fib 2003 Symposium
CONCRETE STRUCTURES IN SEISMIC REGIONS

FRP Seismic Strengthening of Frames

Mihaela-Anca CIUPALA
Kypros PILAKOUTAS

Centre for Cement and Concrete
Department of Civil and Structural Engineering
The University of Sheffield, UK

Acknowledgements of EU projects:
Craft G1ST-CT-2002-50365 – CURVEDNFR
Marie Curie Fellowship HPMF-CT-2001-01279EU TMR Network ConFibreCrete ERB-FMRX-CT-97-0135
Ecoleader Project

Durability of EBR

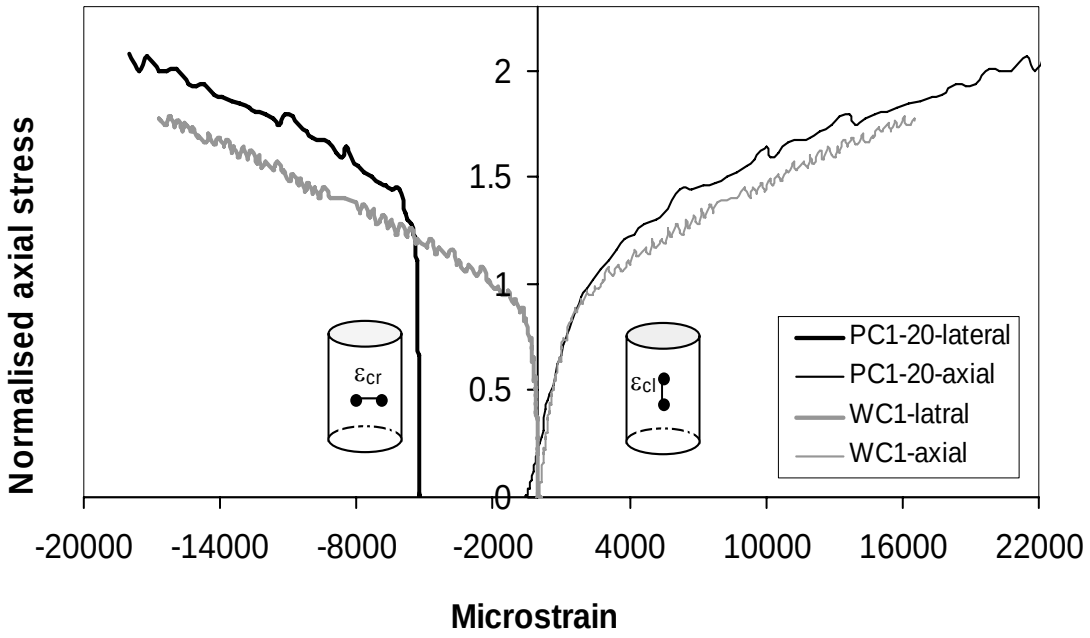
Content

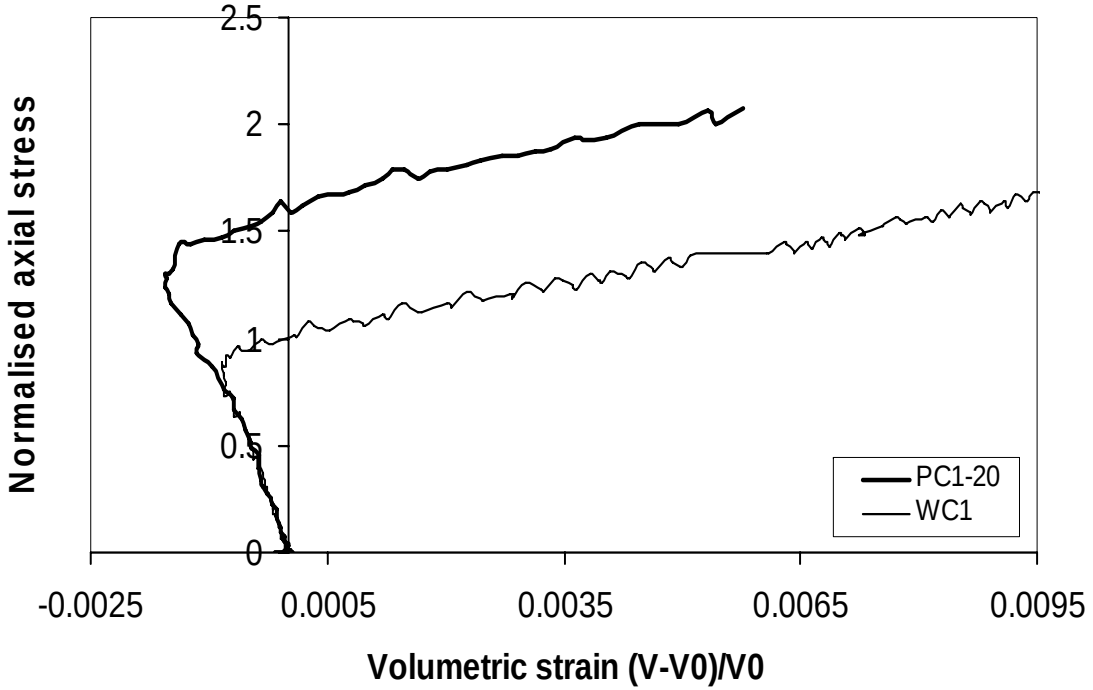
- Introduction
- Plastic hinge region
- FRP confinement models
- Test frame
- Predictions
- New ideas

