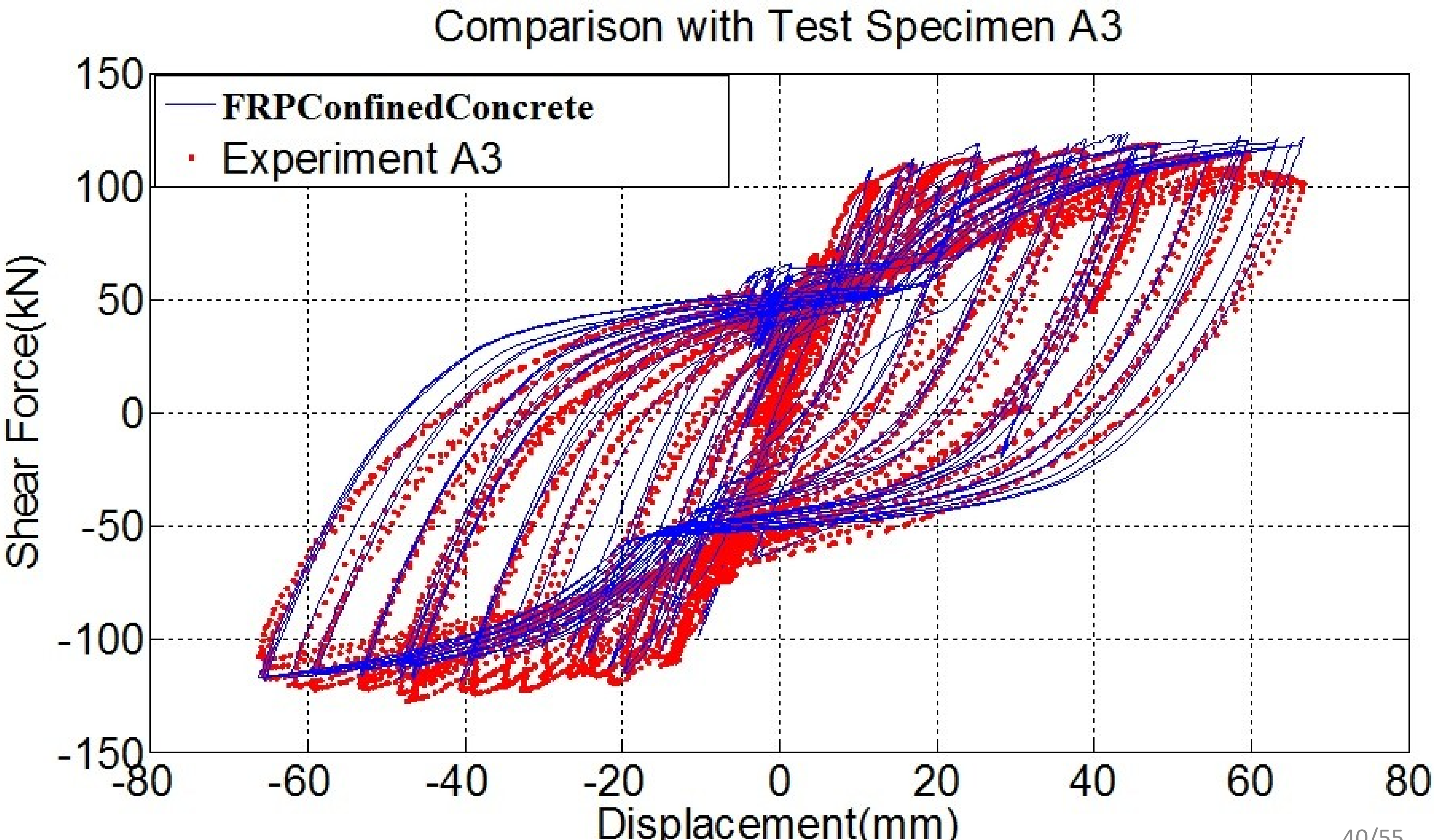
Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Correlation with Experimental Results:



