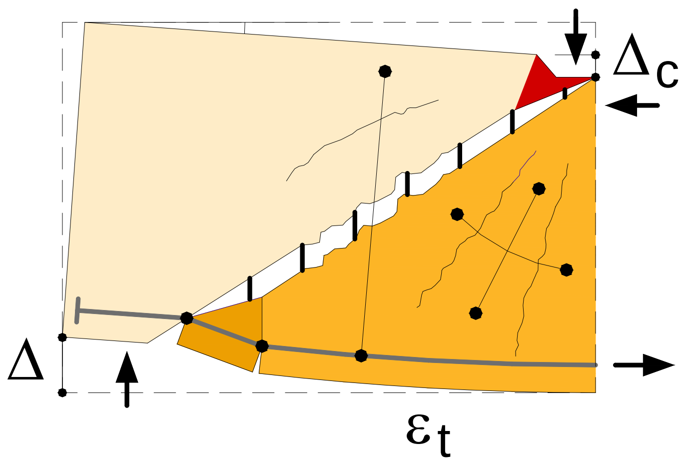
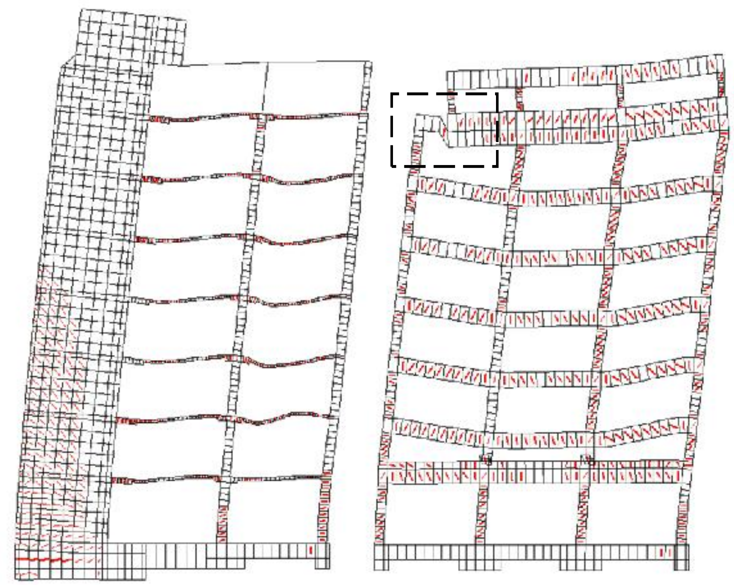
![Université de Liège logo]

Deformation Capacity and Resilience of Structures

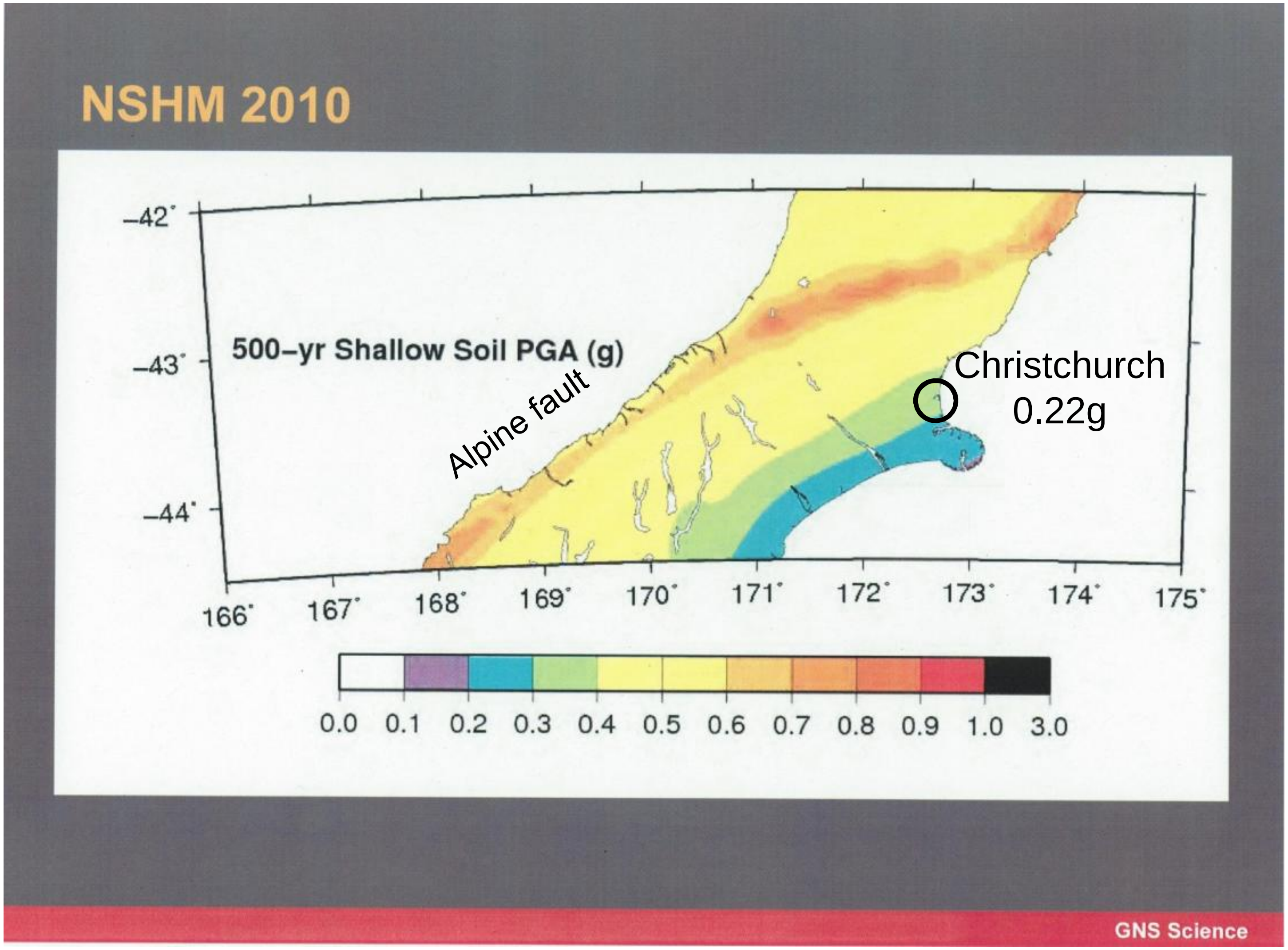




Boyan Mihaylov

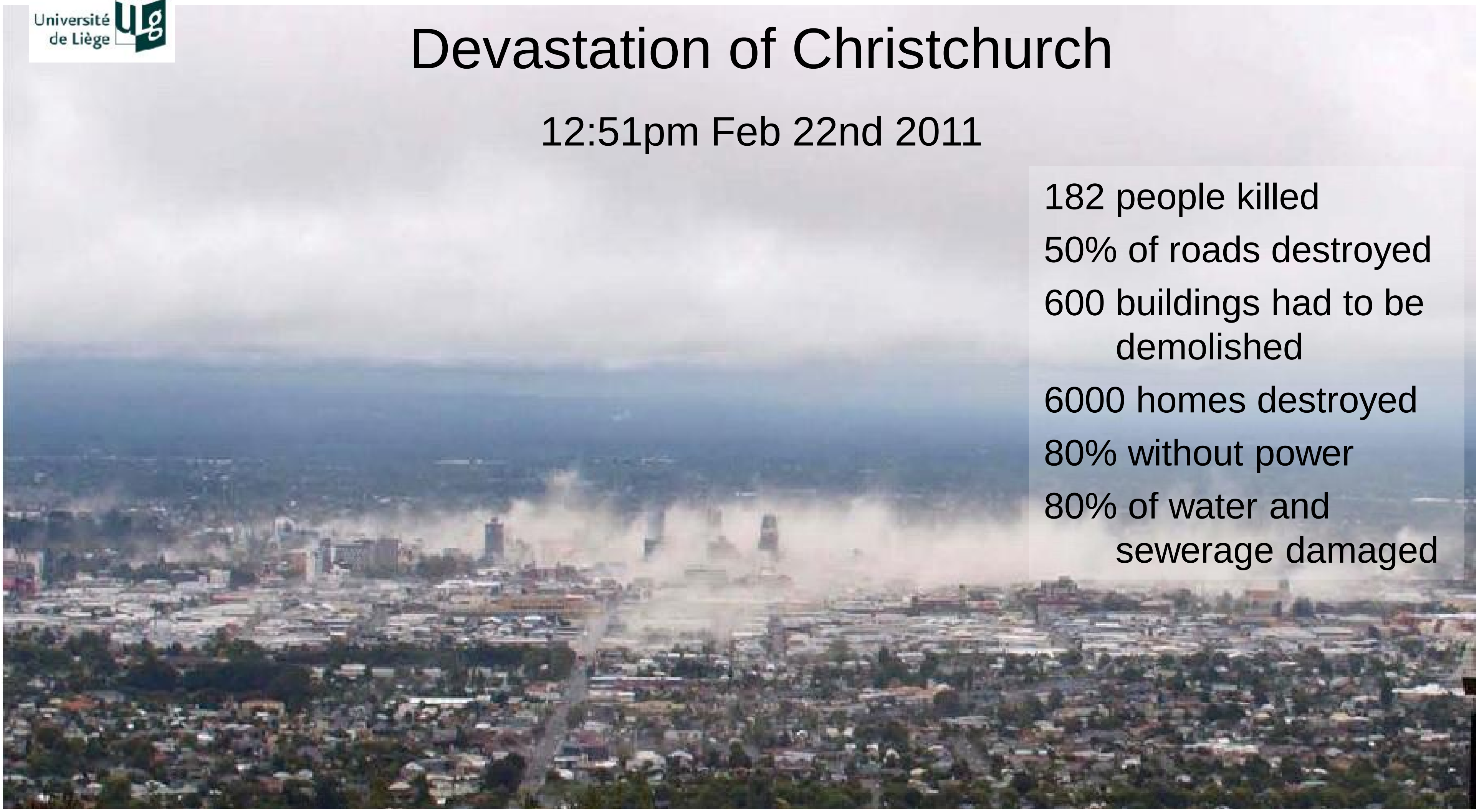
University of Liege, February 4th, 2013

Seismic Hazard Map of New Zealand 2010



Devastation of Christchurch

12:51pm Feb 22nd 2011



182 people killed

50% of roads destroyed

600 buildings had to be demolished

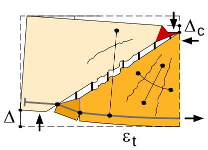
6000 homes destroyed

80% without power

80% of water and sewerage damaged

Horizontal PGA ≈1.0g   Vertical PGA ≈1.8g   Return period ≈2500 years

(design PGA=0.22g)



Design for Rare Events?

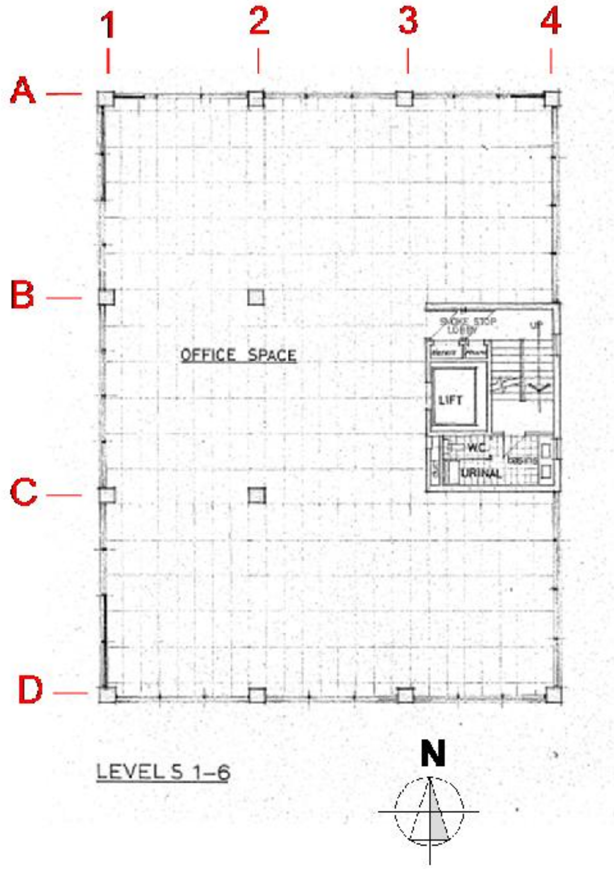
- **Structural resilience**

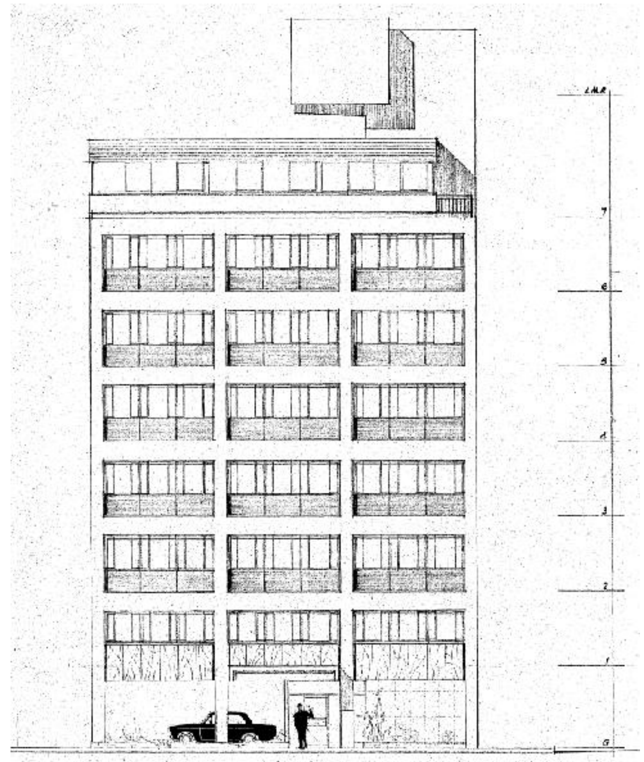
non-resilient structure

resilient structure

- Need for displacement-based **analysis of failure mechanisms** for direct assessment / design for structural resilience