Introduction

- **Difference with steel**
  - **Yielding**
  - **Stiffness**
  - **Energy dissipation**
- **Rectangular sections**
- **Joints**

FRP strengthening





Stress-strain curve for WC1 and PC1-20 specimens

Volumetric Strain for WC1 and PC1-20 specimens

Conventional Ductility

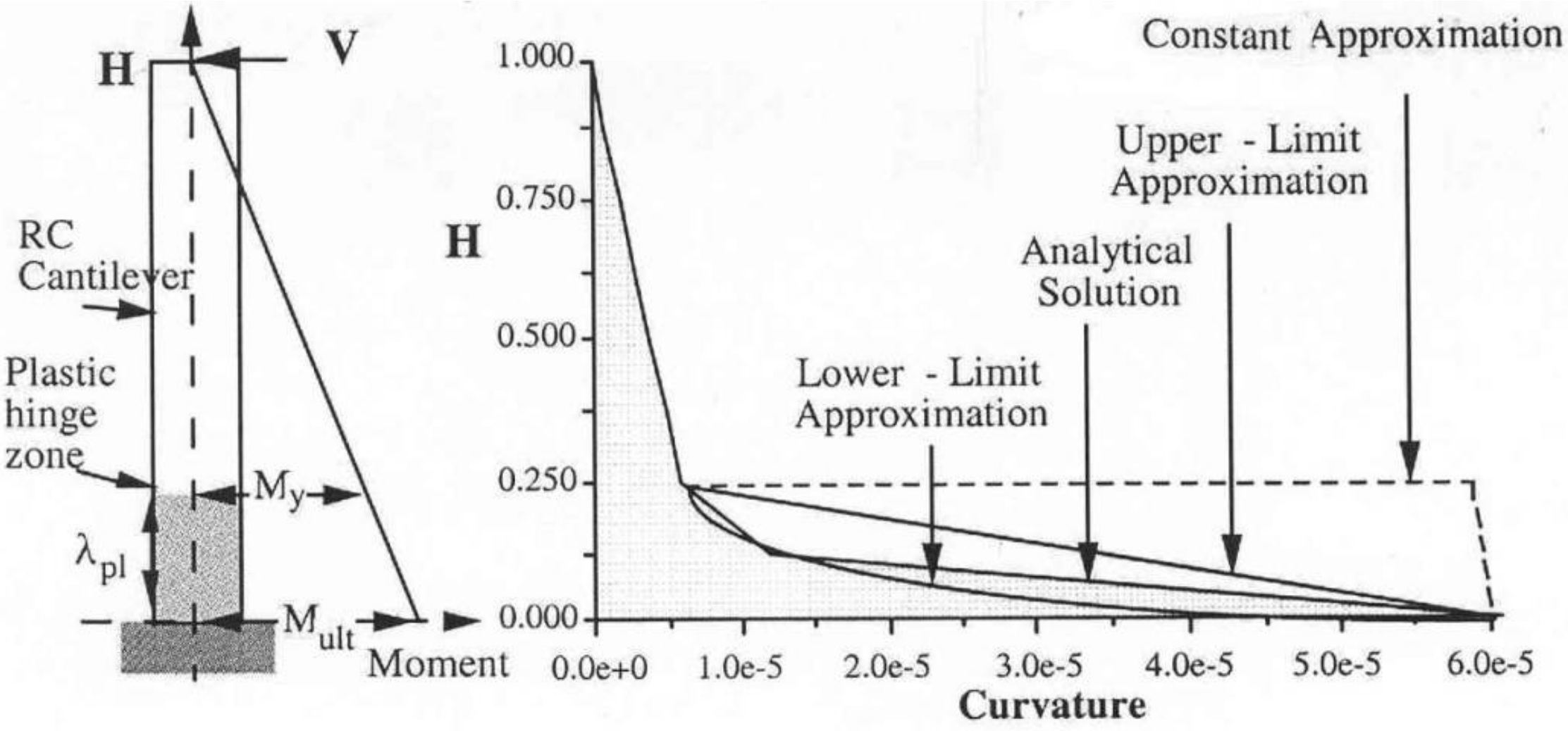
$$\mu_\phi = 1 + \frac{\mu_\Delta - 1}{3(L_p / L)\left(1 - 0.5 L_p / L\right)} = 1 + \frac{\mu_\Delta - 1}{3\lambda_{pl}\left(1 - 0.5\lambda_{pl}\right)}$$

$$L_p = 0.08L + 0.022 f_y d_l \geq 0.044 f_y d_l$$

- Curvature in plastic hinge region in constant
- Plastic hinge region estimated roughly
- Yield penetration at plastic stage only

Conventional Ductility

Curvature ductility from Displacement ductility:



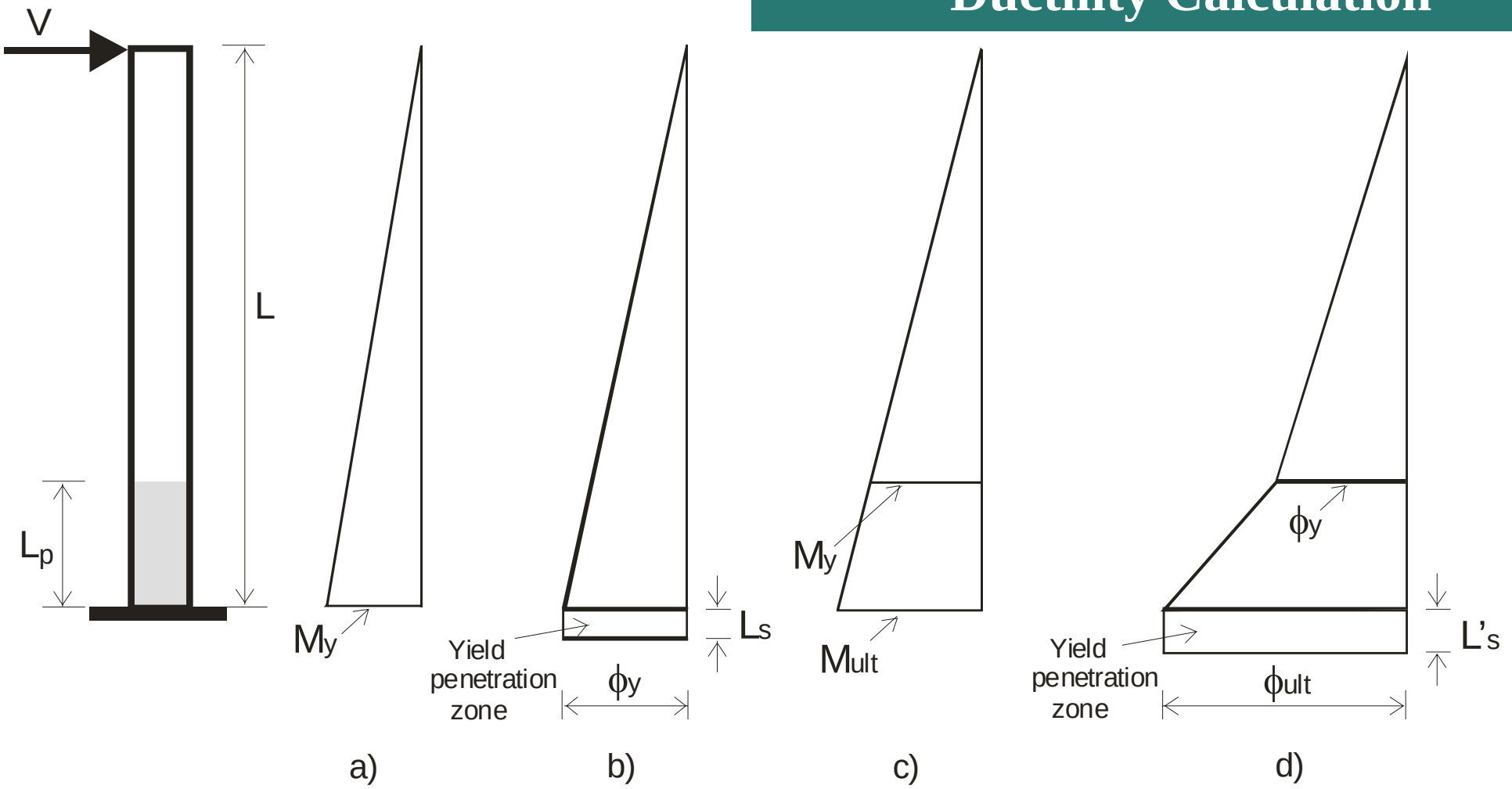
Ductility Issues

$$\mu_\phi = 1 + \frac{\mu_\Delta - (1 + \lambda_{pl})}{\lambda_{pl}\left(1.5 - 0.5\,\lambda_{pl}\right)p}$$

$$\lambda_{pl} = 1 - \frac{M_y}{M_{ult}}$$

- Curvature in plastic hinge region varies if bars are fully bonded due to high confinement
- Plastic hinge region depends on moments
- Yield penetration at yield and plastic stage

Ductility Calculation



Moments and curvatures at yielding

Moments and curvatures at maximum response (ultimate state)

Ductility equations

$$\mu_\phi = \frac{\mu_\Delta - (1 - 0.5\lambda_{pl}) \cdot 0.9 \cdot (1 - 15\alpha)}{\left(1.3\lambda_{pl} + 42\alpha\beta + 294\alpha^2\beta^2\right) \cdot 0.9 \cdot (1 - 15\alpha)}$$

where

$$\alpha = \frac{d}{L} \cdot \frac{f_y}{500}$$

$$\beta = \frac{f_{ult}}{f_y}$$

$$\varepsilon_{cc,85} = \phi_u \cdot x = \mu_\phi \cdot \phi_y \cdot x$$

Maximum concrete Strain

$$\varepsilon_{cu} = \varepsilon_{cc}\left[\frac{E_{\sec}\left(E_c - E_{\sec,u}\right)}{E_{\sec,u}\left(E_c - E_{\sec}\right)}\right]^{\frac{E_{\sec}}{E_c}}$$