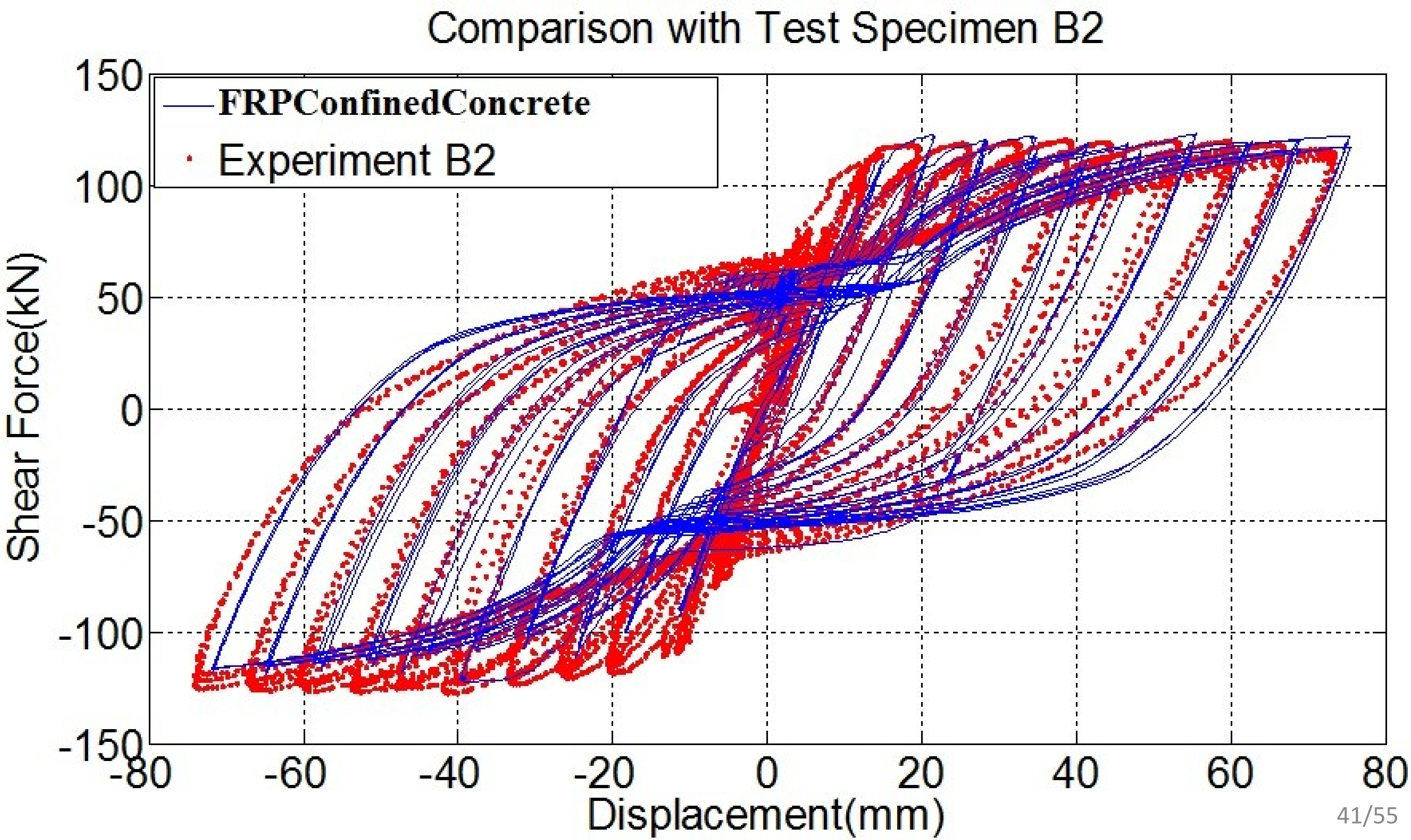
Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., “Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete”, *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Correlation with Experimental Results:



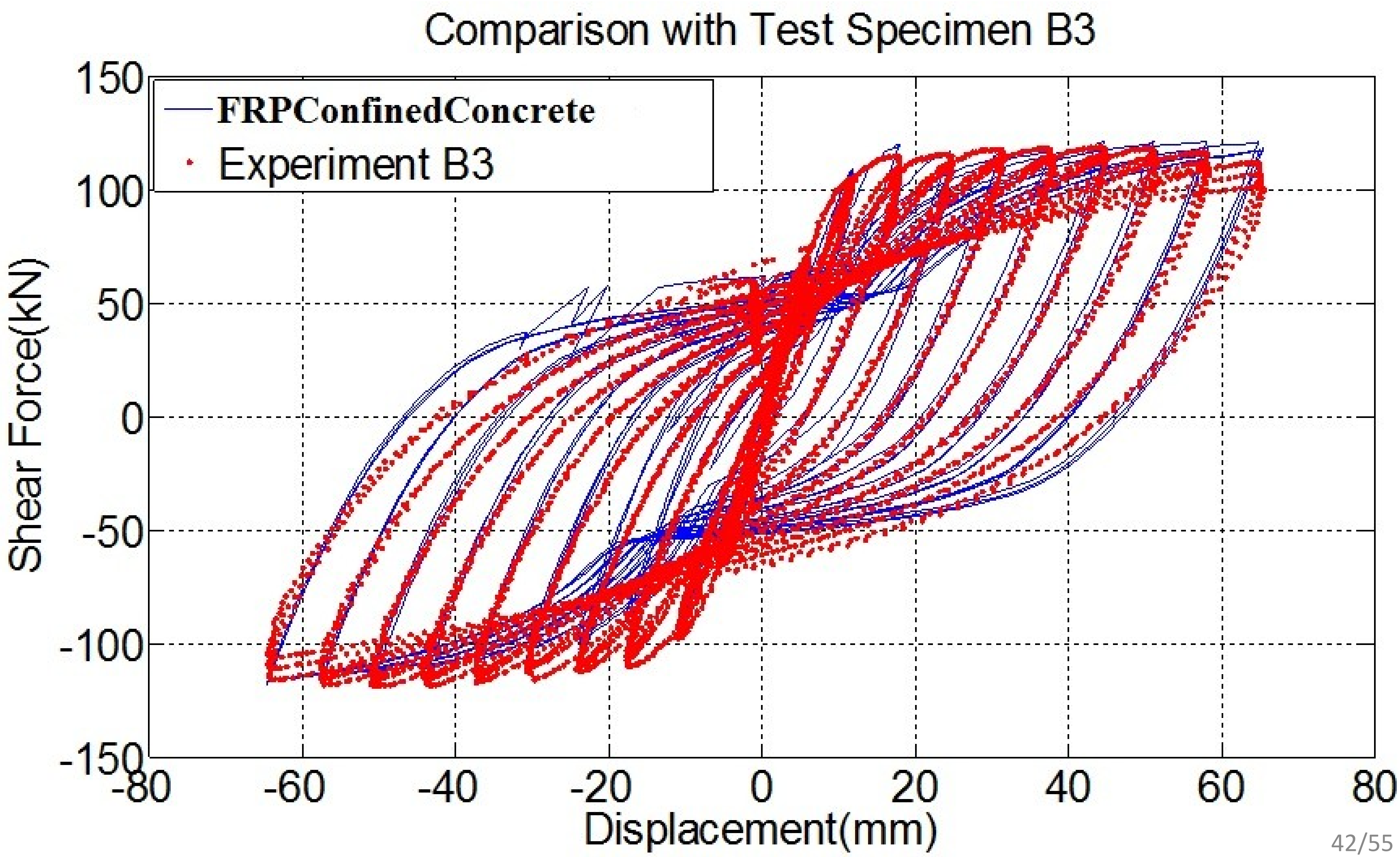
Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Correlation with Experimental Results:



Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Correlation with Experimental Results:

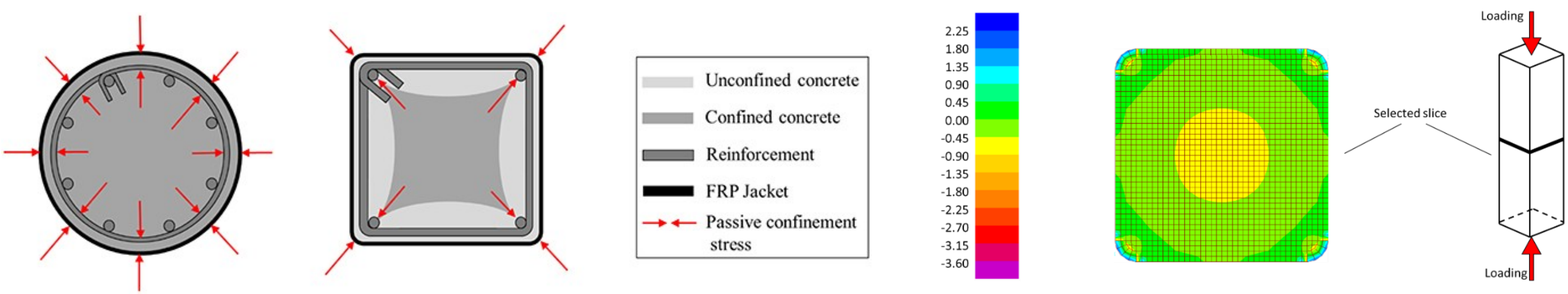


University of Cyprus

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

Seismic Retrofit of Substandard RC Columns with FRP Jacket:

- **Circular FRP-confined RC sections → radial dilation → uniform stresses**
- **Rectangular FRP-confined RC sections → more efficient confinement at the corners → non-uniform stresses**
- **Analysis-oriented model → easy application in practice & implementation in software**