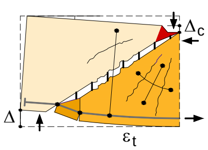
Building in Christchurch





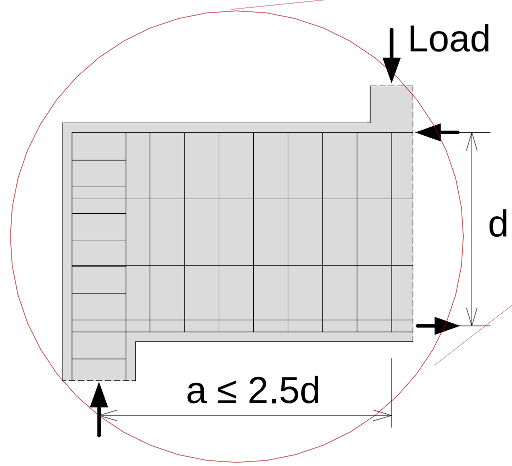
SOUTH

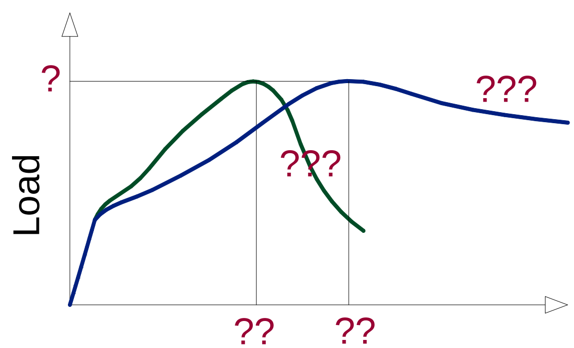
ELEVATION

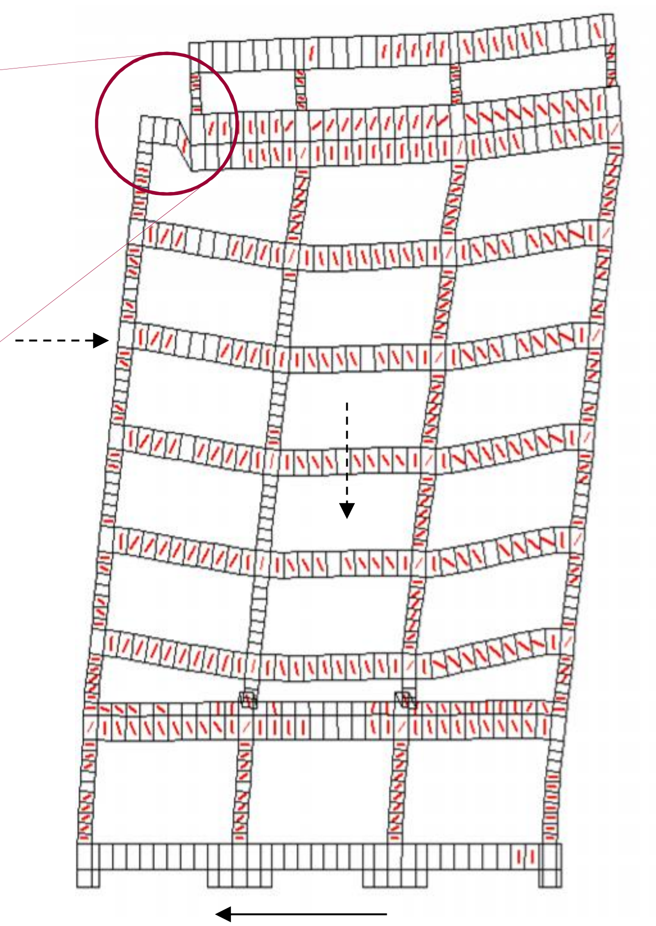


Failure Mechanisms and Deformation Capacity of Structural Members

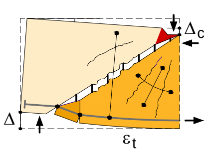
Deep beams $a/d \leq 2.5$







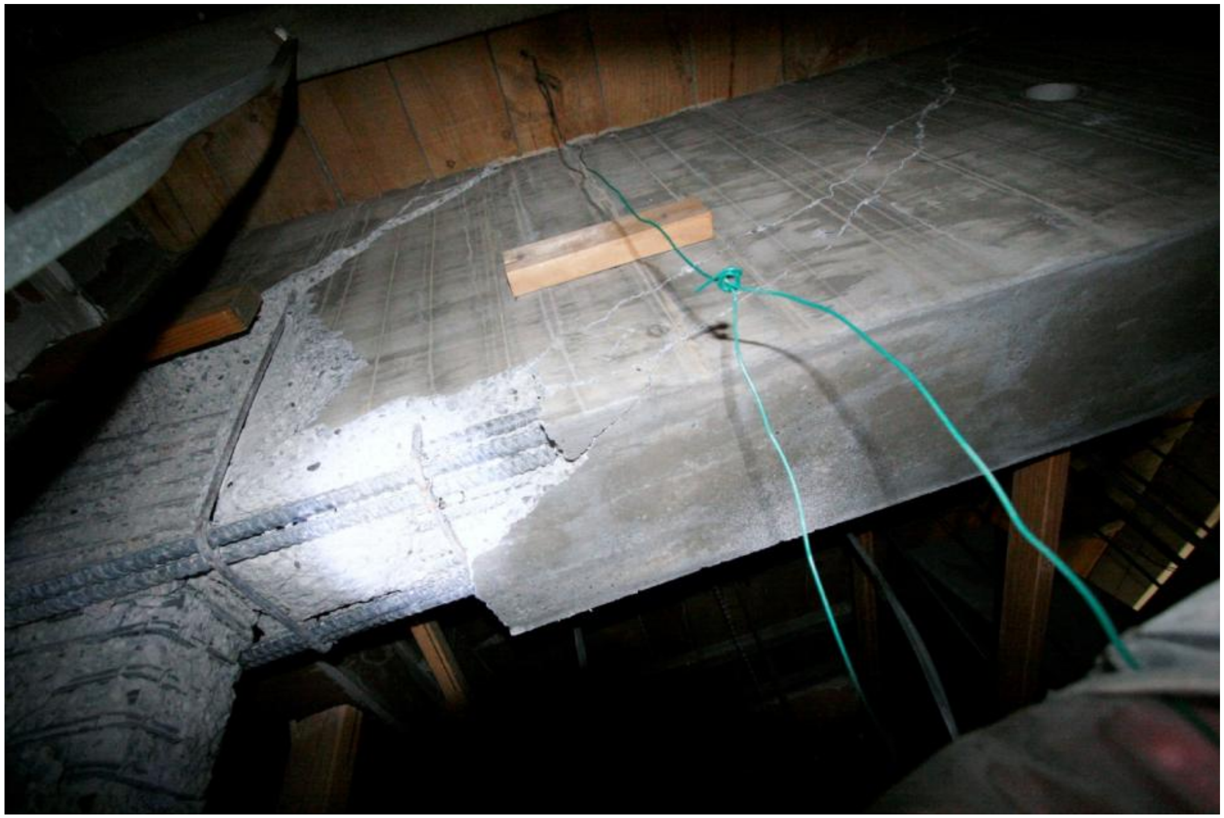
Pushover Analysis by Ruggiero: Augustus-II



