FRPRCS6

FRP Seismic Strengthening of Columns in Frames

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  - **EU *Ecoleader*** project
  - ***University of Sheffield***
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Outline

- Introduction and Context of work
- Design procedure
- FRP confinement models
- Test frame
- Strengthening design example
- Conclusions

Context of work

- *Centre of Cement and Concrete* - The University of Sheffield, UK
- EU TMR Network *ConFibreCrete*
- EU *Ecoleader* research project

- Full scale 3D – two storey RC frames
- Tamaris Laboratory, CEA Saclay, France

Introduction

- Use of FRP in columns
- Confinement objective
- Difficulties:
  - ➢ most existing models for confined concrete and strengthening design guidelines are based on steel confinement
  - ➢ confinement of rectangular sections is not always dealt properly by models developed for circular sections
  - ➢ joint confinement is not always easy to achieve

Design procedure for plastic hinge confinement

Target
μ_Δ

↓

μ_ϕ

↓

Required
$\varepsilon_{cu} = \mu_\phi \cdot \phi_y \cdot x$

↓

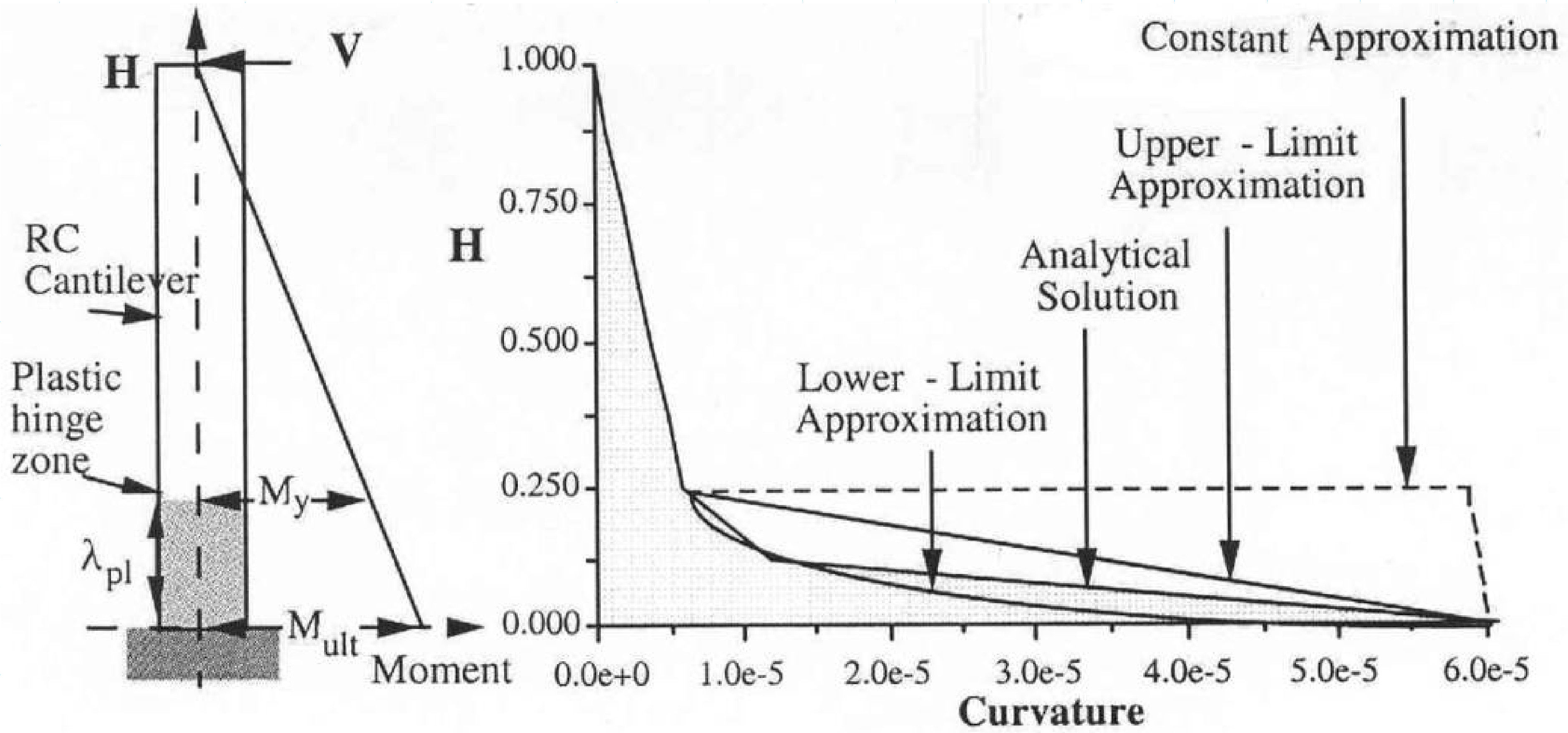
Required thickness of FRP
- Confinement model