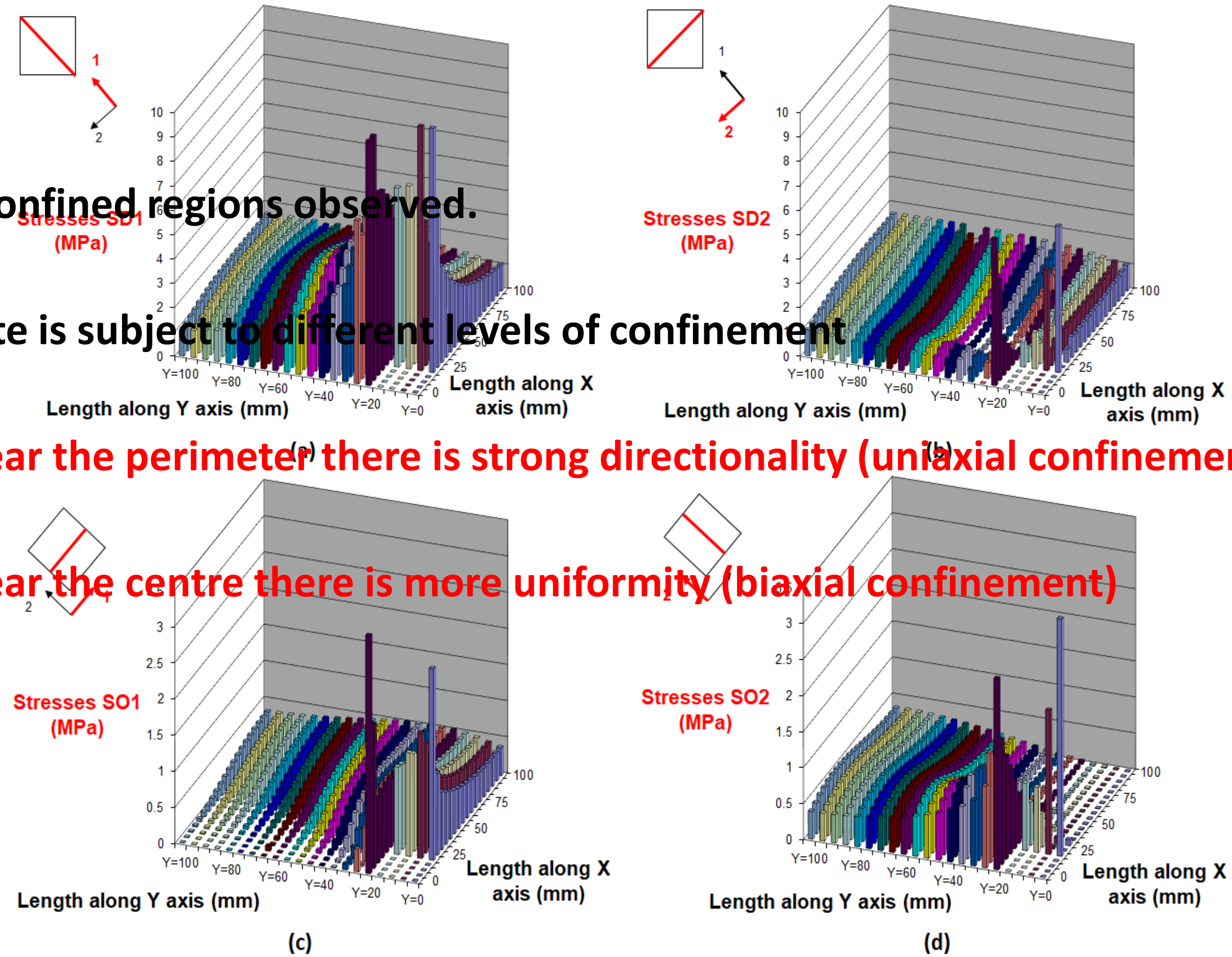


University of Cyprus

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

3D FEM Analysis Results:

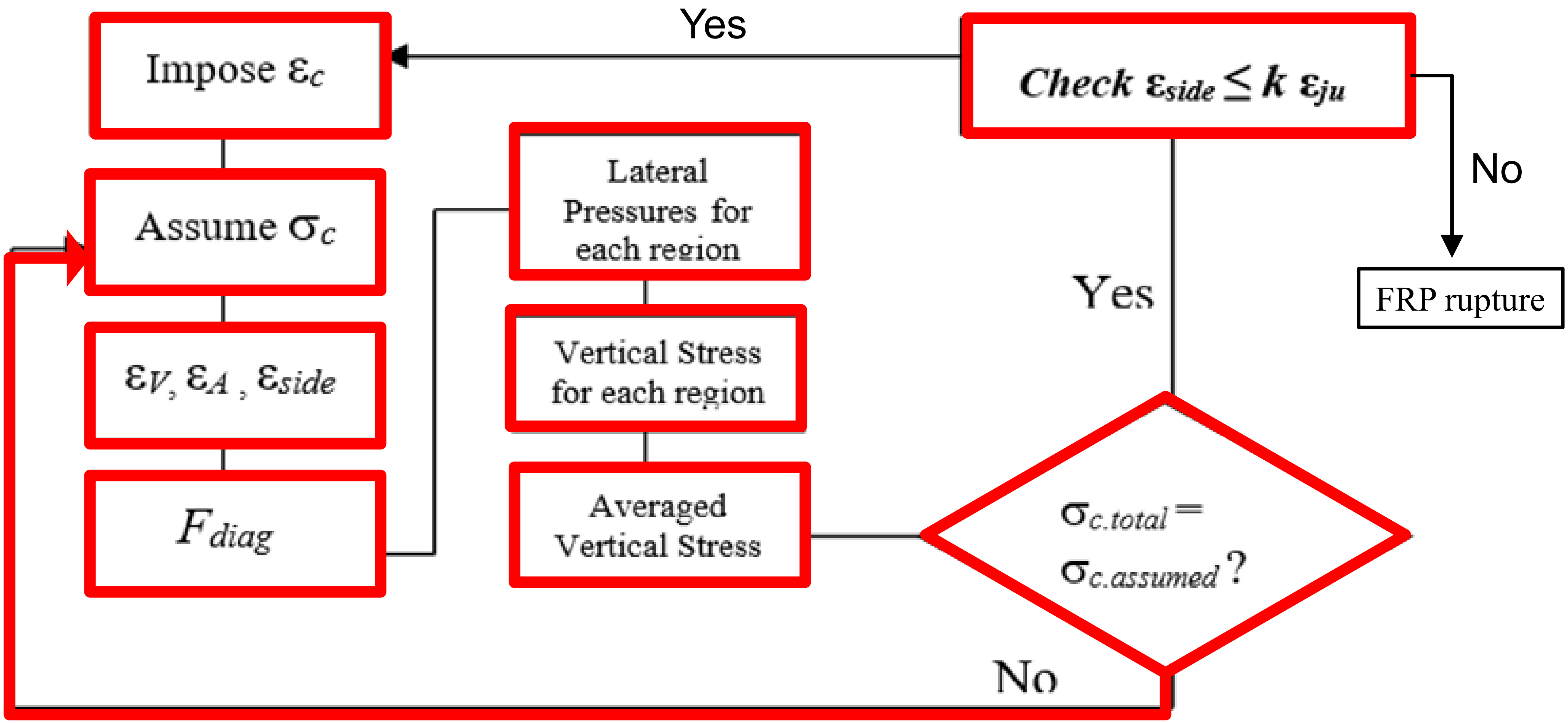
- **No unconfined regions observed.**
- **Concrete is subject to different levels of confinement**
    - **Near the perimeter there is strong directionality (uniaxial confinement)**
    - **Near the centre there is more uniformity (biaxial confinement)**