Deep Transfer Girder

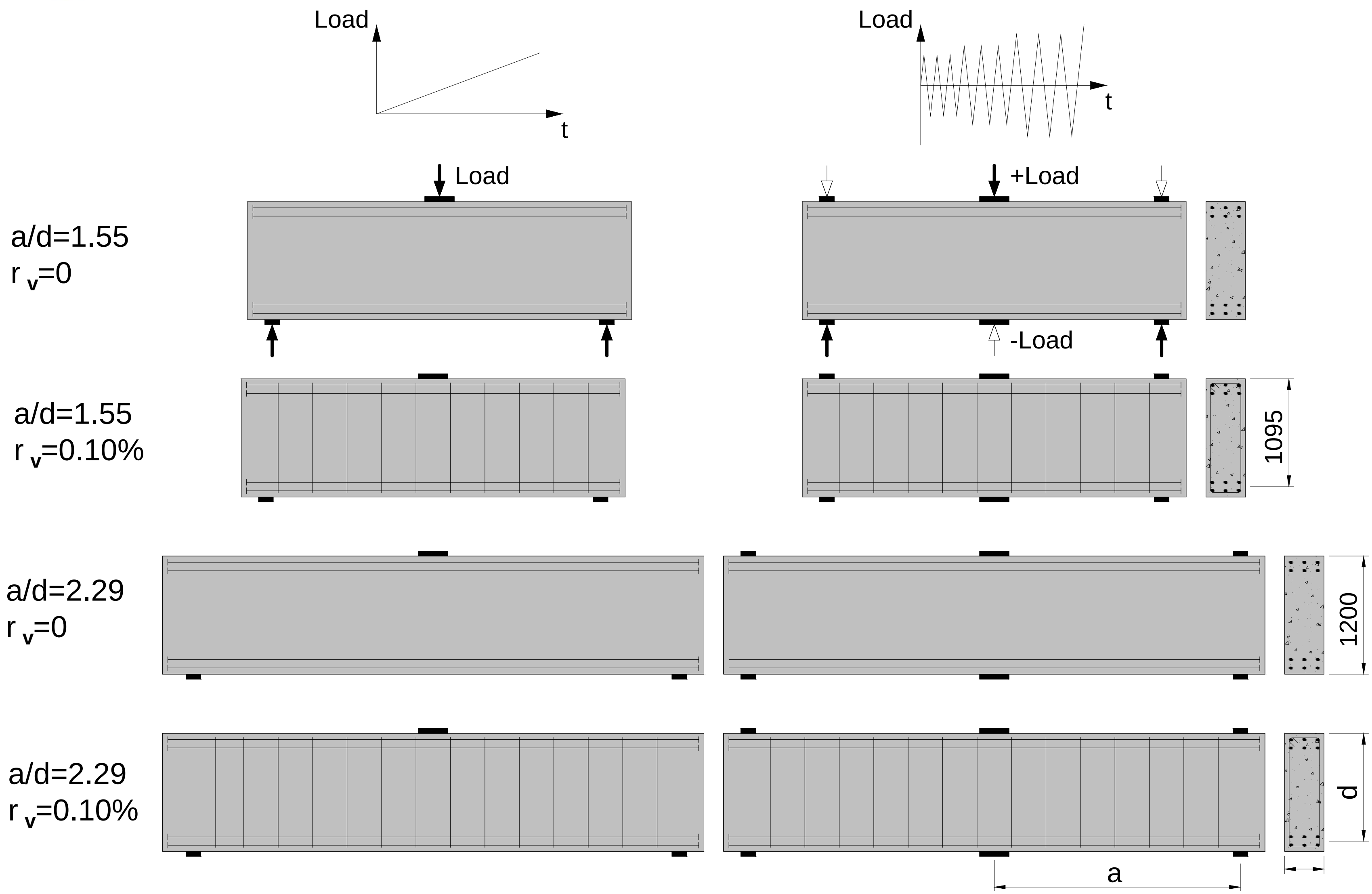
Photograph: Bentz 2008

Deep Transfer Girder

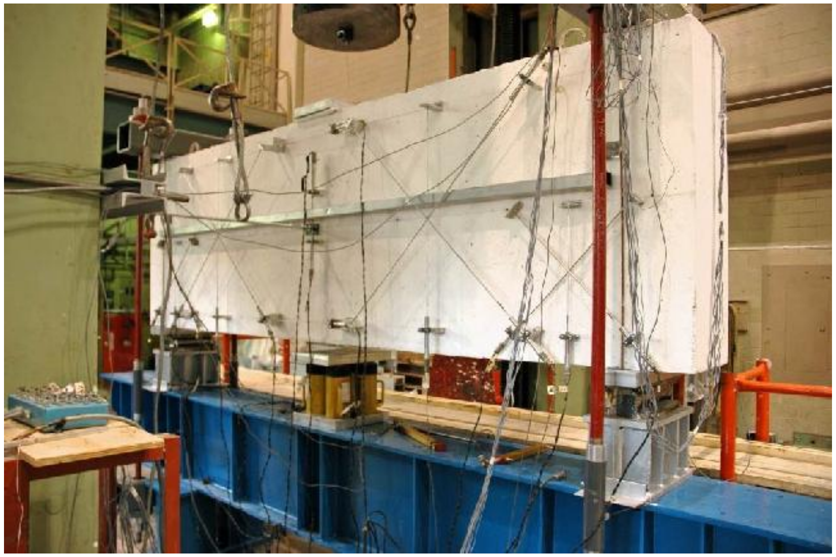


Photograph: Russell Berkowitz, Christchurch 14.03.2011

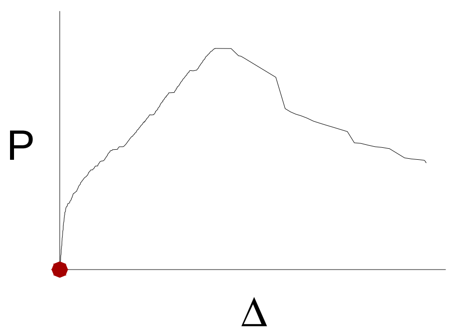
Tests of Deep Beams

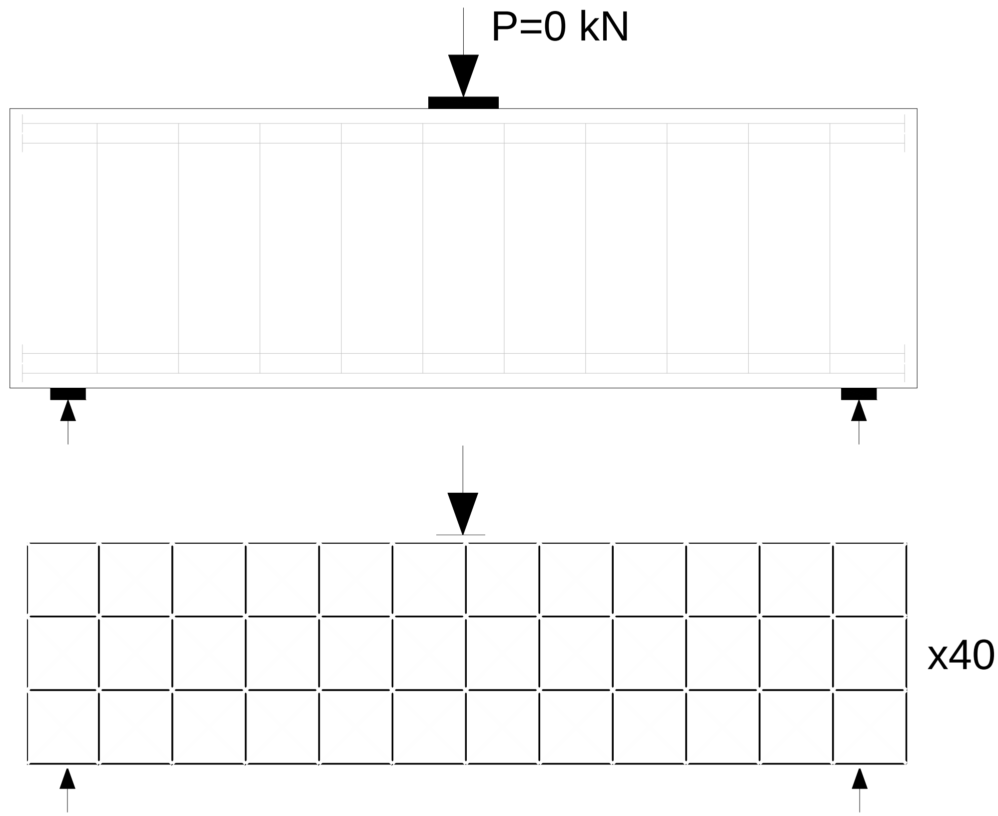


Tests of Deep Beams

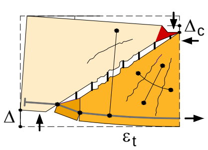


Behaviour of Deep Beams

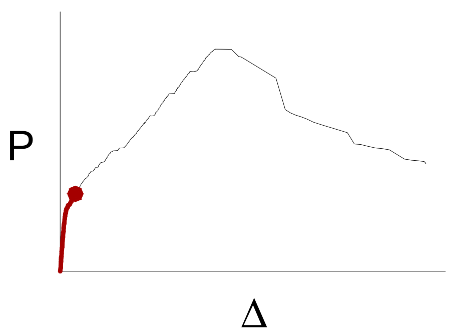


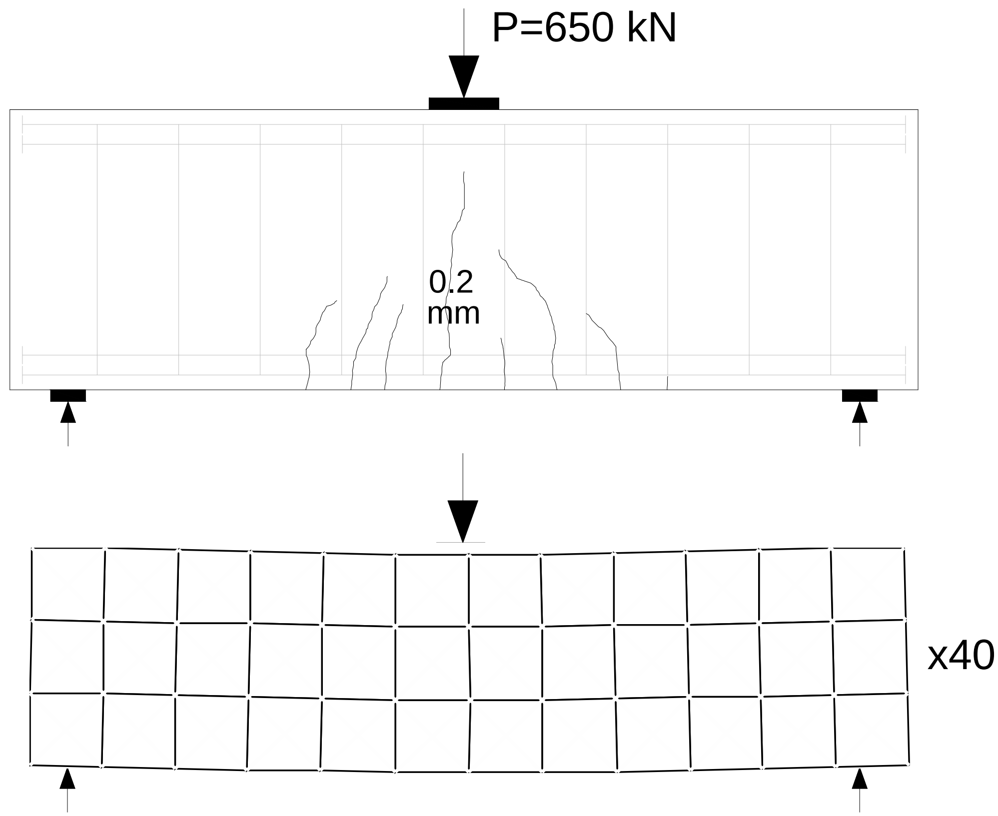


Δ=0 mm



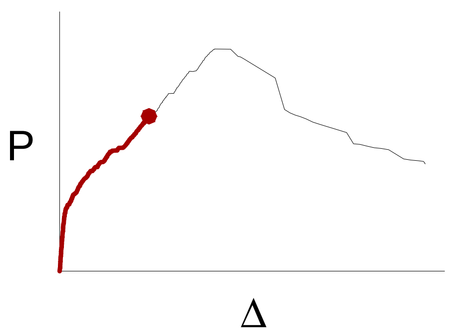
Behaviour of Deep Beams

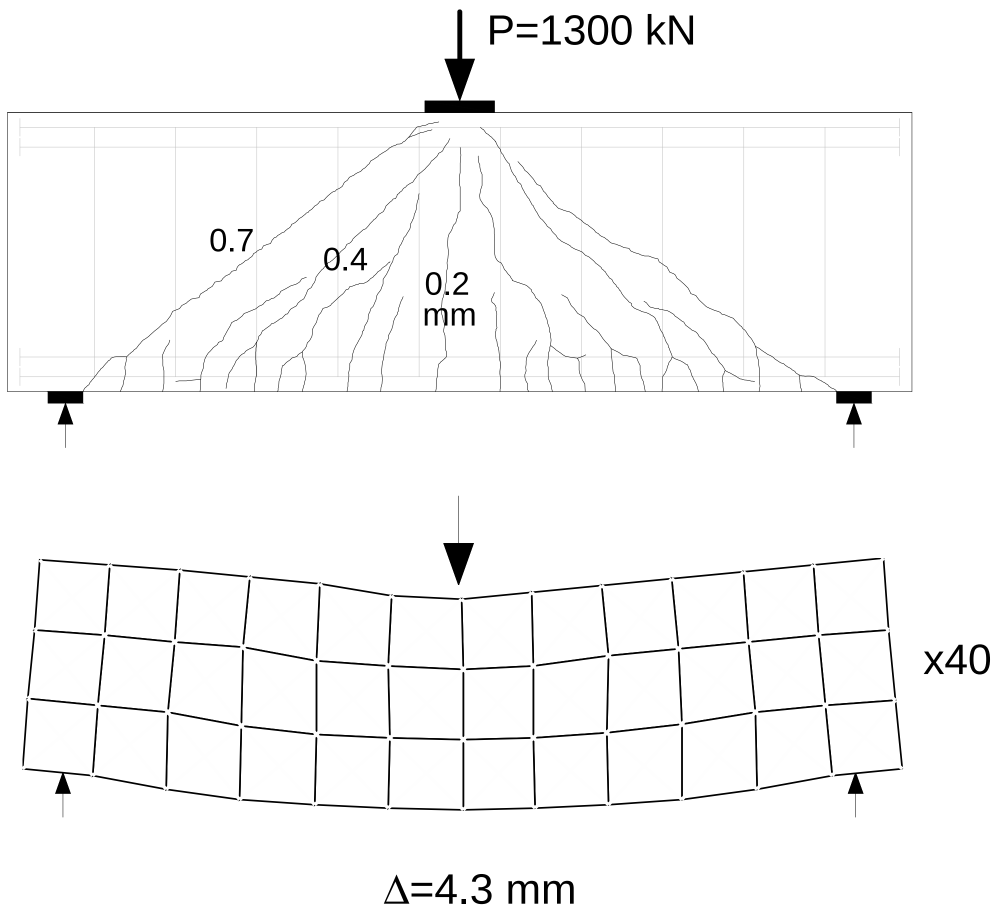


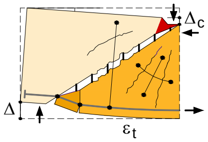


Δ=0.7 mm

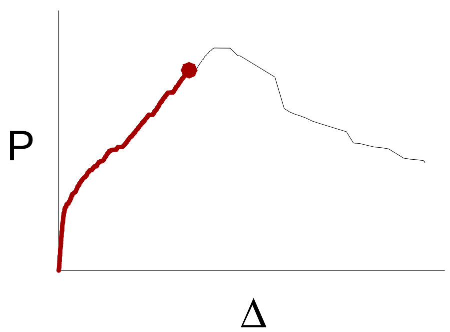
Behaviour of Deep Beams

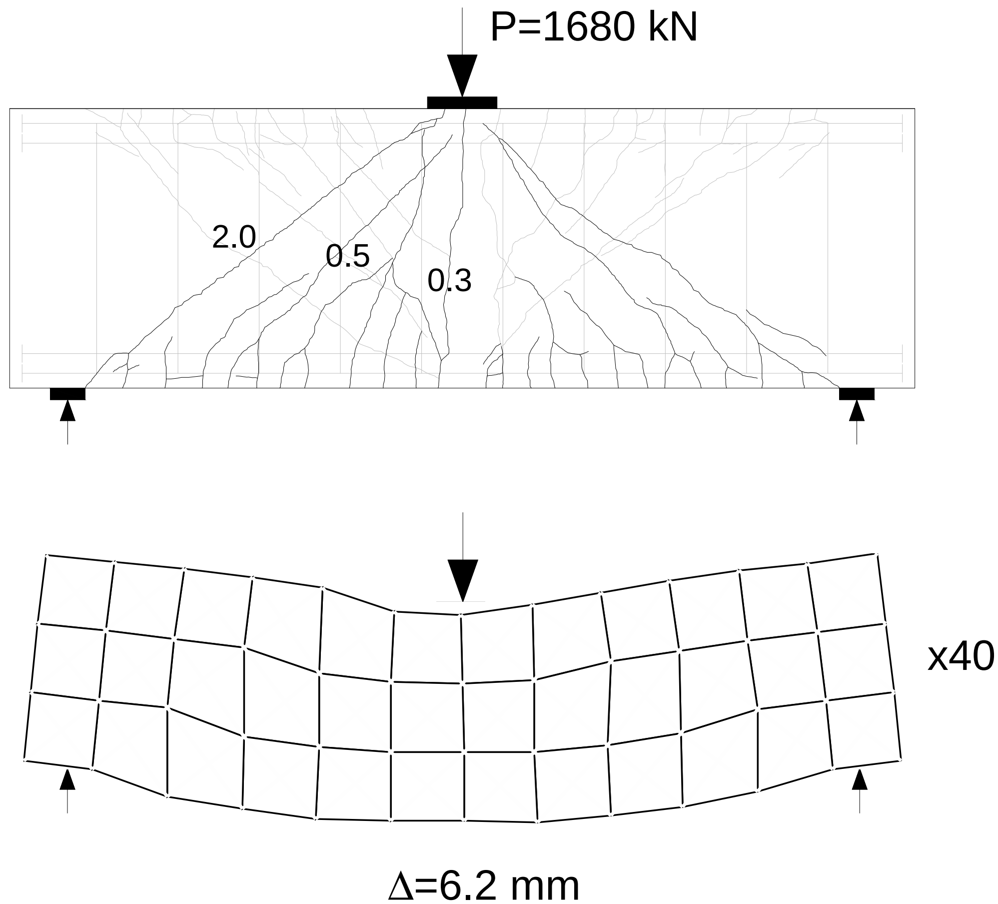


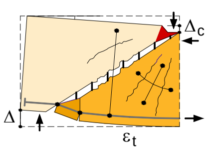




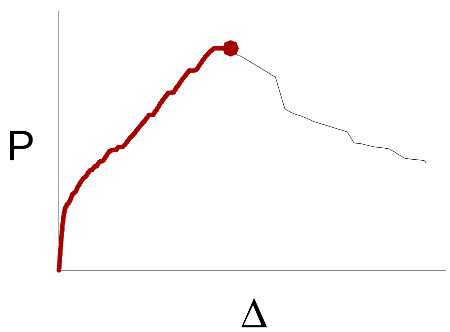
Behaviour of Deep Beams

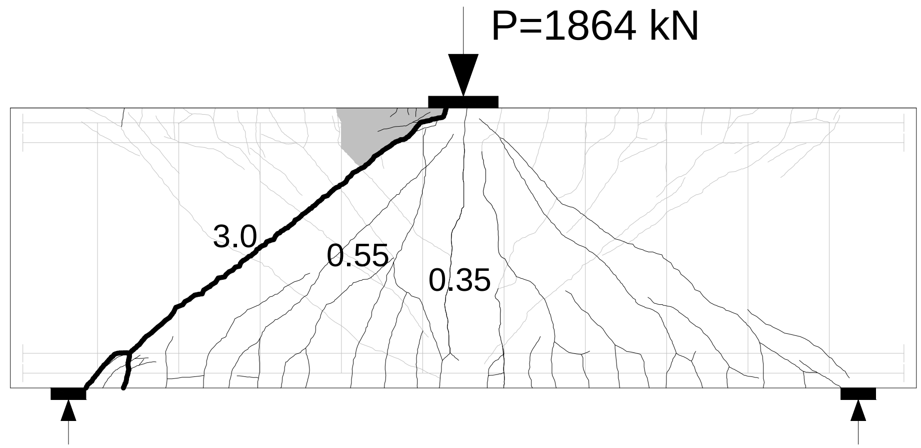


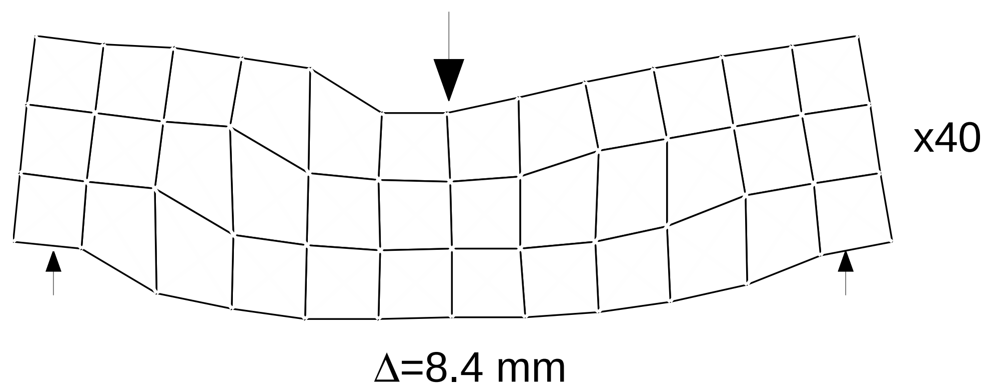