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

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

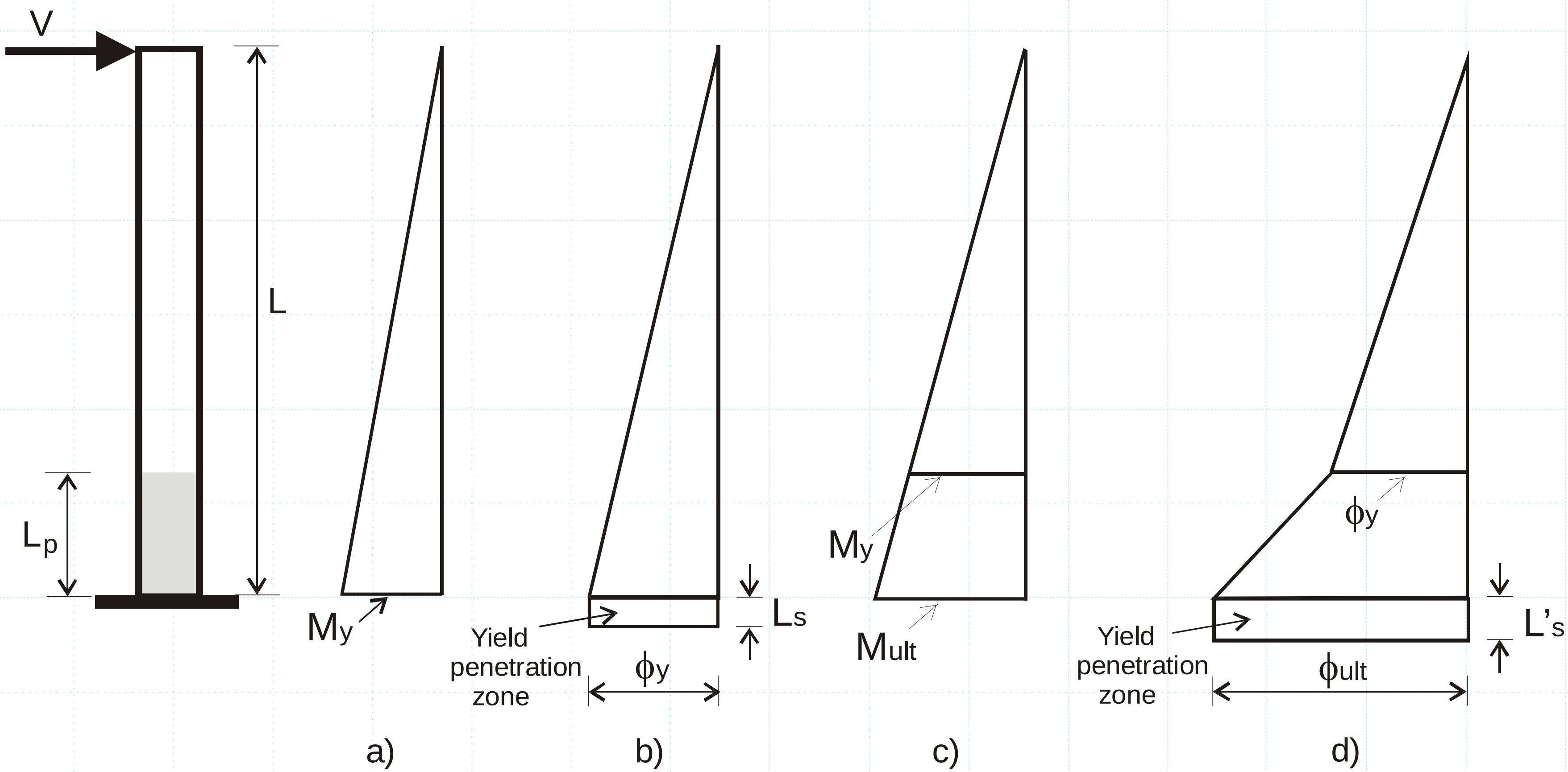
Conventional ductility

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



Ductility issues

- 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



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

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

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

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

Design procedure for plastic hinge confinement

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- Confinement model

Models for FRP-confined rectangular columns

- ***Wang & Restrepo***

$$f'_{cc} = \alpha_1 \alpha_2 f'_{co}$$

- ***Spoelstra & Monti***

$$\varepsilon_{cu} = \varepsilon_{cc} \left[\frac{E_{\sec}\left(E_c - E_{\sec,u}\right)}{E_{\sec,u}\left(E_c - E_{\sec}\right)} \right]^{1-\frac{E_{\sec}}{E_c}} \qquad f'_{cu} = E_{\sec,u} \varepsilon_{cu}$$