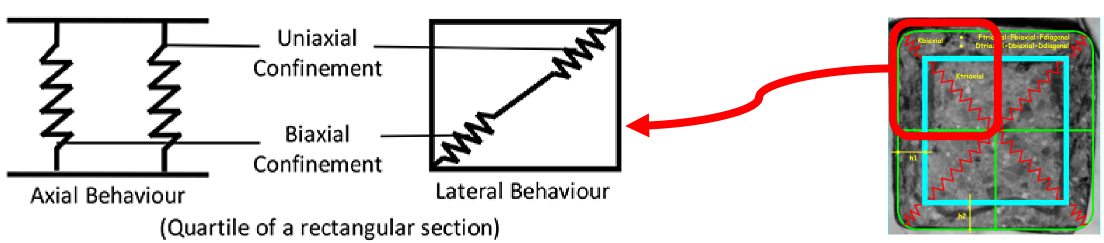


University of Cyprus

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

Proposed Iterative Procedure :





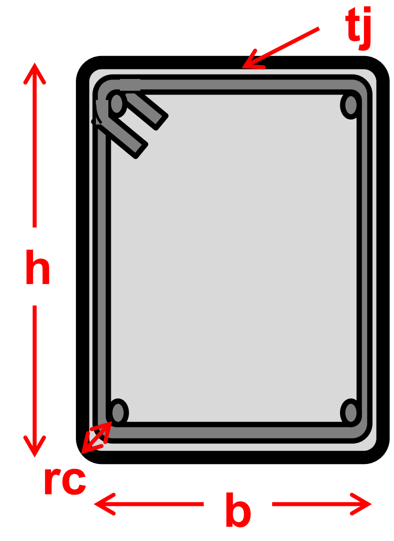
University of Cyprus

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

New Version of Uniaxial Material - "FRPConfinedConcrete" - in OpenSees:

uniaxialMaterial FRPConfinedConcrete ***$matTag $SecTyp $h $w $rc $fpc $Ej $tj $eju $k***

matTag	**Material tag**
SecTyp	**Section Type→ C: circular, R: rectangular**
h	**Section Depth (mm)**
w	**Section Width (mm)**
rc	**Radius of Rounding Corners (mm)**
fpc	**Concrete Strength of Existing RC Column (MPa)**
Ej	**FRP Jacket Elastic Modulus (MPa)**
tj	**FRP Jacket total thickness (mm)**
eju	**Rupture Strain of the FRP jacket from tensile coupons.**
k	**Reduction factor for the rupture strain of the FRP jacket, recommended values 0.5-0.8. (Lam & Teng, 2003)**