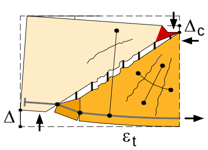


Behaviour of Deep Beams

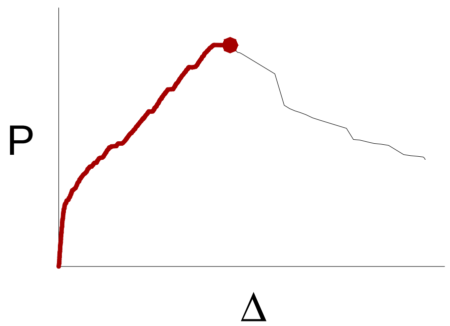


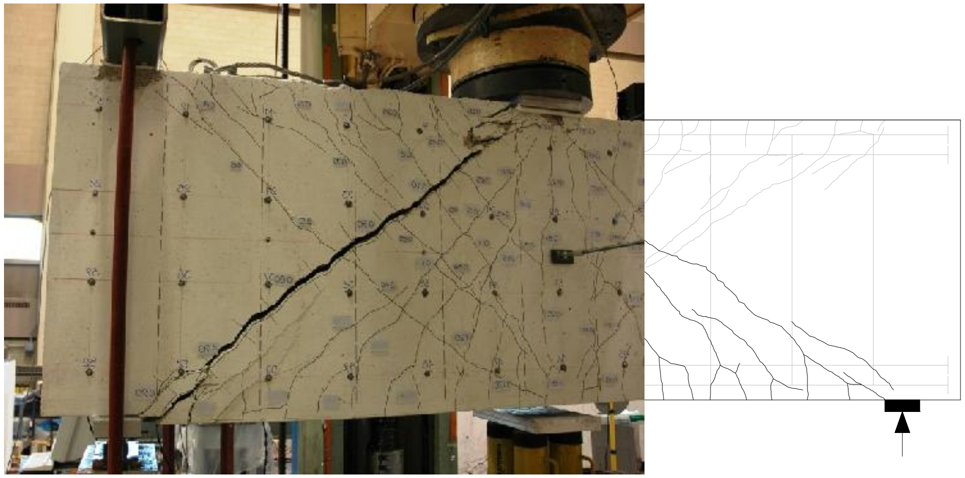


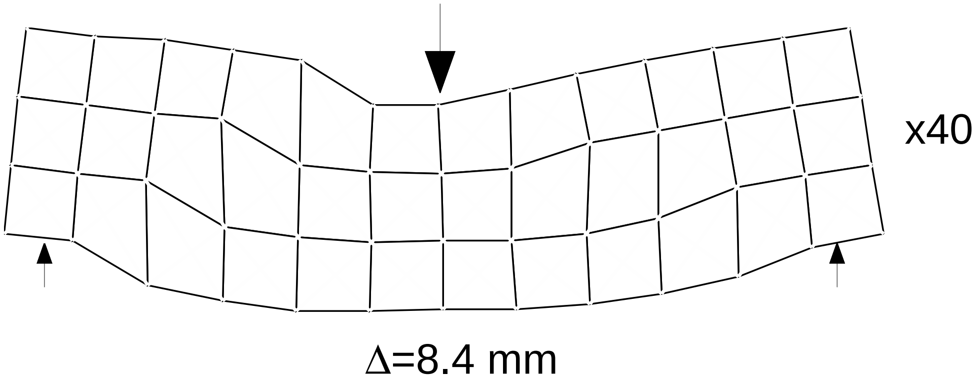


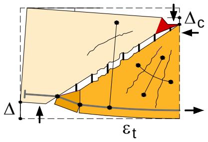


Behaviour of Deep Beams

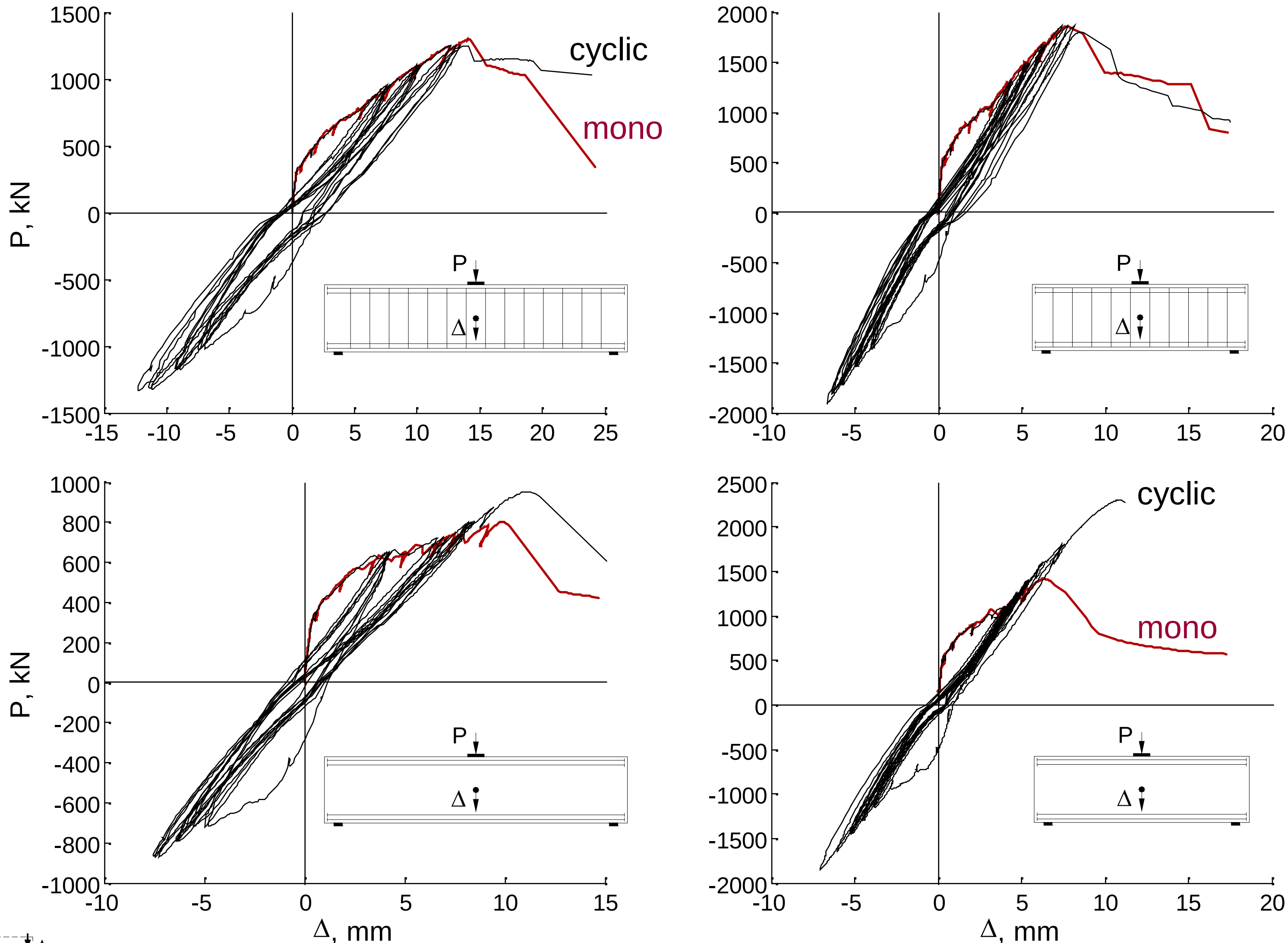


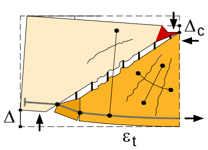




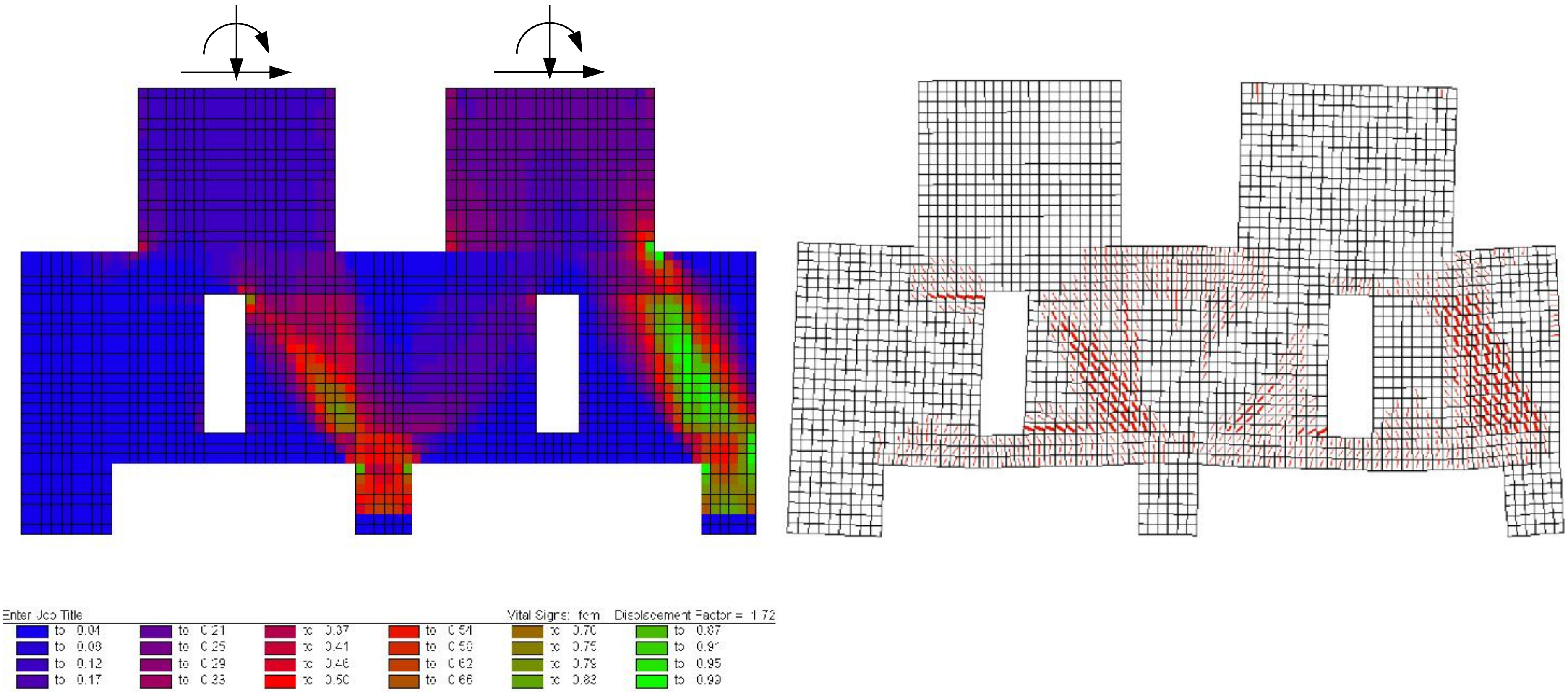


Measured Load-Displacement Response

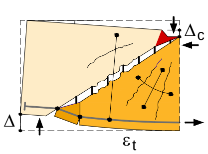




FE Modeling of Deep Beams

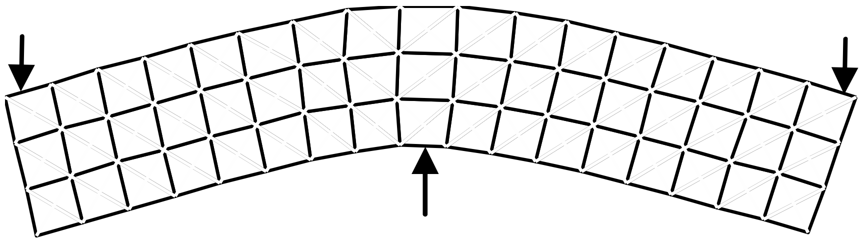


Program VecTor2, F.J. Vecchio, University of Toronto

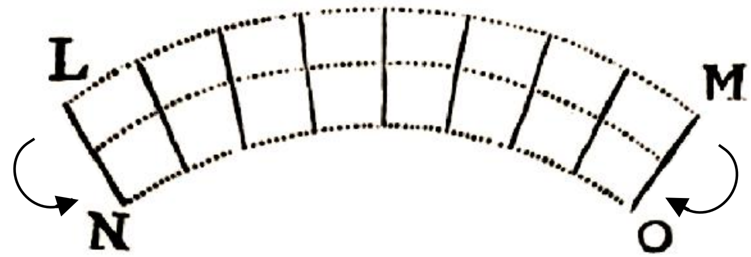


Modeling of Deep Beams – Kinematic Approach

Slender Beams



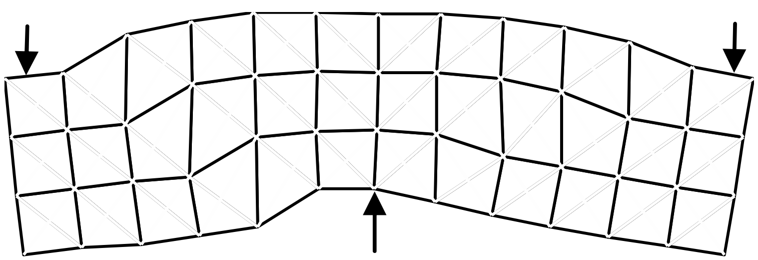
Measured deformations



Plane sections remain plane hypothesis

Robert Hooke 1678

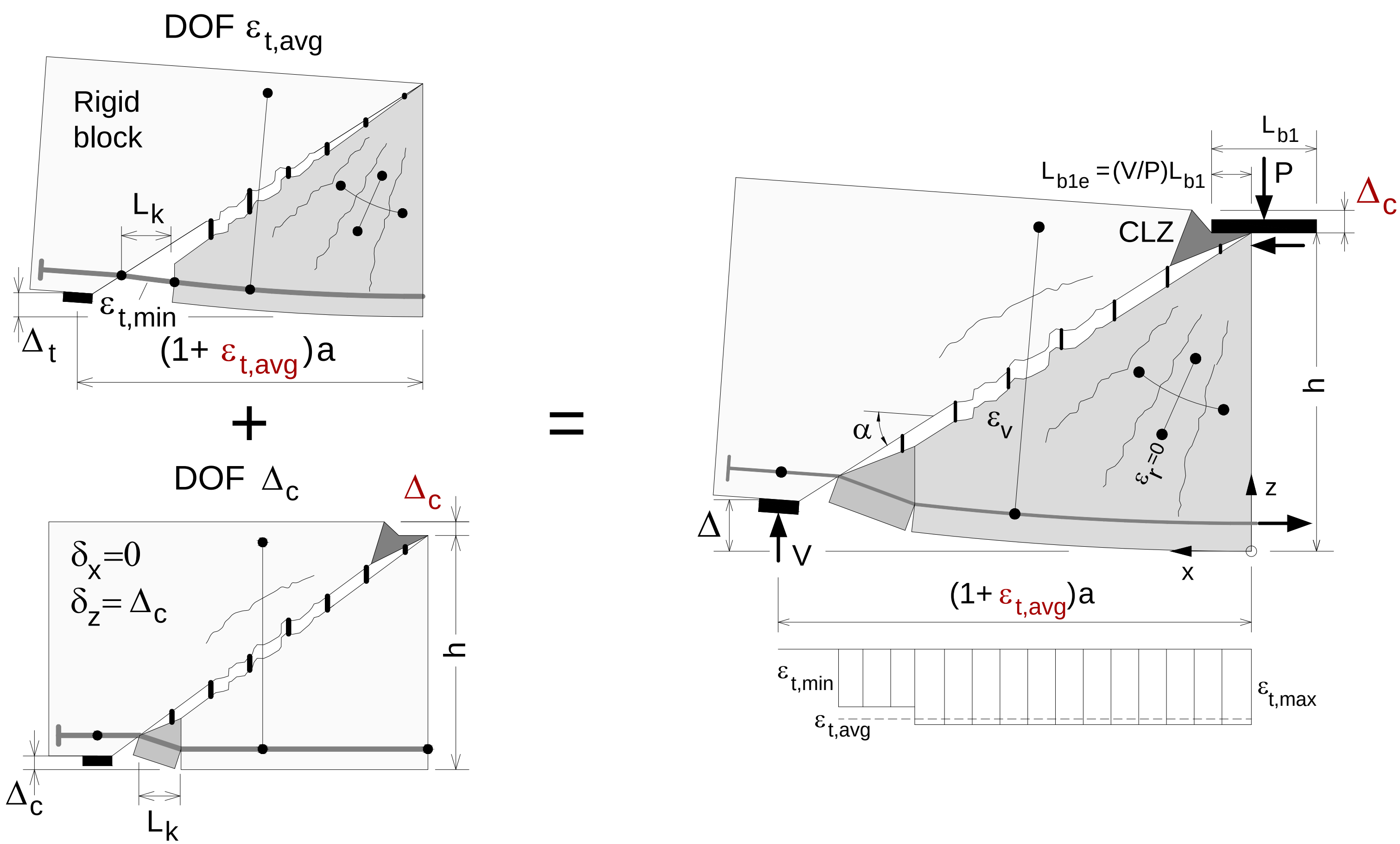
Deep Beams



Measured deformations

Simple kinematic conditions for deep beams?