$$f'_{cu} = E_{\sec,u}\,\varepsilon_{cu}$$

- ***Spoelstra and Monti***

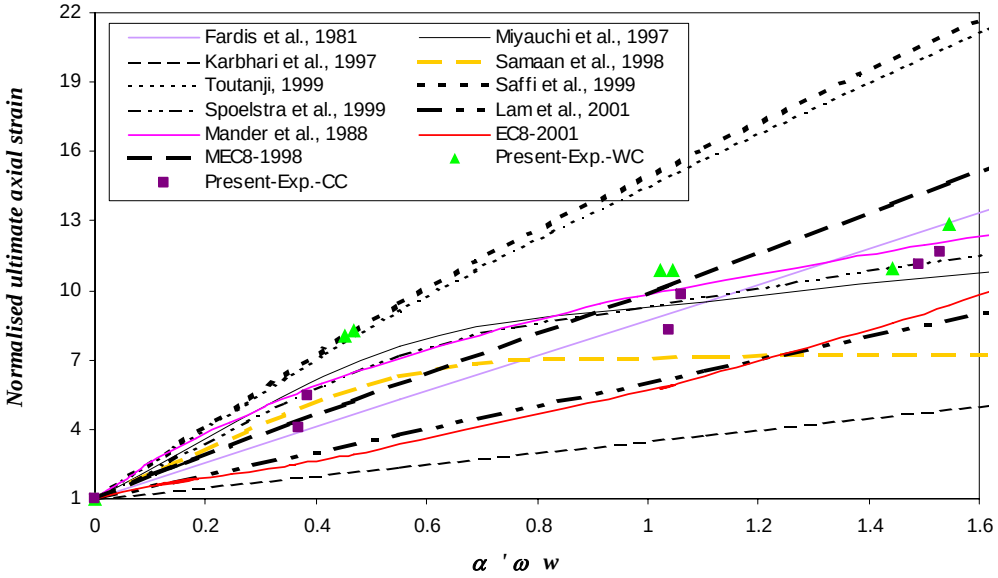
$$\varepsilon_{cc} / \varepsilon_{co} = 1.75 + m(f'_l / f'_{co})$$

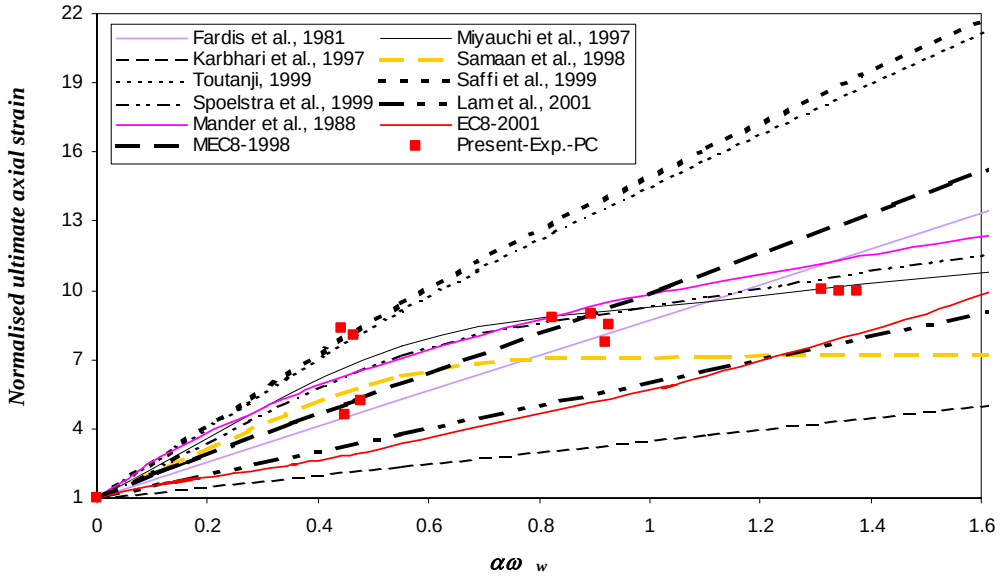
- ***Lam and Teng (m 10-22)***

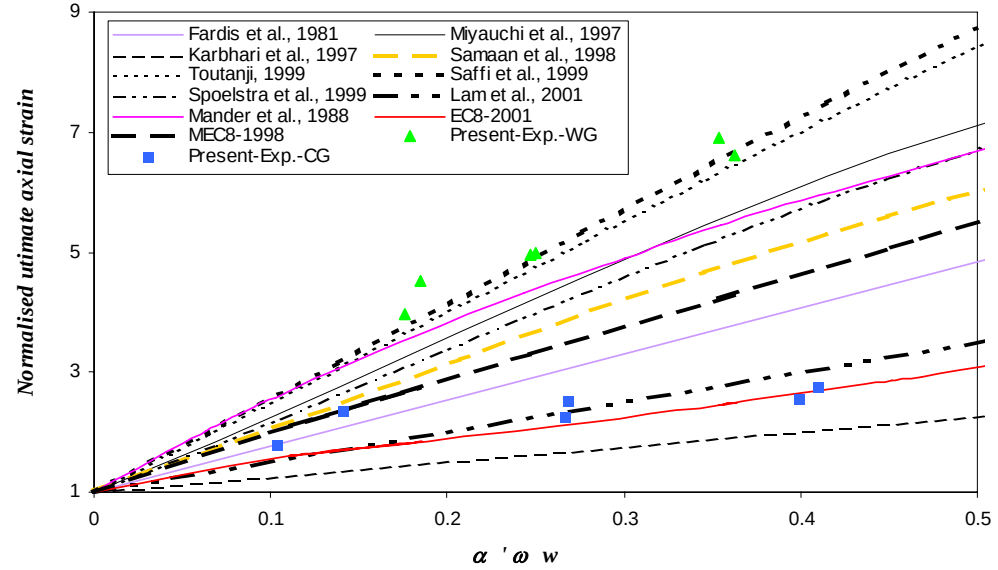
$$\varepsilon_{cu} = 0.0035 + 0.1 \cdot \alpha\omega_{wd}$$