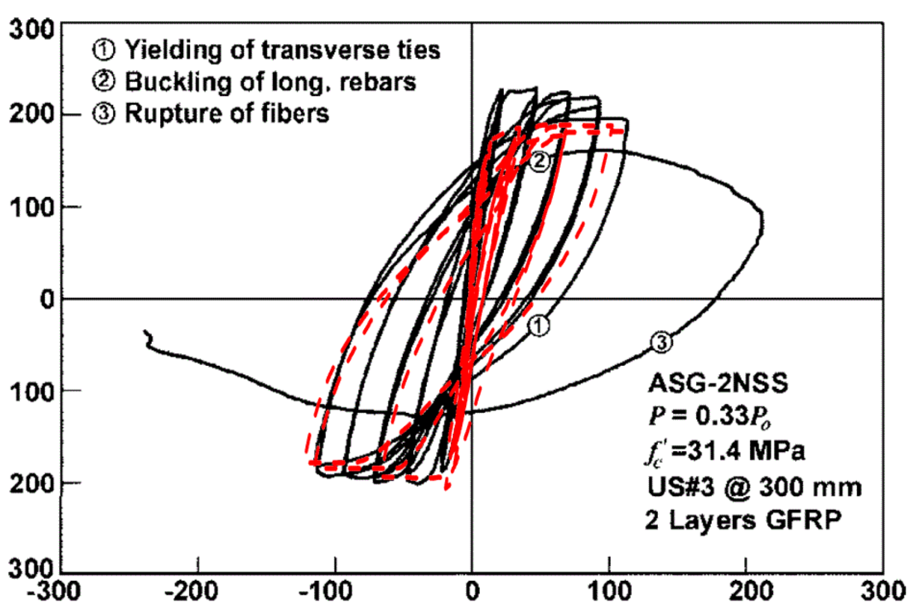


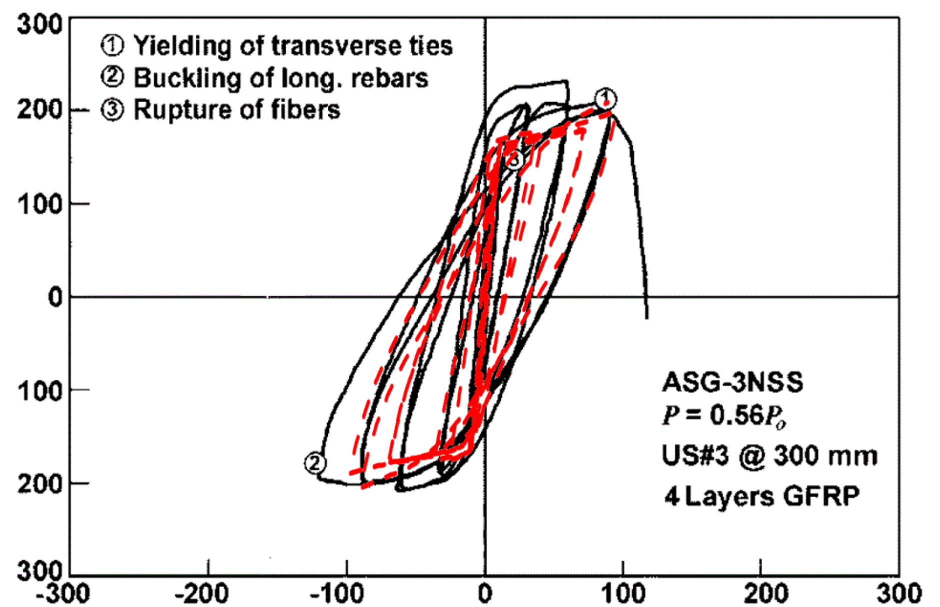
University of Cyprus

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

Correlation with Experimental Results :

Memon and Sheikh (2005)





[x-axis: Curvature x10^{-6} (rad/mm), y-axis: Moment (kNm)]

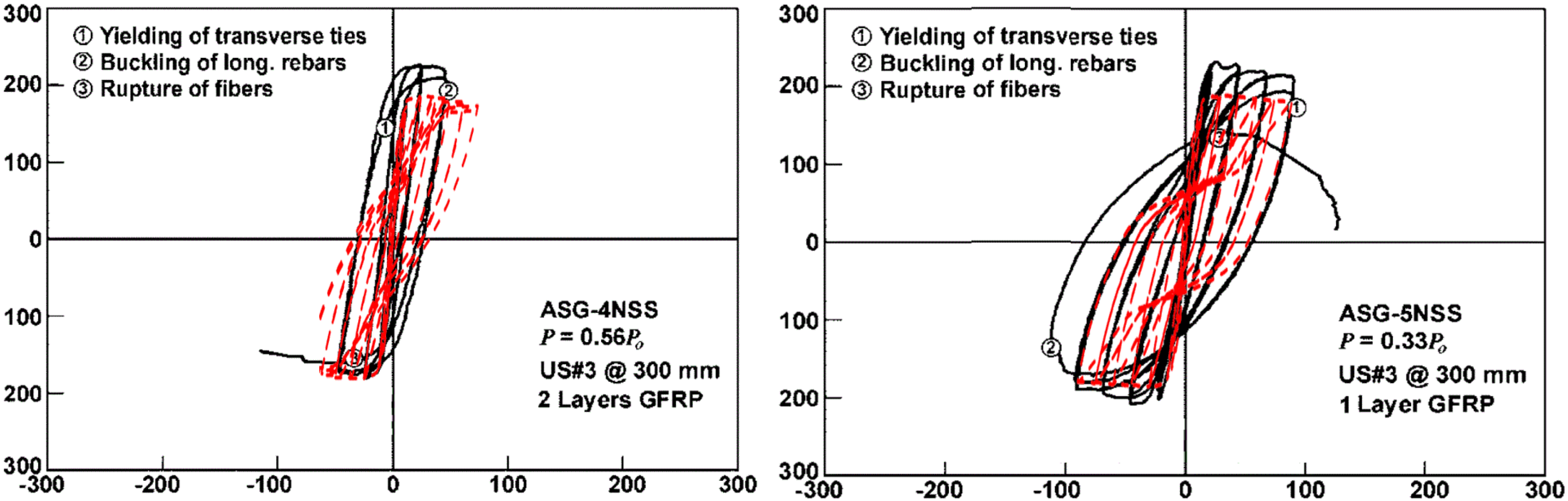
Experiment
Analysis with OpenSees

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

University of Cyprus

Correlation with Experimental Results:

Memon and Sheikh (2005)