Two Parameter Kinematic Model



Below the crack:

$$\delta_x(x,z) = \varepsilon_{t,avg}\, x$$

$$\delta_z(x,z) = \frac{\varepsilon_{t,avg}\, x^2}{h - z}$$

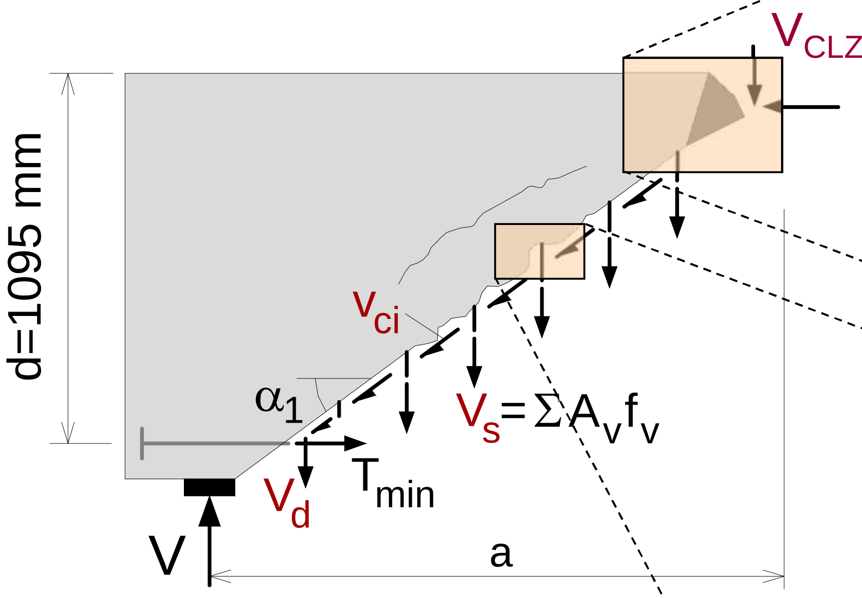
Above the crack:

$$\delta_x(x,z) = \varepsilon_{t,avg}(h - z)\cot\alpha$$

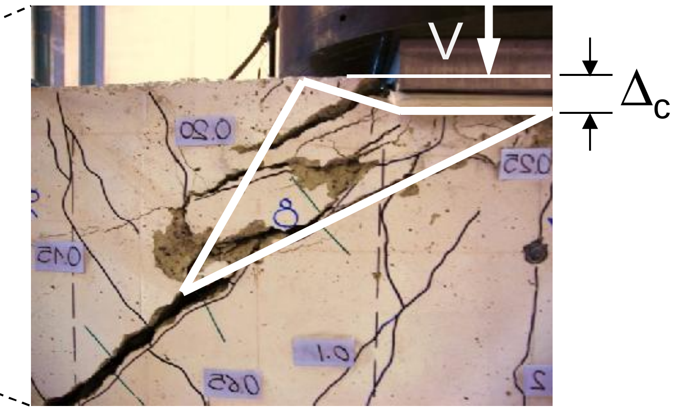
$$\delta_z(x,z) = \varepsilon_{t,avg}\, x \cot\alpha + \Delta_c$$

Boyan Mihaylov

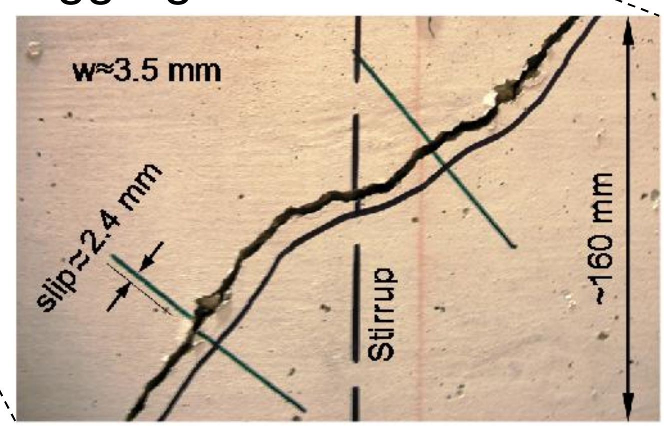
Components of Shear Resistance



Critical Loading Zone



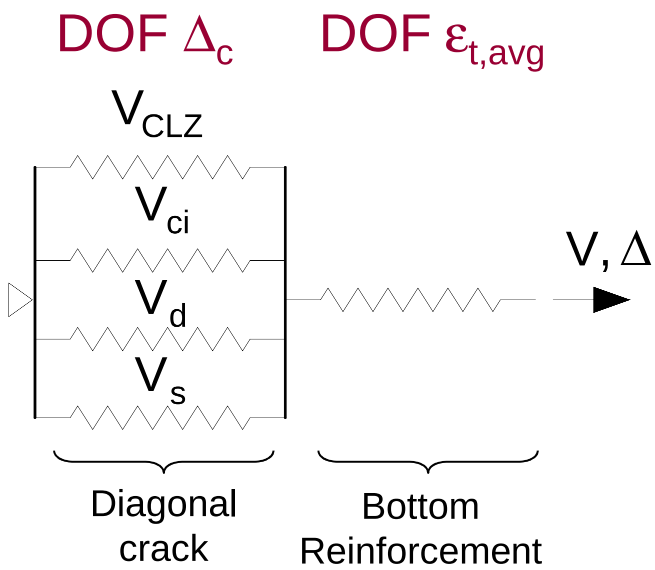
Aggregate interlock

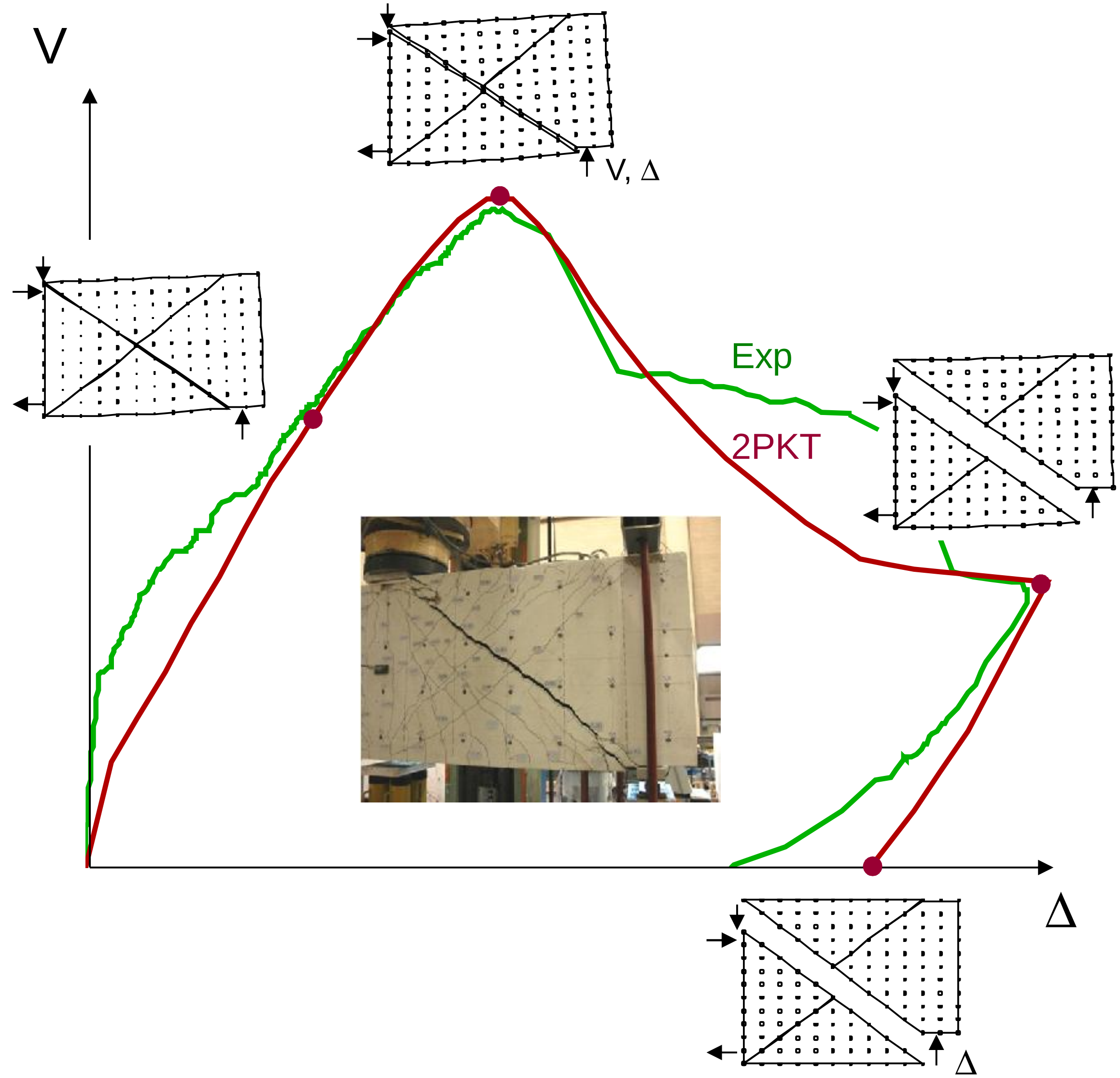


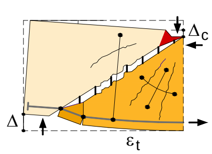
$$V = V_{CLZ} + V_{ci} + V_s + V_d$$

Boyan Mihaylov

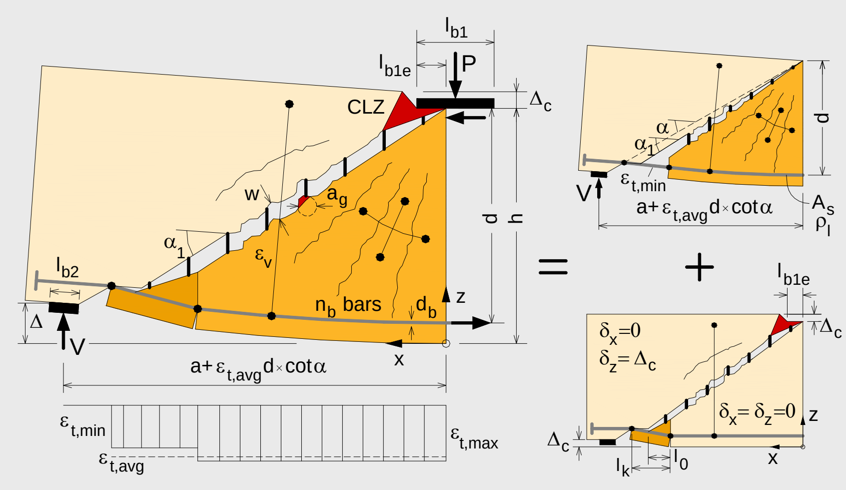
2PKT for Complete Response of Deep Beams







2PKT for Ultimate Response of Deep Beams



1. Degrees of Freedom

(1) $\varepsilon_{t,avg} \approx \varepsilon_{t,\min} \approx \dfrac{Va}{0.9d \times E_s A_s}$

(2) $\Delta_c = 3 \times 0.0035 l_{b1e} \cot\alpha$

2. Geometry

Effective loading plate

(3) $l_{b1e} = (V/P) l_{b1} \ge 3a_g$

Dowel length

(4) $l_k = l_0 + d(\cot\alpha - \cot\alpha_1)$

$l_0 = 1.5(h-d)\cot\alpha_1 \ge s_{\max}$

$s_{\max} = \dfrac{0.28 d_b}{\rho_l}\dfrac{2.5(h-d)}{d}$ *(Ref. 1)*

Crack angle

(5) $\alpha_1 = \max(\alpha, \beta)$

β – based on Simplified MCFT *(Ref. 2)* or 35°

Area of effective stirrups

(6) $A_{ve} = \rho_v b(d\cot\alpha_1 - l_0 - 1.5 l_{b1e}) \ge 0$

3. Compatibility

Displacement field

– below critical crack

(7) $\delta_x = \varepsilon_{t,avg} x$

(8) $\delta_z = \dfrac{\varepsilon_{t,avg} x^2}{h-z}$

– above critical crack

(9) $\delta_x = \varepsilon_{t,avg}(h-z)\cot\alpha$

(10) $\delta_z = \varepsilon_{t,avg} x \cot\alpha + \Delta_c$

Crack width

(11) $w = \Delta_c \cos\alpha_1 + \dfrac{\varepsilon_{t,\min} l_k}{2\sin\alpha_1}$

Stirrup strain

(12) $\varepsilon_v = \dfrac{\Delta_c + 0.25\varepsilon_{t,avg} d \cot^2\alpha_1}{0.9d}$