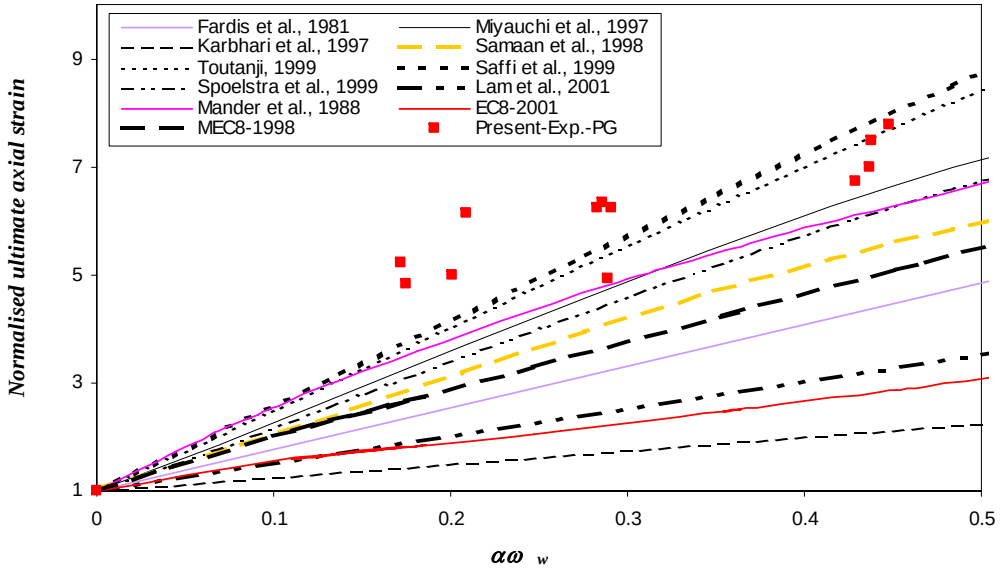
- ***Model code***

Maximum concrete Strain

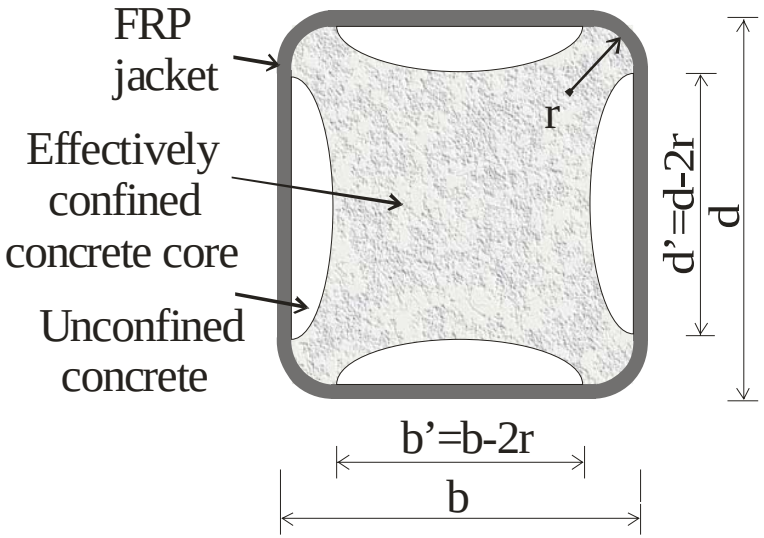






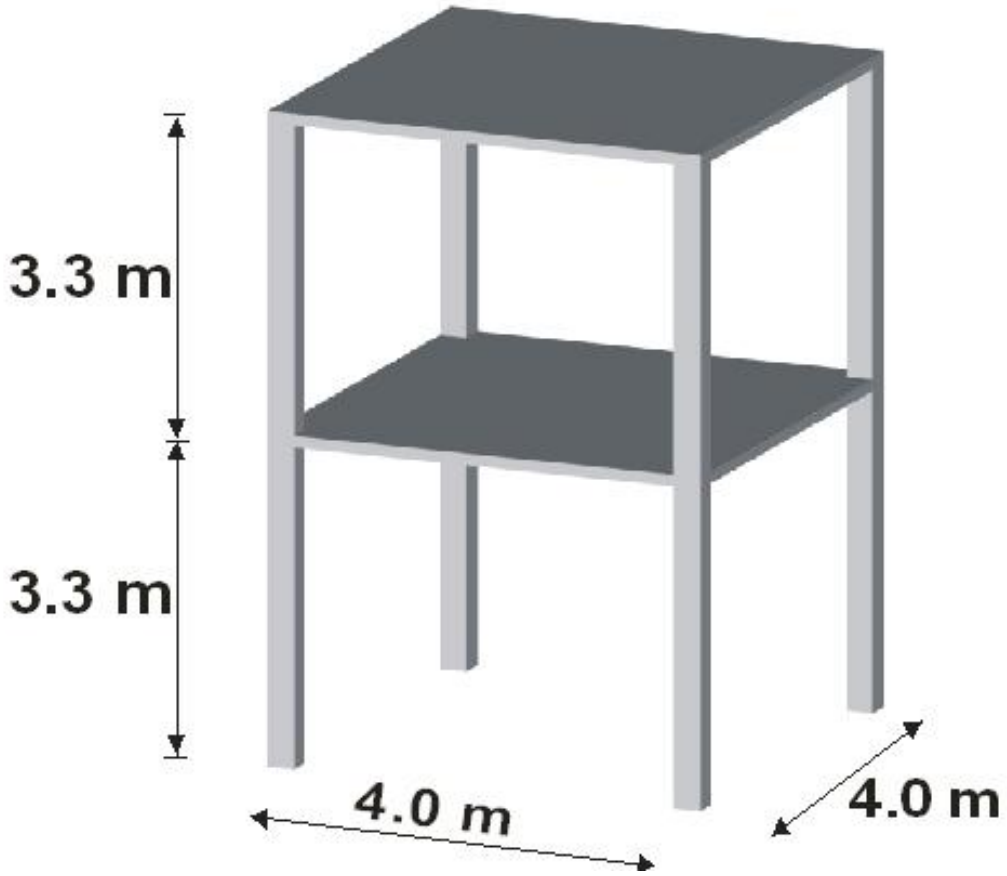


Rectangular columns



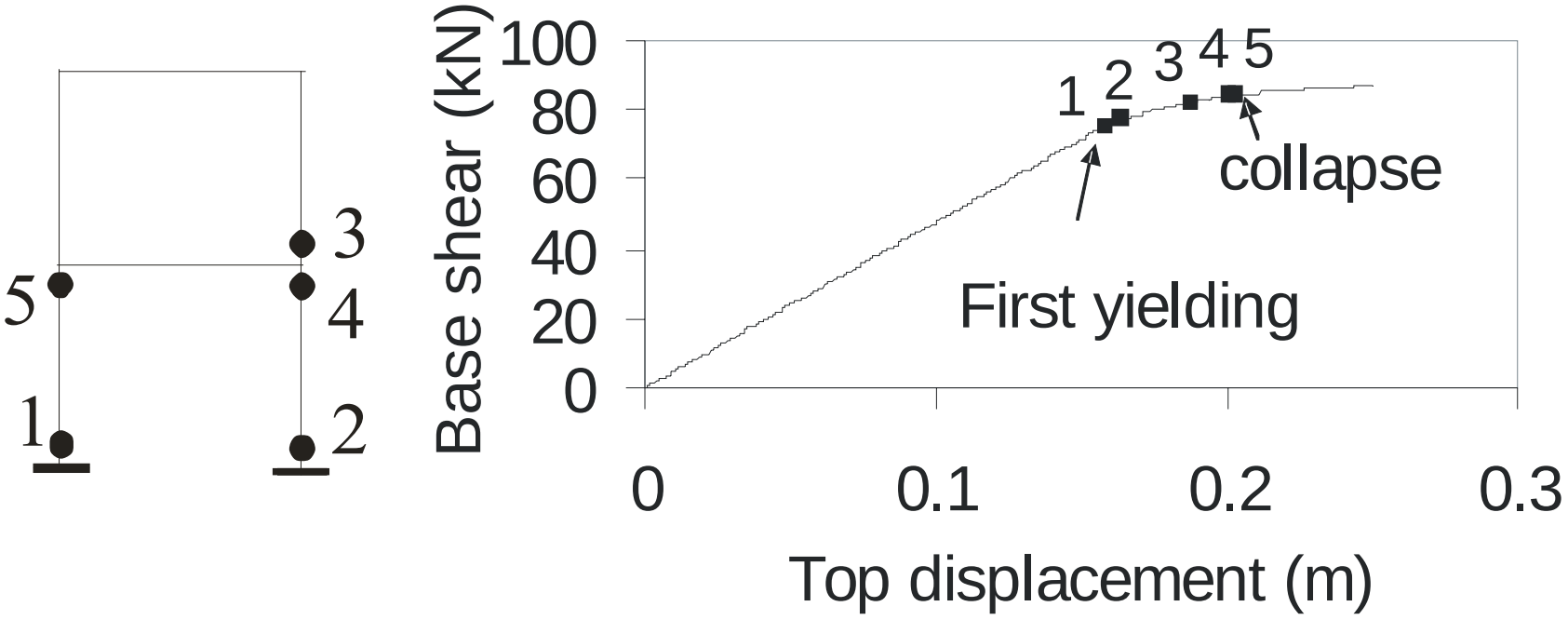
- ***Mander's*** **model modified by several researchers**
- **Lateral stress is not calculated and effective stress not properly addressed**
- **Energy approach!**
- ***Spoelstra and Monti*** **calculate lateral stress**
- **Model code model simple**

RC FRAME



- 3 RC frames to be tested by the Ecoleader project
- Frames designed to old standards
- Strengthening with FRP after damaging on Shake-table
- Participants: Roma, Ghent, Patras, Sheffield