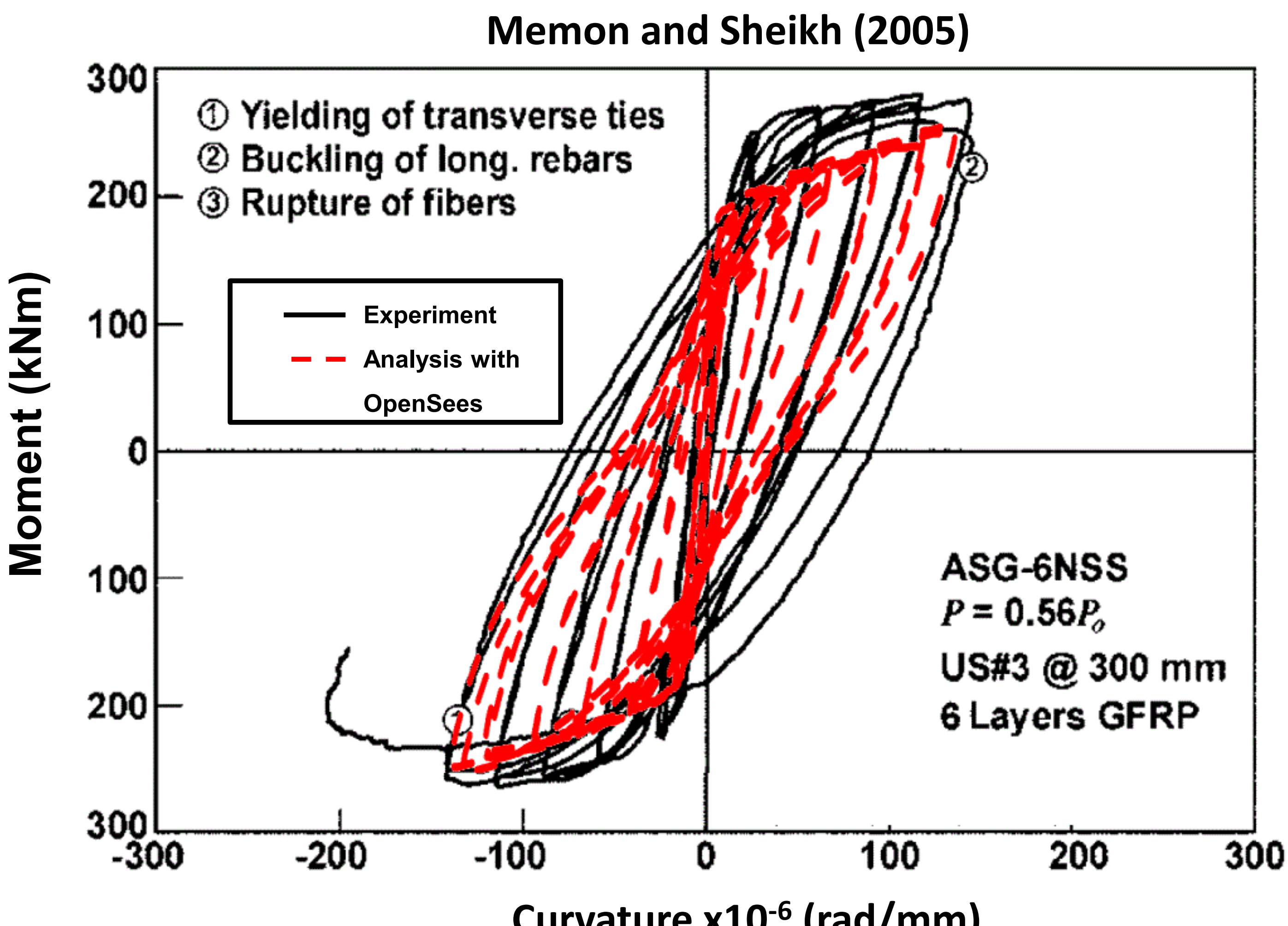


[x-axis: Curvature x10^{-6} (rad/mm), y-axis: Moment (kNm)]

——	Experiment
– –	Analysis with OpenSees

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

Correlation with Experimental Results:



Reference: MEGALOOIKONOMOU KG, Tastani SP, Pantazopoulou SJ. (2018) Effect of Yield Penetration on Column Plastic Hinge Length, *Engineering Structures*, Vol. 156, p. 161-174.

Conclusions:

- **Yield penetration occurs from the critical section towards both the shear span and the support of columns (nonlinear region of reinforcement = Plastic Hinge Length, P.H.L.)**

  ➔ pull-out slip measured at the critical section ➔ contribution of pullout rotation to column drift and column stiffness

- **Contrary to the fixed design values adopted by codes of assessment, the yield penetration length is actually the only consistent definition of the notion of the P.H.L.**

- **In order to establish the plastic hinge length in a manner consistent to the above definition, we pursued the explicit solution of the field equations of bond over the shear span of a column:**

  ➔ principal flexural cracking before stabilization

  ➔ reinforcing bar strain distribution in the disturbed region

  ➔ at ultimate: extent of yield penetration = P.H.L.

- **The numerical results show <u>good agreement</u> with the experimental evidence.**

Reference: MEGALOOIKONOMOU KG (2018) PHAETHON: Software for Analysis of Shear-Critical Reinforced Concrete Columns, *Modern Applied Science*, Vol. 12, No.3, p. 1-22.