4. Shear Strength
$V = V_{CLZ} + V_{ci} + V_d + V_s$

Critical loading zone, CLZ

(13) $V_{CLZ} = 1.43 f_c'^{0.8} k b l_{b1e} \sin^2\alpha$

$0 \le k = 1 - 2(\cot\alpha - 2) \le 1$

Dowel action

(14) $V_d = n_b f_{ye} \dfrac{d_b^3}{3 l_k}$

$f_{ye} = f_y\left[1 - \left(\dfrac{\varepsilon_{t,\min} E_s}{f_y}\right)^2\right] \le 500\,MPa$, ≥ 0

Aggregate interlock

(15) $V_{ci} = \dfrac{0.18\sqrt{f_c'}}{0.31 + \dfrac{24w}{a_g + 16}} bd$ *(Ref. 3)*

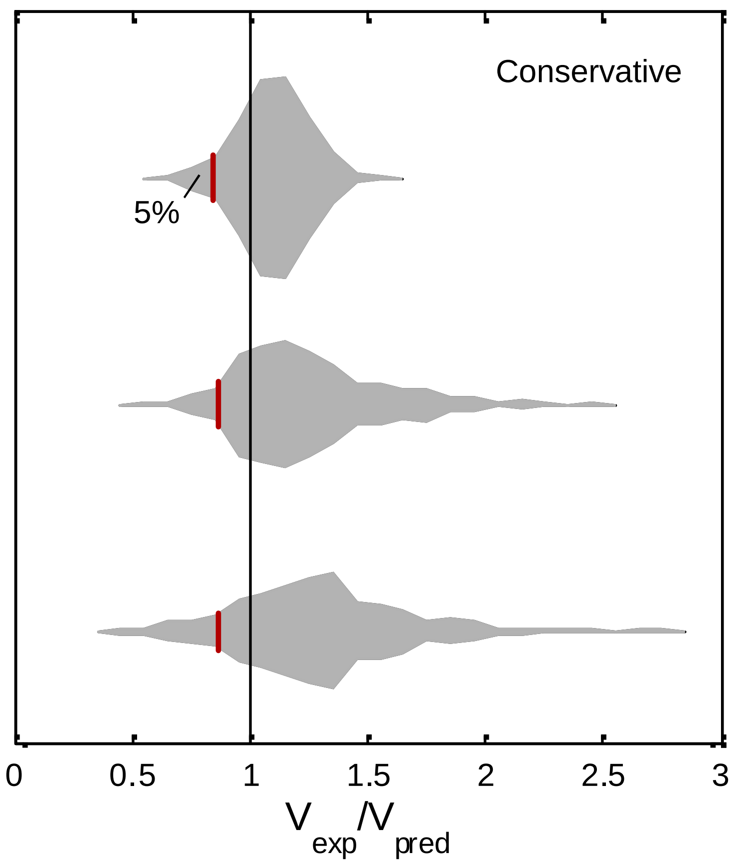
Stirrup capacity

(16) $V_s = A_{ve} f_v$

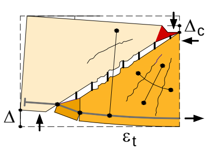
$f_v = E_s \varepsilon_v \le f_{yv}$

Boyan Mihaylov

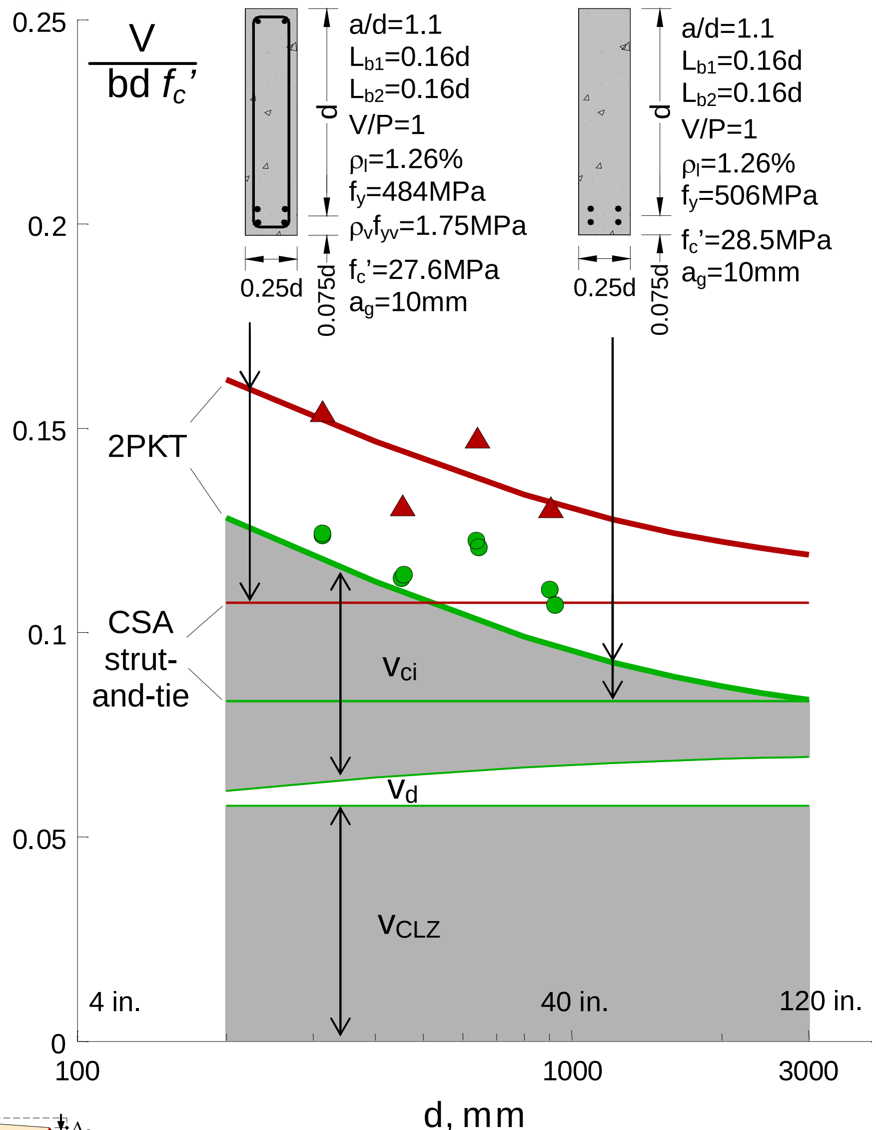
Predicted Shear Strength, 434 Tests

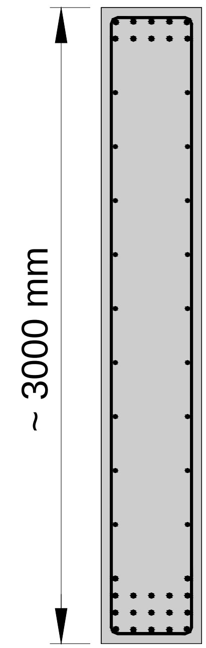


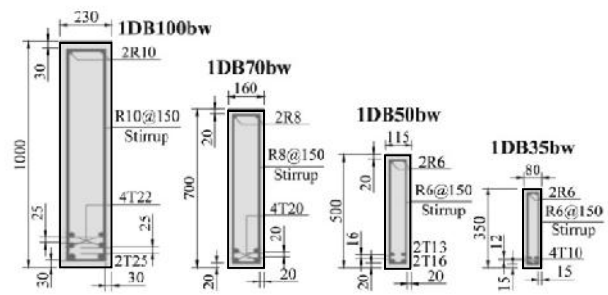
	Avg.	COV
2PKT	1.10	13.7%
Canadian Standards Association	1.25	24.6%
American Concrete Institute	1.30	29.0%



Size Effect in Deep Beams



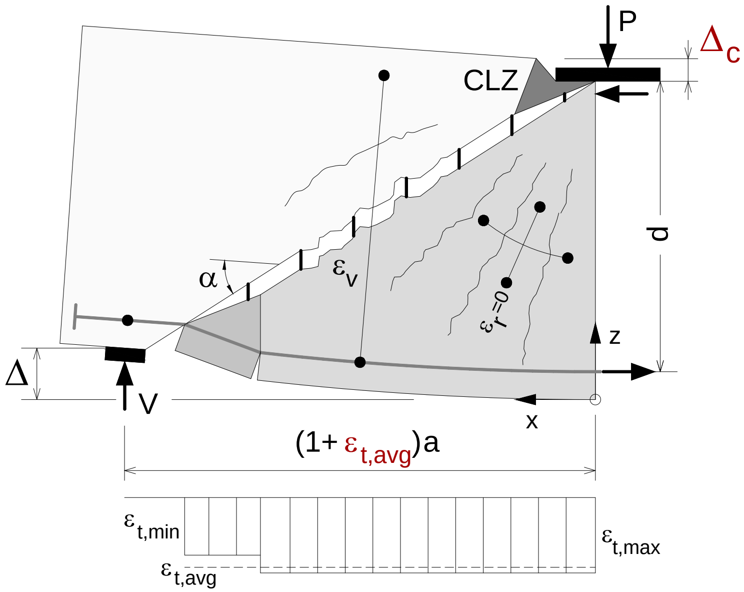




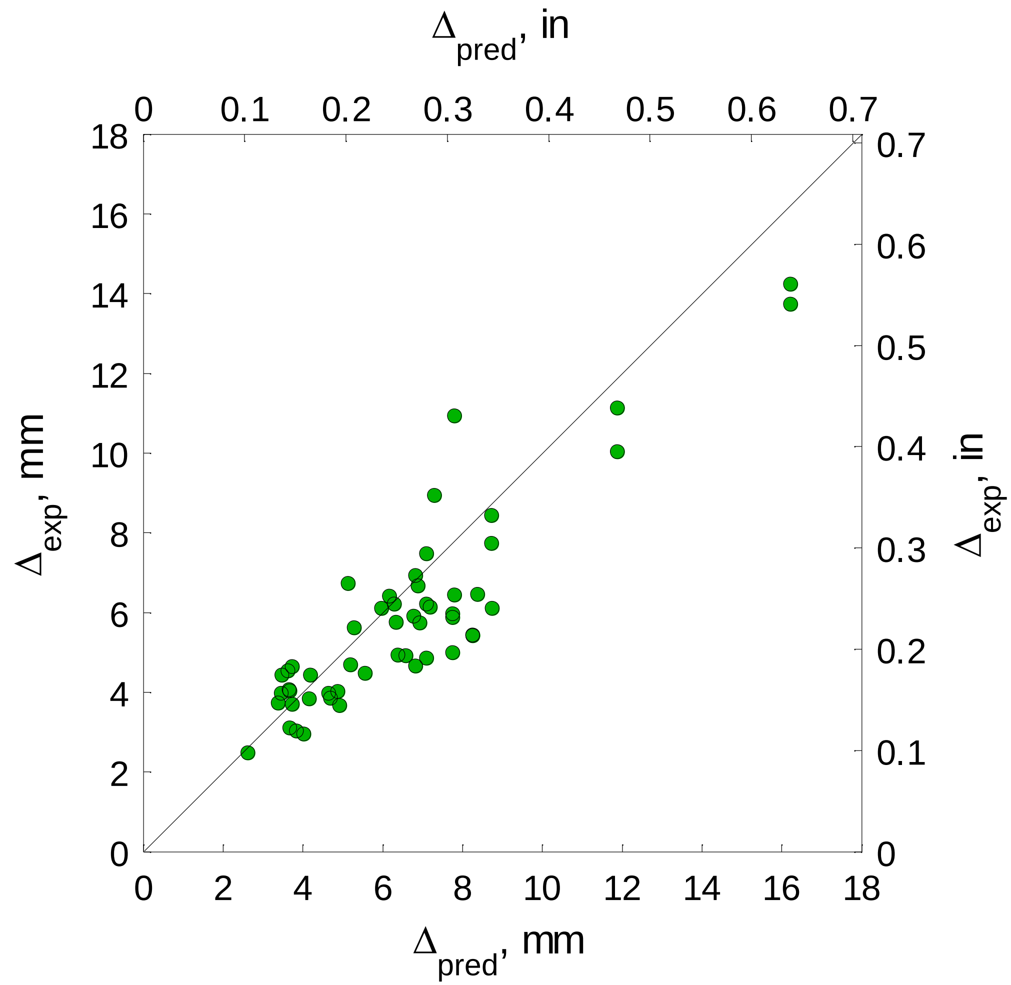
Transfer girder in building

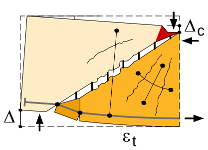
Tests by Zhang & Tan, 2007

Predicted Displacement Capacity, 53 Tests

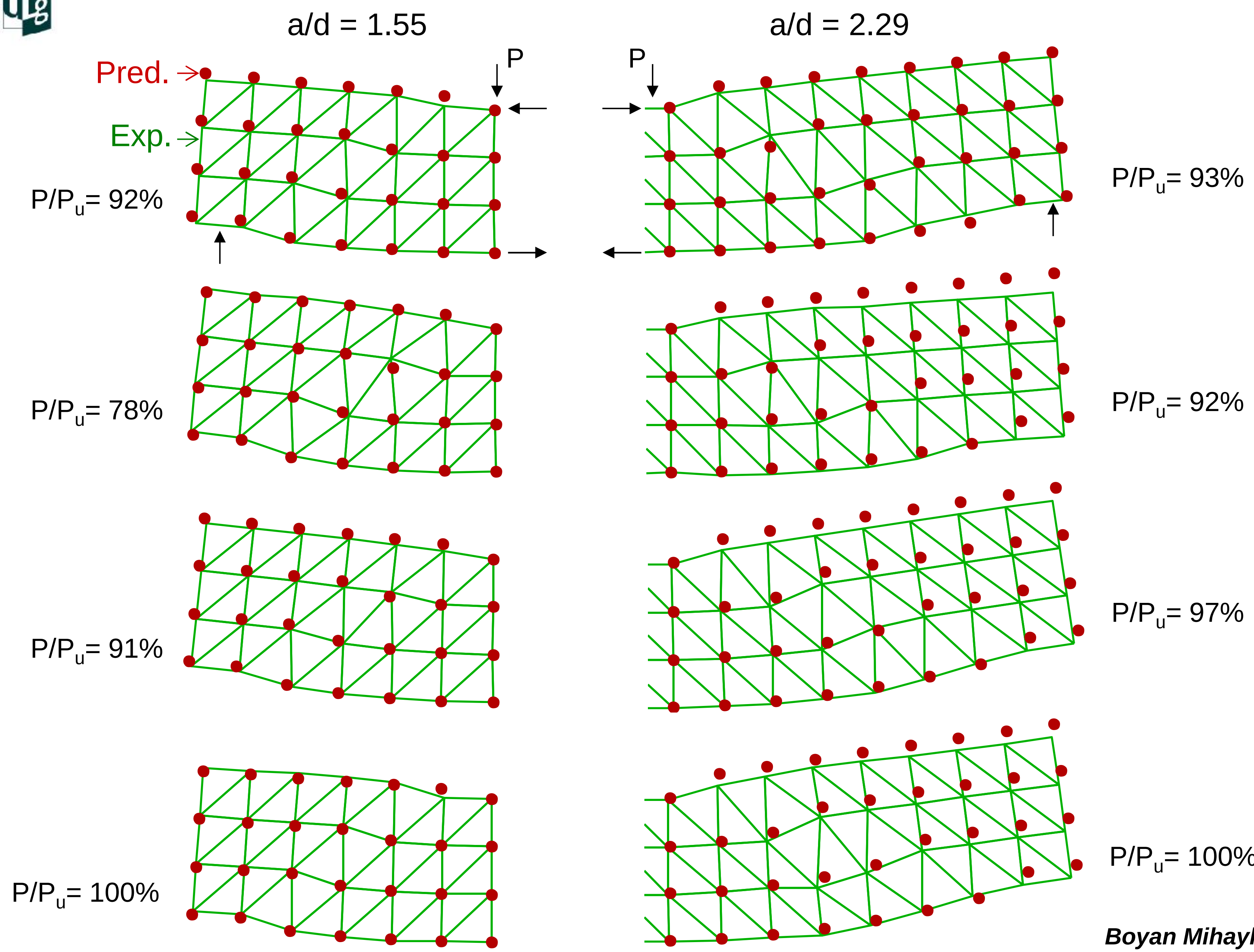


$$\Delta = \Delta_c + \left[\varepsilon_{t,\max}\left(d\cot\alpha - L_k\right) + \varepsilon_{t,\min}L_k\right]\frac{a}{d}$$