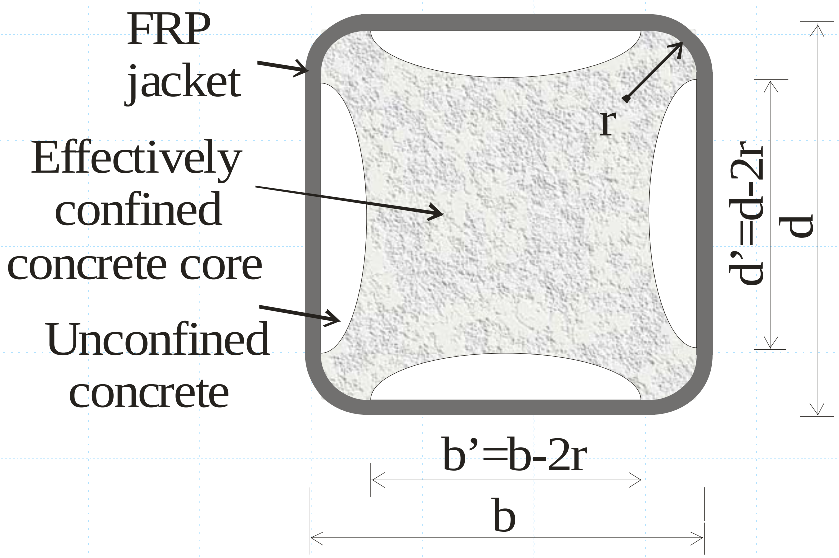
- ***Lam & Teng***

$$\varepsilon_{cc} / \varepsilon_{co} = 1.75 + m(f'_l / f'_{co}) \qquad f'_{cc} / f'_{co} = 1 + 2 f'_l / f'_{co}$$

- ***CEB-FIB Model Code 1990***

$$\varepsilon^*_{c,85} = 0.0035 + 0.1 \cdot \alpha \omega_{wd}$$

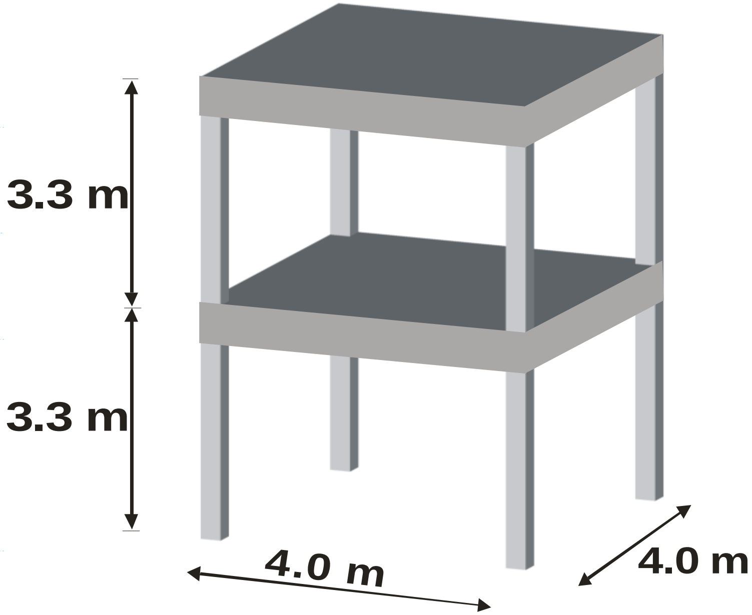
Rectangular columns

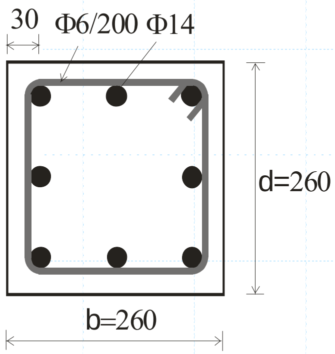


- *Mander's* model modified by several researchers
- Lateral stress is not calculated and effective stress not properly addressed
- Energy approach!
- *Spoelstra and Monti* calculate lateral stress
- *Model code '90* model simple