Push-over analysis



- **target displacement ductility of** $\mu_{\Delta} = 8$

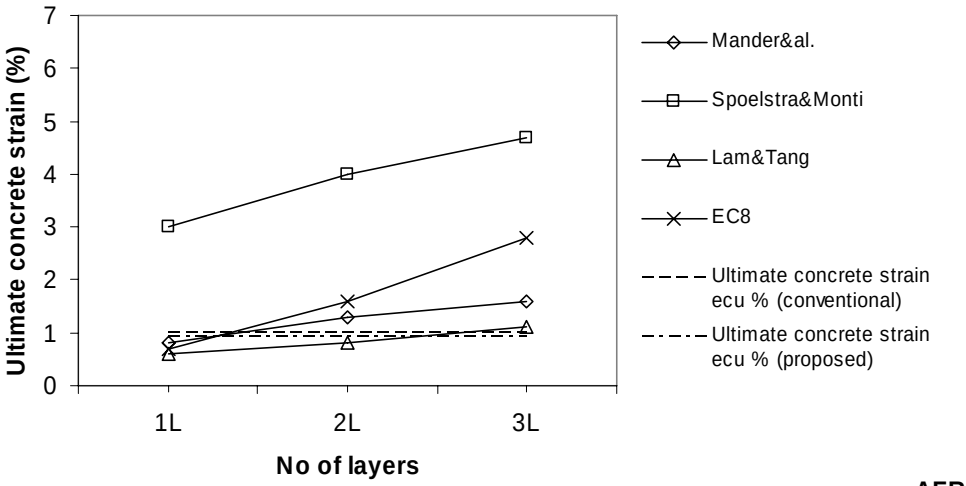
Data

Fibre type	t_j (mm)	E_j (MPa)	f_{ju} (MPa)	ε_{ju} (%)
CFRP	0.117	240000	3900	1.55
GFRP	0.068	65000	1700	2.80
AFRP	0.280	120000	2000	1.55

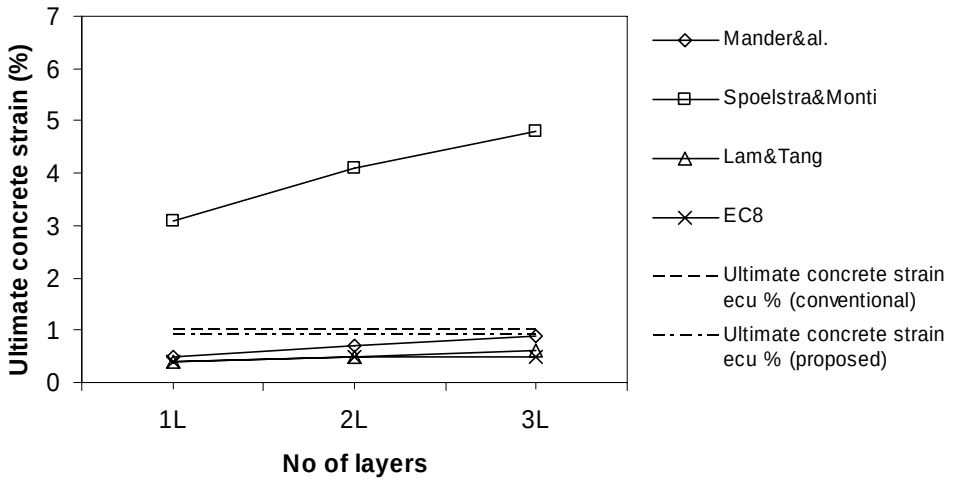
	Plastic hinge length L_p (mm)		Curvature ductility μ_ϕ		Ultimate concrete strain $\varepsilon_{cc,85}$ (%)
Conventional	Eq.2	340	Eq.1	13.66	1.00
Proposed	Eq.4	400	Eq.5	12.22	0.925