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.**

Reference: MEGALOOIKONOMOU K.G., Monti G., Santini S., "Constitutive Model for Fiber –Reinforced Polymer - and Tie – Confined Concrete", *ACI Structural Journal,* Vol. 109, No. 4, July 2012, pp. 569-578.

Conclusions:

- **A recently developed material model for FRP and Steel – confined concrete was implemented in OpenSees under the name 'FRPConfinedConcrete' with no tensile strength and degraded linear unloading/reloading stiffness in the case of cyclic loadings based on the work of Karsan and Jirsa .**

- **In case of bridge pier modelling with a fiber nonlinear beam-column element in which the developed constitutive law for concrete is implemented, the averaged response of the two different regions - concrete core (confined both by the FRP & the existing reinforcement) and concrete cover (confined only with the FRP wrap) - in the cross-section allows the assignment of a unique stress-strain law for all the fibers/layers of the circular section.**

- **The results yielded by the analytical modelling of the cyclic loading procedure of FRP-confined bridge piers are indicative of the effectiveness of the applied material model, i.e. the 'FRPConfinedConcrete', as they were found to simulate with adequate accuracy the records of the experimental procedure.**

Reference: MEGALOOIKONOMOU KG, Papavasileiou GS (2019) Analytical Stress-Strain Model for FRP-Confined Rectangular RC Columns, *Frontiers in Built Environment, Section Earthquake Engineering*. Vol.5, p.39.

Conclusions:

- **A mechanistic model was developed to evaluate the confining effects of FRP jacketing used as a means of retrofitting old columns with a rectangular cross section, in terms of confined concrete stress-strain response.**
- **The model illustrated that the arching action effect which is widely accepted in the literature oversimplifies the true nature of the state of confinement in the encased member.**
- **Confining forces near the perimeter were found to have strong directionality effects. A novel constitutive approach that accounts for the kinematics of the restrained region was developed and implemented along with the fiber model in OpenSees.**
- **All developed methodologies correlate adequately to experimental findings.**

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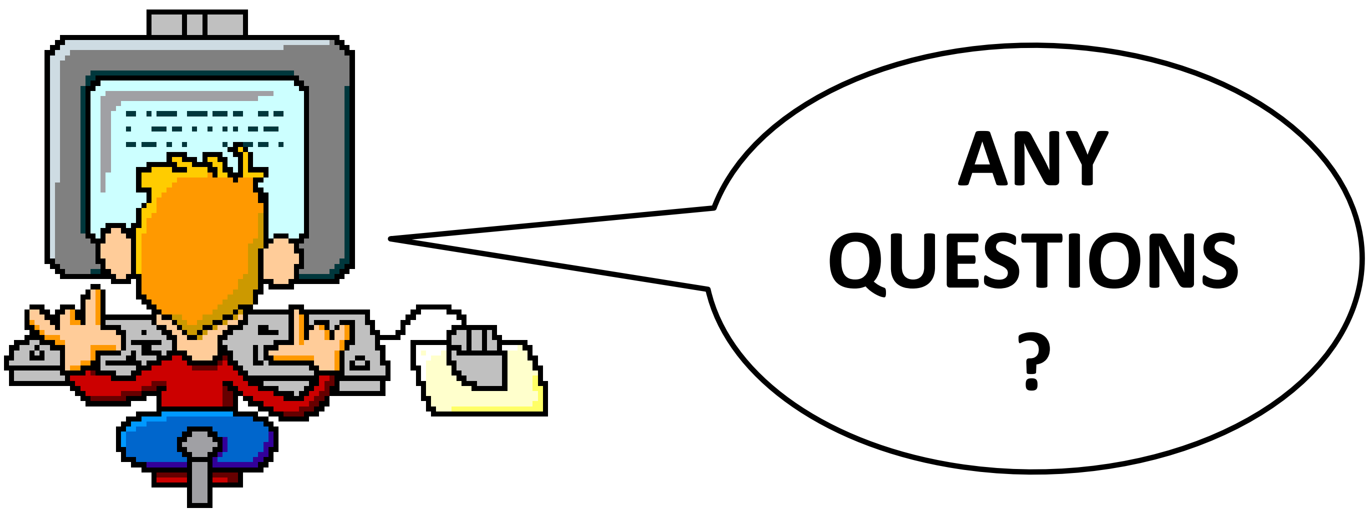
Future Research Priority:

- The Performance-Based Earthquake Engineering main objective is to define an "acceptable" probability of collapse. Collapse shall be quantified as realistically as possible, using non-linear dynamic analysis which incorporates several suites of ground motions.
- A comprehensive set of guidelines will form the starting point for addressing the complexity inherent in nonlinear softening response under large displacements and deformations and will contribute to the acceptance of nonlinear response studies in professional practice.
- The deployment of a new class of column models that account for localized phenomena such as shear and reinforcement pull-out in a consistent iterative element formulation will help minimize the non-convergence issues that arise with the large collection of zero length nonlinear spring and plastic hinge elements currently in use in nonlinear column response simulations.

THANK YOU FOR YOUR ATTENTION!



ACKNOWLEDGEMENTS

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