RC frame

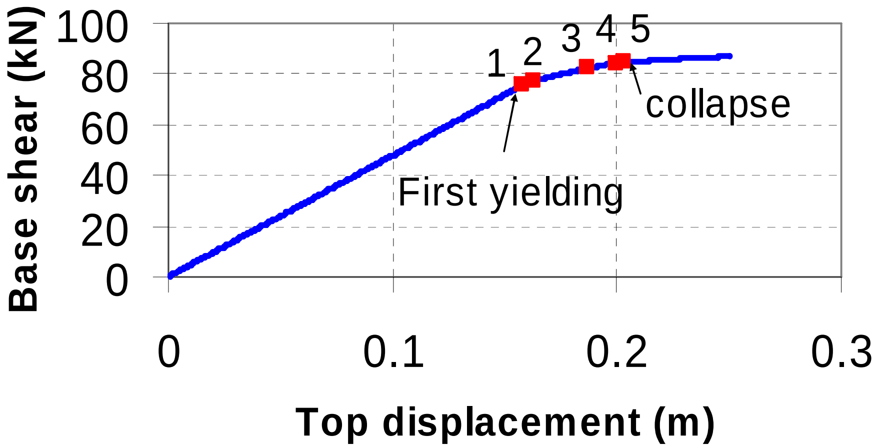
- 3 RC frames to be tested by the Ecoleader project

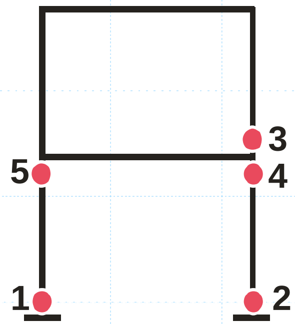




- ➢ Designed using old standards
- ➢ Strengthening with FRP after damaging on shaking table

- ➢ Pushover analysis of the frame was carried out to determine the failure mechanism





Design procedure for plastic hinge confinement

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$\varepsilon_{cu} = \mu_\phi \cdot \phi_y \cdot x$

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Required thickness of FRP
- Confinement model