Results – Layers Required

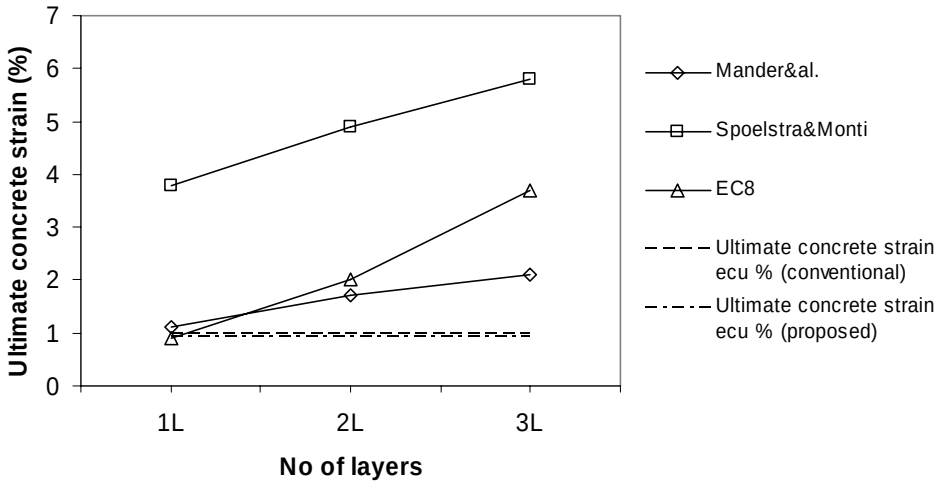
CFRP



GFRP

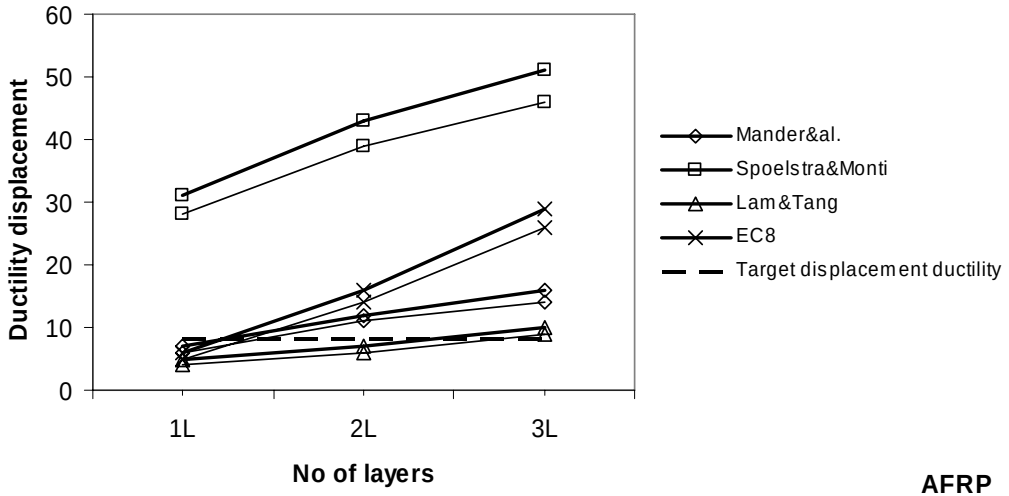


AFRP

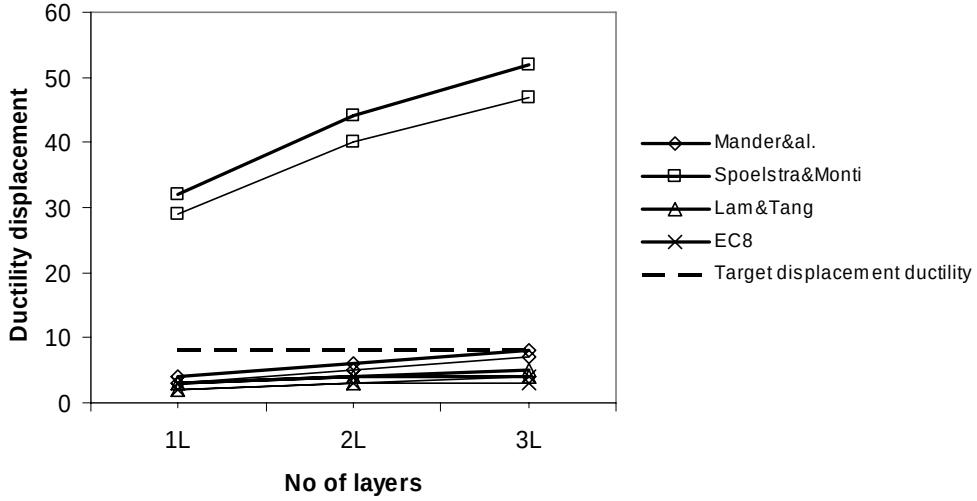


Results – Layers Required

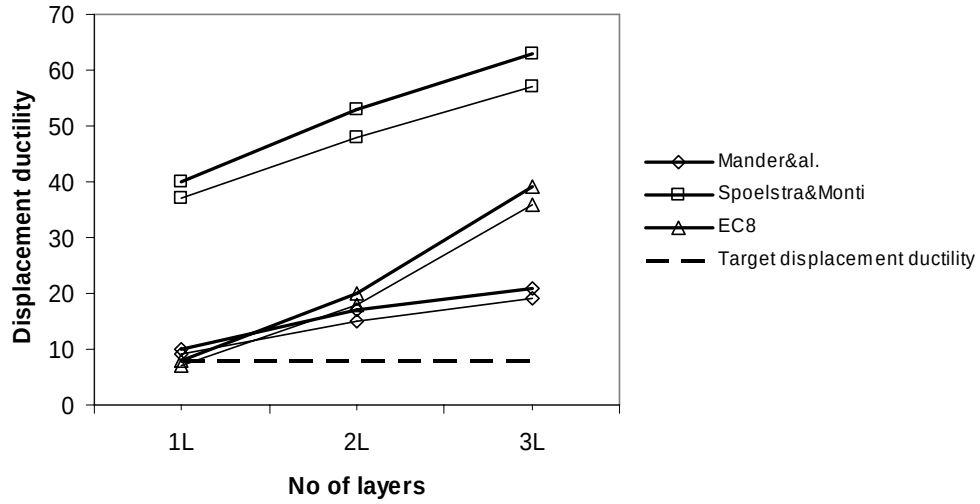
CFRP



GFRP



AFRP



Conclusions

- FRP strengthening differs in behaviour (and design) from steel jacketing
- FRP jacketing can enhance bond slip characteristics and lead to different plastic hinge lengths
- The main design parameter for confinement strengthening is maximum concrete axial strain
- Many models, but not enough accuracy
- Results of design dominated by the model inaccuracy
- More research to be done at the element and structural level