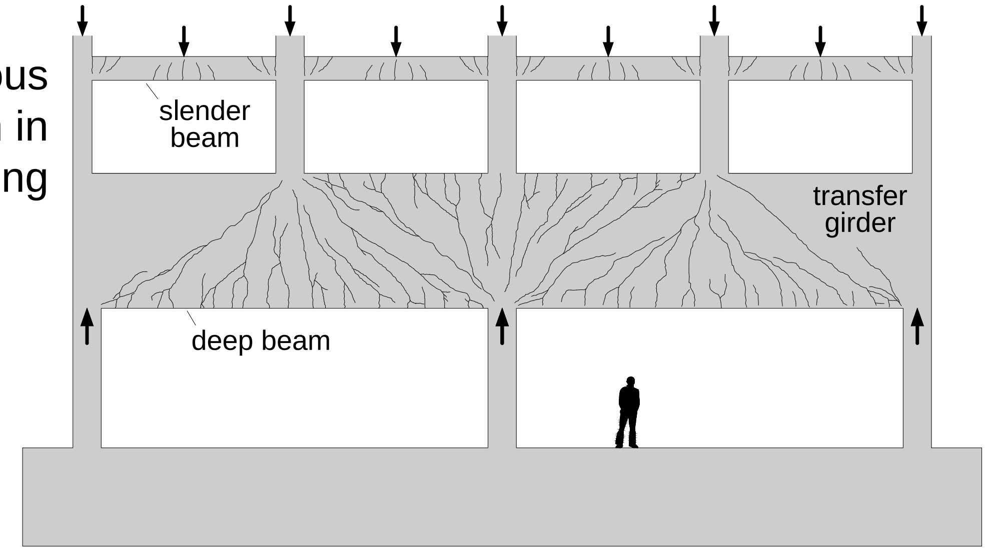
Predicted Deformed Shapes



Boyan Mihaylov

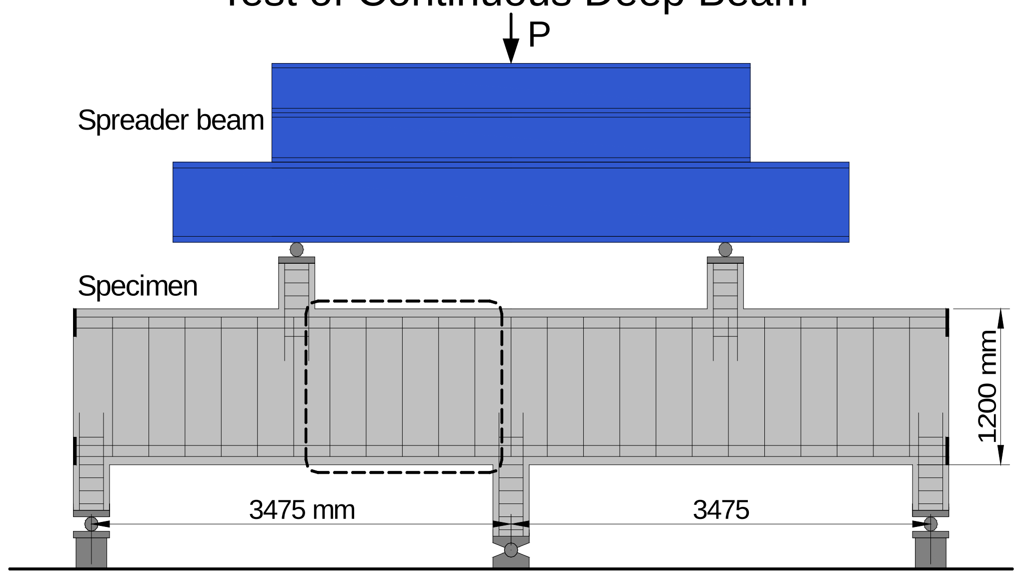
Double-Curvature Bending of Deep Beams

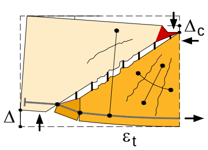
Continuous Deep Beam in Building



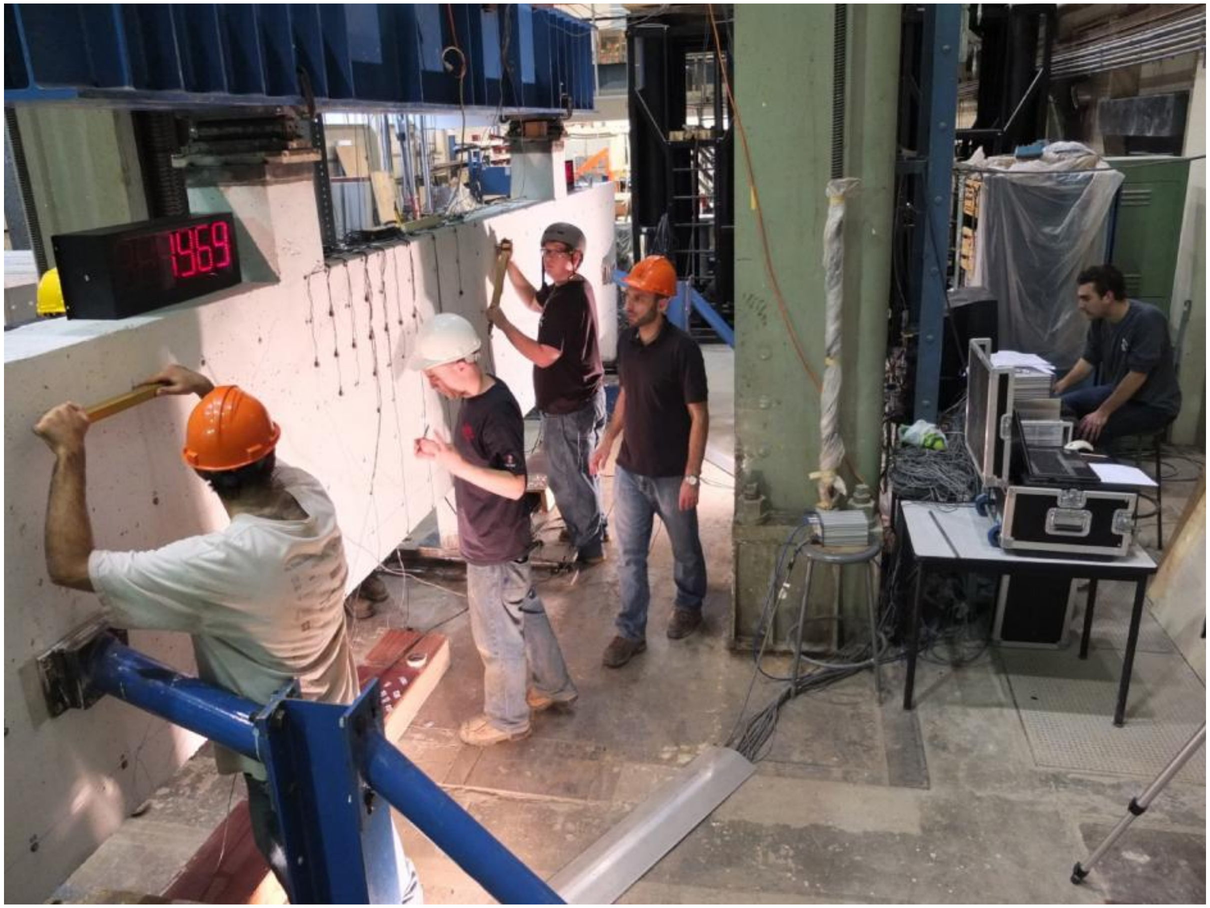
Specimen Construction

Test of Continuous Deep Beam

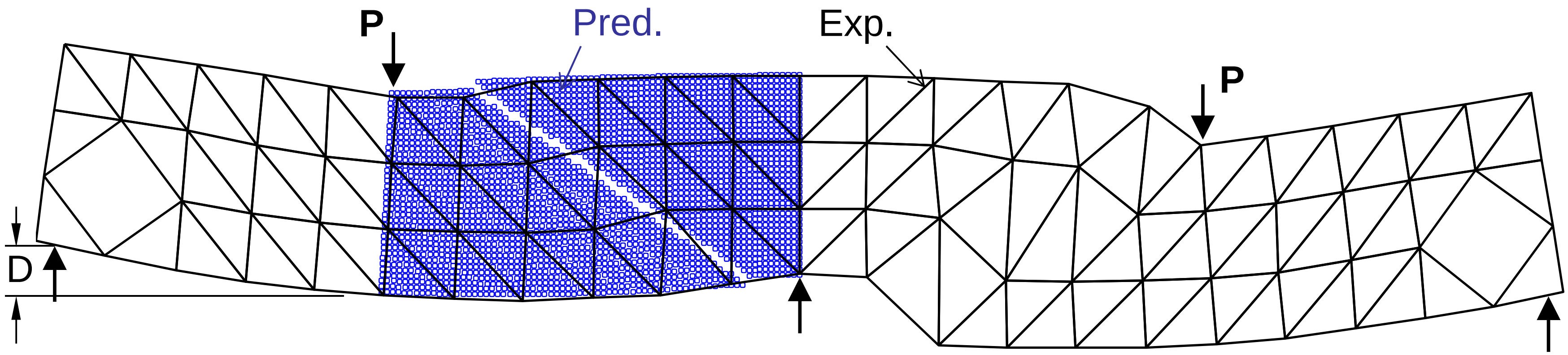


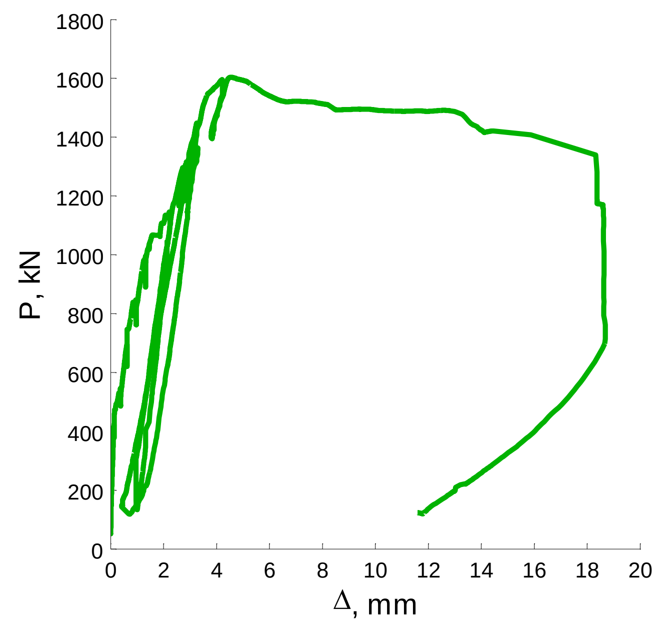


Double-Curvature Bending of Deep Beams

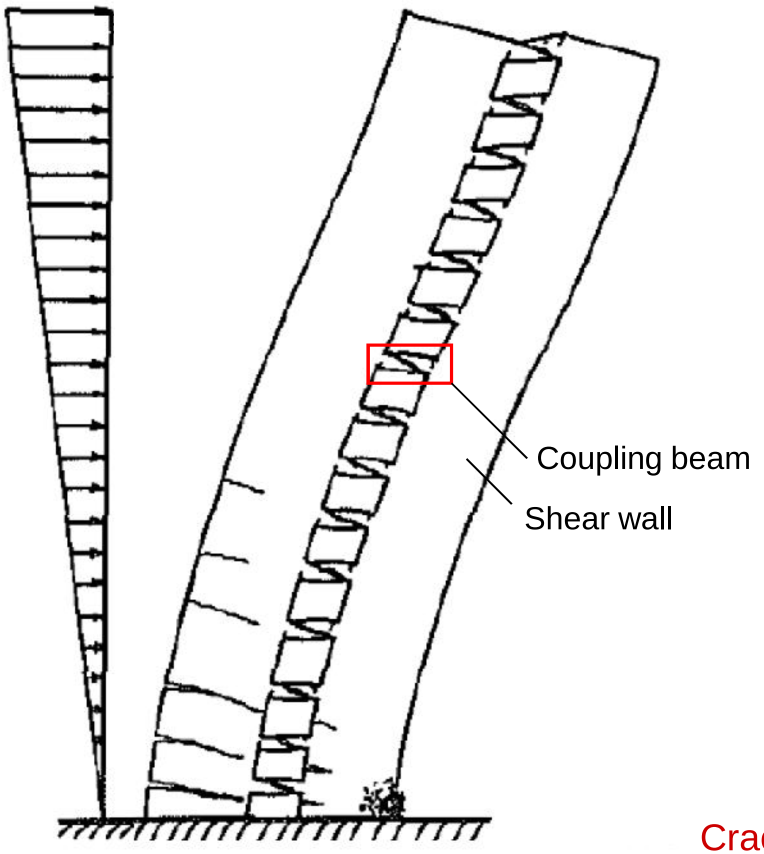


Predicted Deformed Shapes

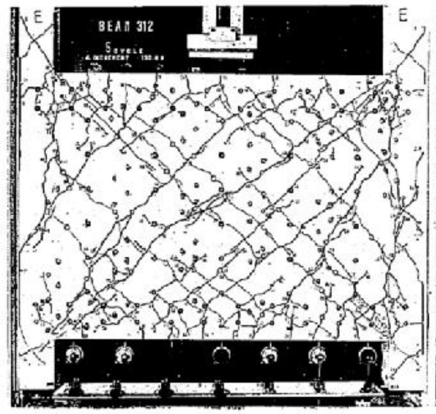


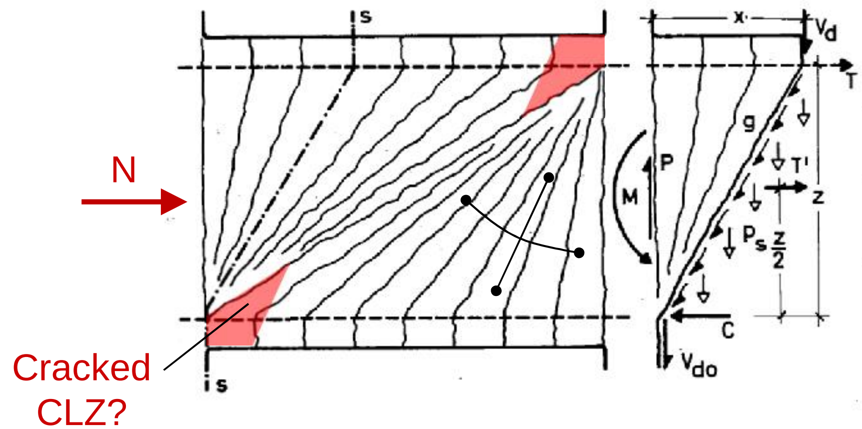


Short Coupling Beams

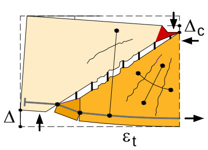


Adapted from Subedi 1999

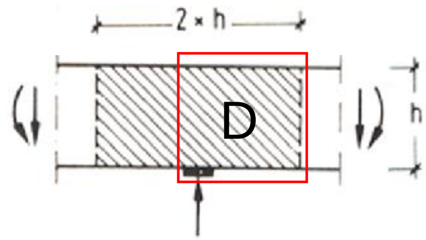


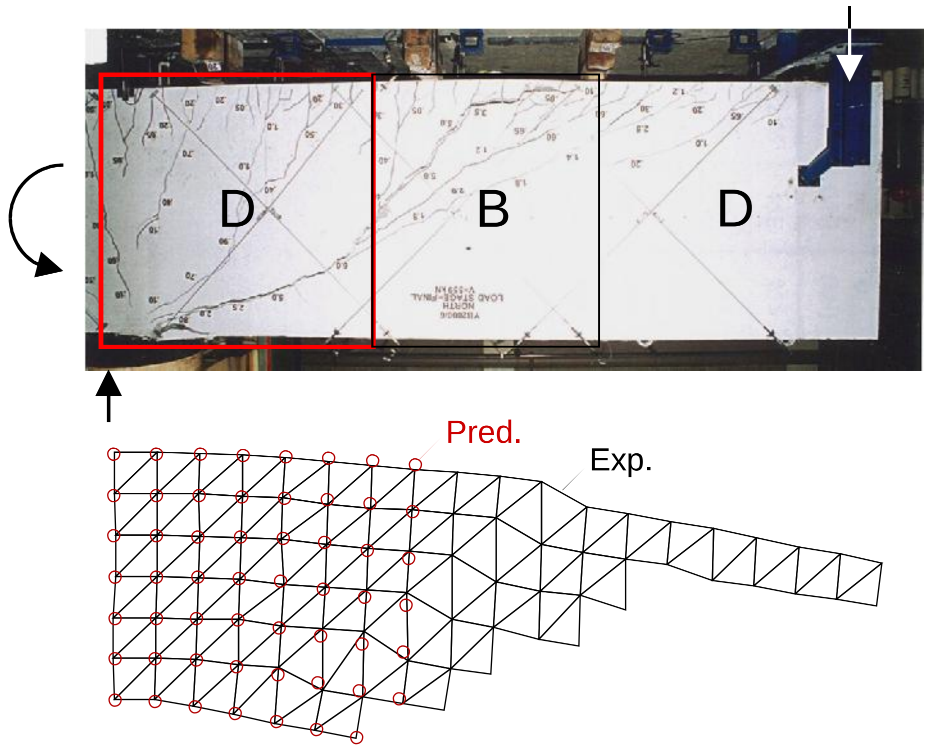


Adapted from Paulay 1971



D Regions in Slender Beams/Columns





Tests by Yoshida, U of Toronto, 2000

Wall Type Bridge Piers

Passerelle, Liège

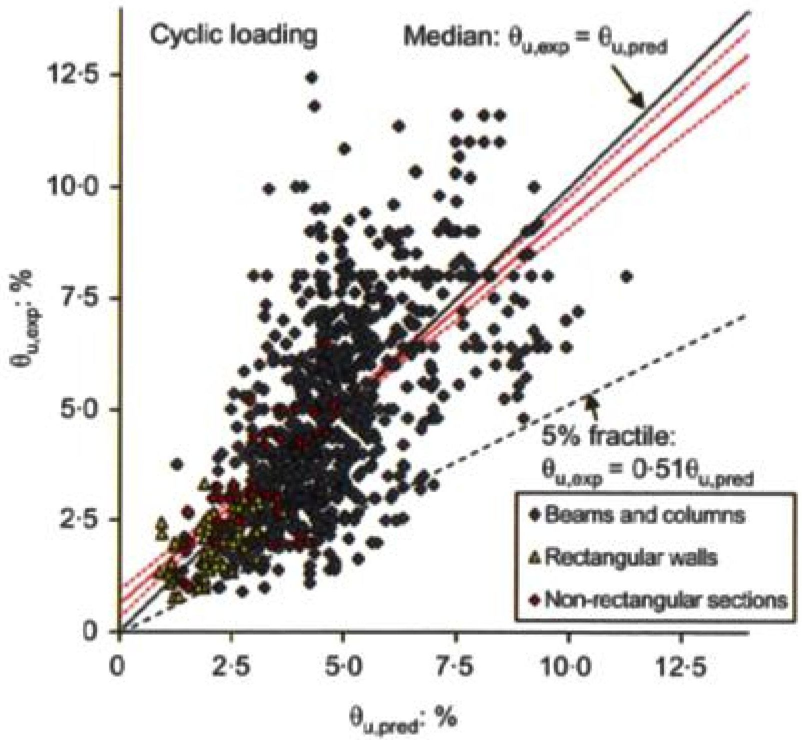
Passerelle, Liège

Pont d'Ougrée, Standard