Strengthening design example for columns

- Confinement of plastic hinge region
- Jacket thickness of 1, 2, 3 fibre sheets

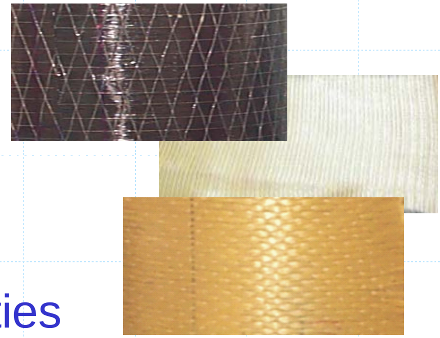


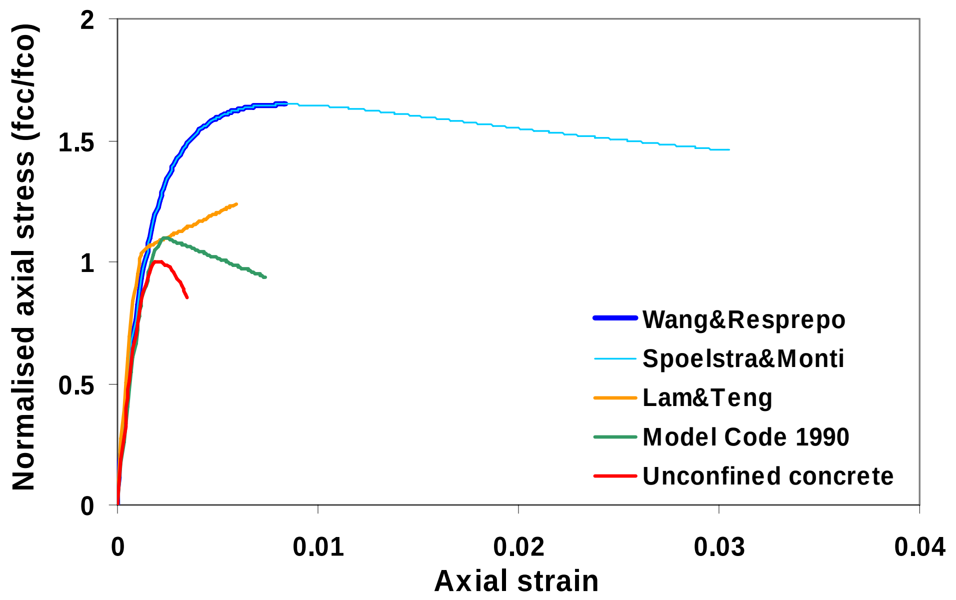
Table 1. Fibre properties

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

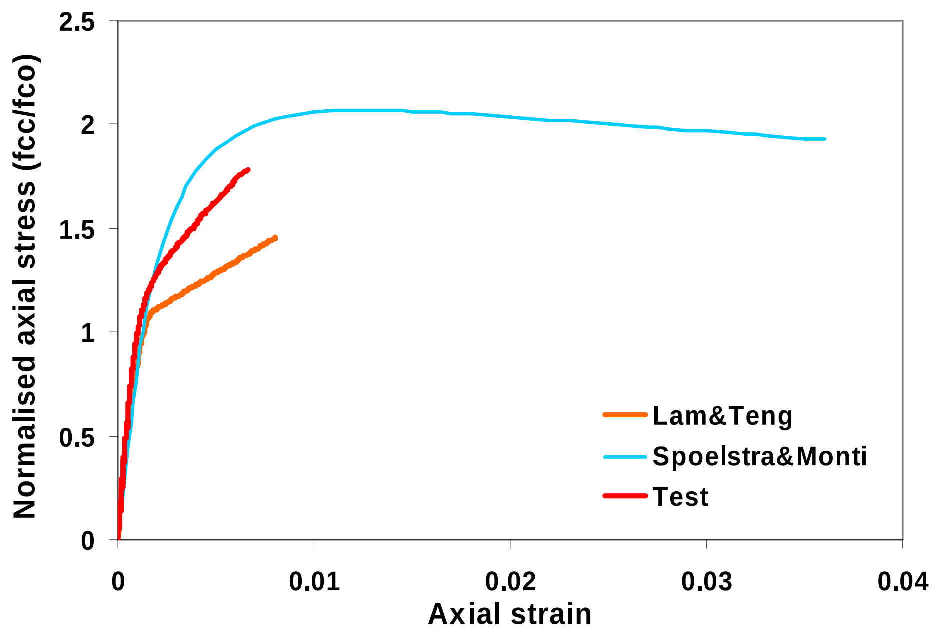
- Strengthening objective $\mu_\Delta = 8$
- Effective column length is 1.65 m and the expected L_p=301 mm
- Required curvature ductility is $\mu_\phi = 15$ resulting in a required $\varepsilon_{cu} = 0.01$

Axial stress for 1L of CFRP confinement

Rectangular



Circular



Normalised strength enhancement (f'_{cc} / f'_{co})

	CFRP			GFRP			AFRP		
	1L	***2L***	***3L***	***1L***	***2L***	***3L***	***1L***	***2L***	***3L***
Wang& Restrepo	1.6	2.1	2.4	1.3	1.5	1.7	1.9	2.5	2.9
Spoelstra &Monti	1.6	2.1	2.4	1.3	1.5	1.7	1.9	2.5	2.9
Lam& Teng	1.2	1.5	1.7	1.1	1.2	1.3	-	-	-
fib Model code '90	1.1	1.3	1.6	1.0	1.0	1.0	1.1	1.4	1.9

Ultimate strain ε_{cu} (%)

	CFRP			GFRP			AFRP		
	1L	*2L*	*3L*	*1L*	*2L*	*3L*	*1L*	*2L*	*3L*
Wang& Restrepo	0.8	1.3	1.6	0.5	0.7	0.9	1.1	1.7	2.1
Spoelstra &Monti	3.0	4.0	4.7	3.1	4.1	4.8	3.8	4.9	5.8
Lam& Teng	0.6	0.8	1.1	0.4	0.5	0.6	-	-	-
fib Model code '90	0.7	1.6	2.8	0.4	0.5	0.5	0.9	2.0	3.7

Estimated displacement ductility μ_Δ

	CFRP			GFRP			AFRP		
	1L	*2L*	*3L*	*1L*	*2L*	*3L*	*1L*	*2L*	*3L*
Wang& Restrepo	6	11	14	3	5	7	9	15	19
Spoelstra &Monti	28	38	45	29	39	46	36	47	56
Lam& Teng	4	6	9	3	3	4	-	-	-
fib Model code '90	5	14	26	3	3	3	7	18	35

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