Viaduc de Remouchamps

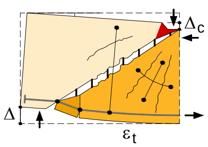
Wall Type Bridge Piers

Empirical Models for Deformation Capacity

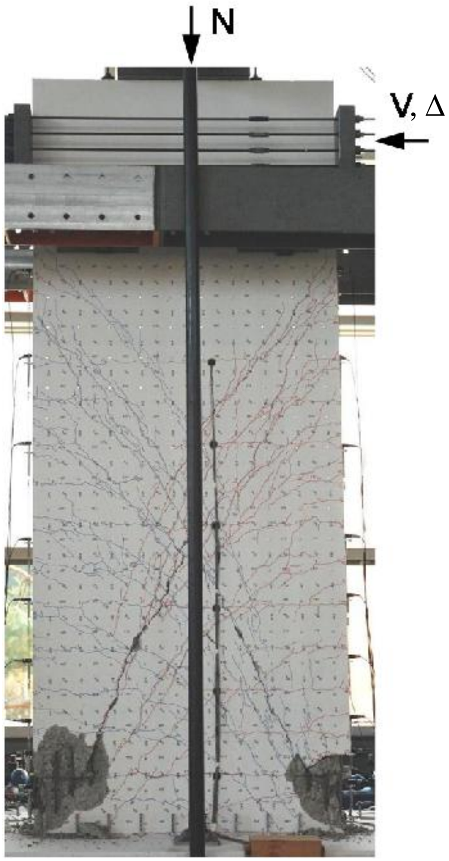


$$\theta_u^{pl} = a_{st}^{hbw}(1-0{\cdot}525a_{cy})(1+0{\cdot}6a_{sl})\left\{1-0{\cdot}052\max\left[1{\cdot}5;\min\left(10;\frac{h}{b_w}\right)\right]\right\}(0{\cdot}2)^{\nu}\left(\frac{\max(0{\cdot}01;\omega_2)}{\max(0{\cdot}01;\omega_1)}\min\left(9;\frac{L_s}{h}\right)\right)^{1/3} f_c^{0{\cdot}2}\, 25^{[(a\rho_w f_{yw})/f_c]}\, 1{\cdot}225^{100\rho_d}$$

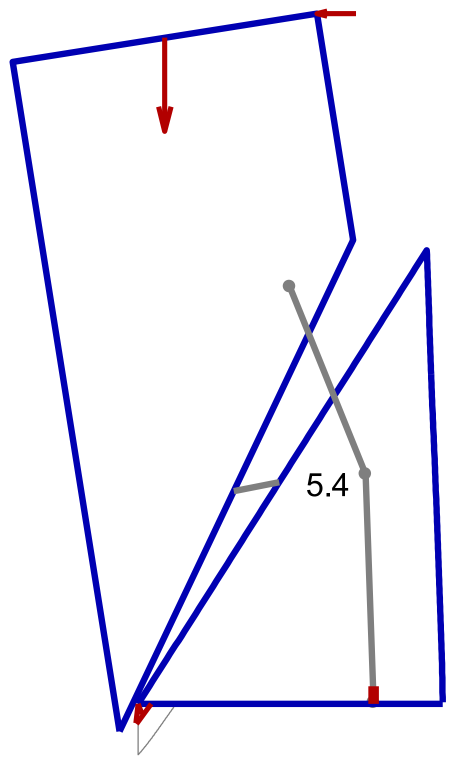
Biskinis and Fardis, 2010

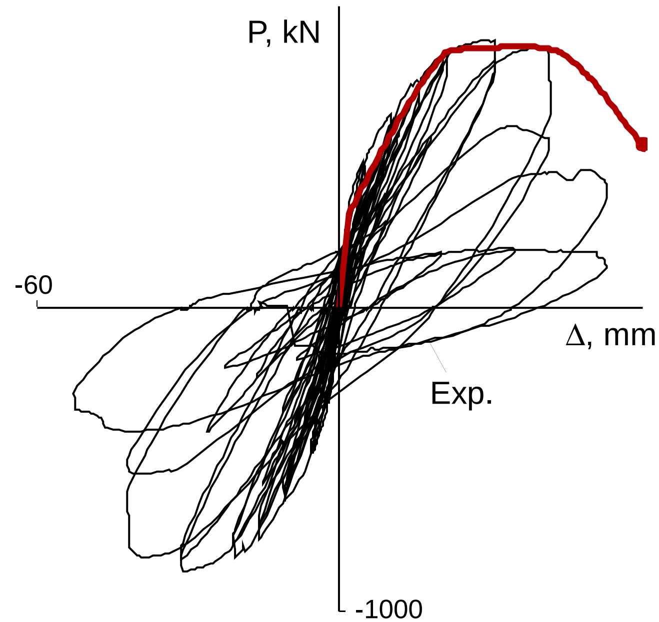


3PKT for Wall Type Piers



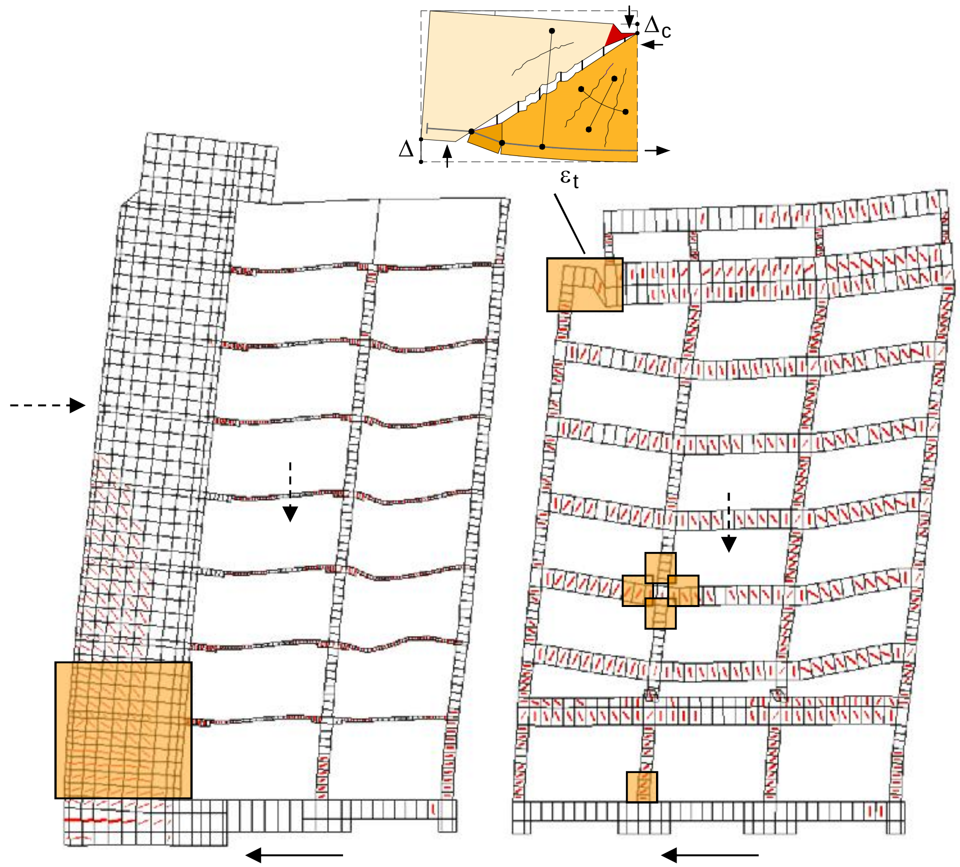
Test by Bischas and Dazio, 2010



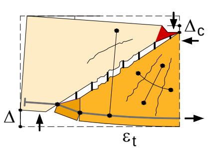


Macro Models for D Regions Combined with Sectional Models for B regions to Study Structural Resilience

Structural Resilience Analysis



Augustus-II (Bentz 2011)



Towards More Resilient Urban Infrastructure

Toronto Canada

Merci!