Experimental and analytical research on seismic retrofitting of old-type RC columns with advanced composite materials

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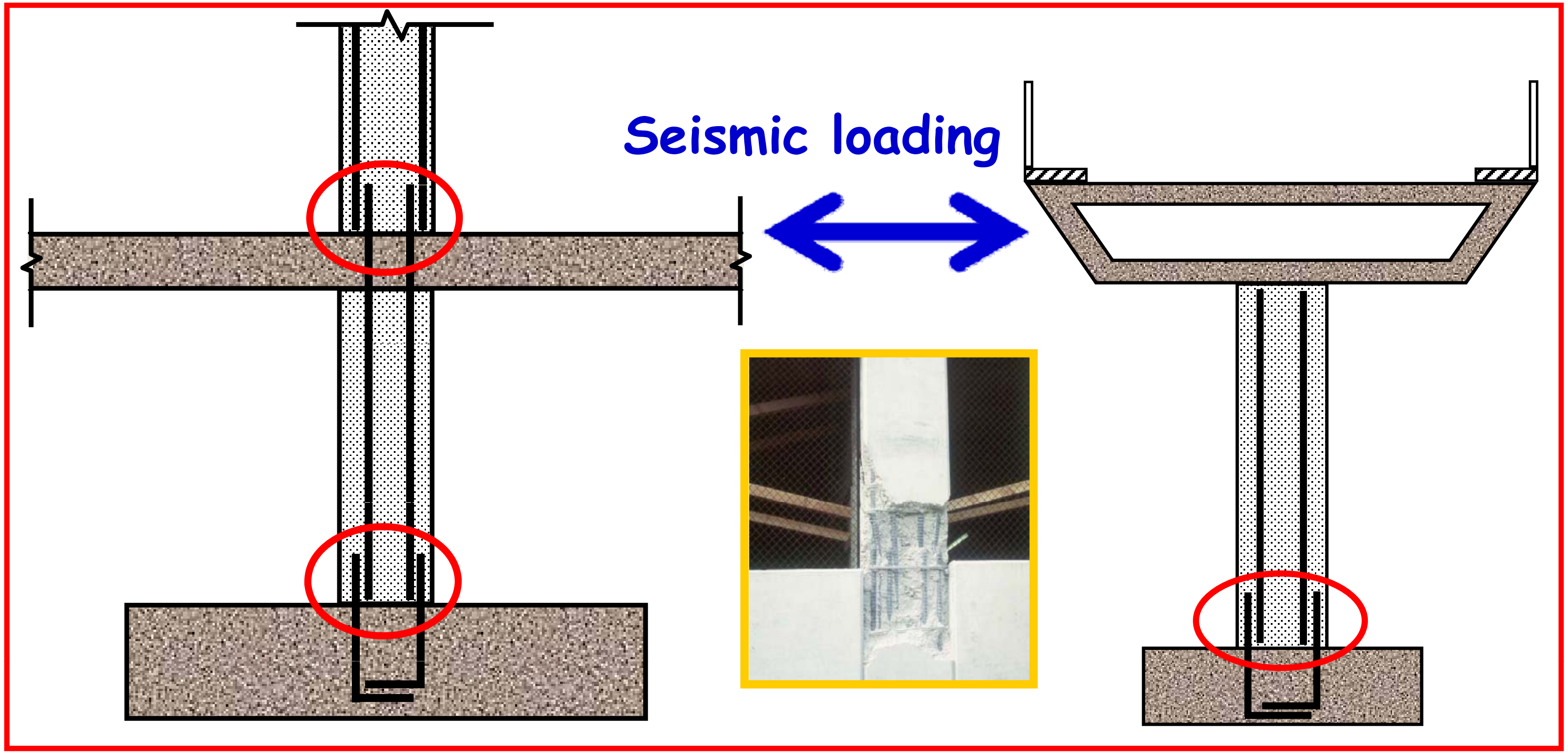
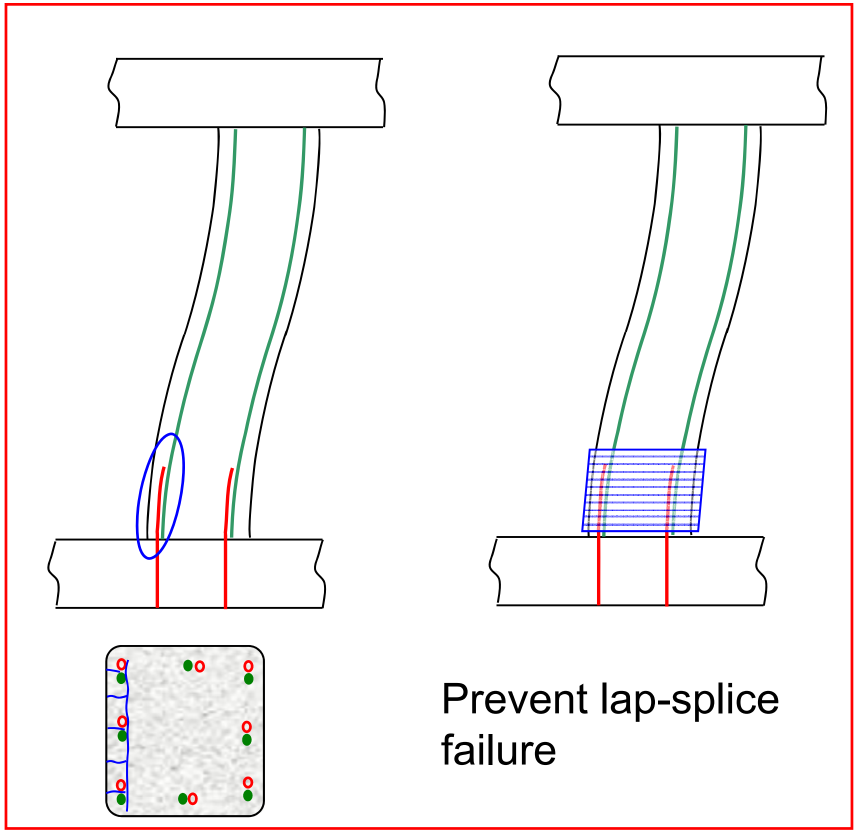
Introduction

Short lap splices develop splitting bond cracks → Failure before reaching columns flexural capacity

Bond-critical regions in locations where plastic hinges are expected to occur → Limitation of plastic hinge length → Lower deformation capacity



CONFINEMENT WITH COMPOSITE MATERIALS



Research Objectives

To assess experimentally the effectiveness of a new jacketing system (Textile-Reinforced Mortar - TRM) vs. FRP as a means of enhancing the bond strength of short lap splices

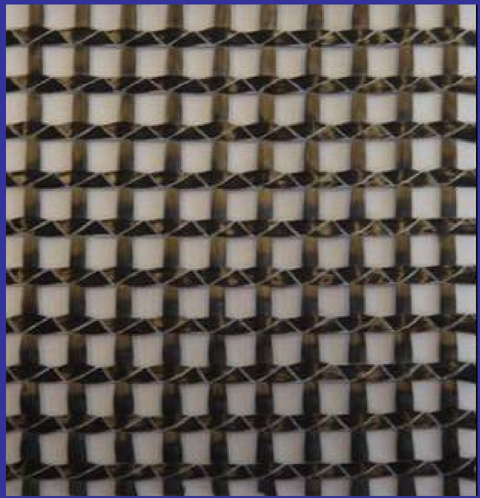
To develop new simple models for calculating the bond strength of lap splices in members confined with composite materials (TRM or FRP)

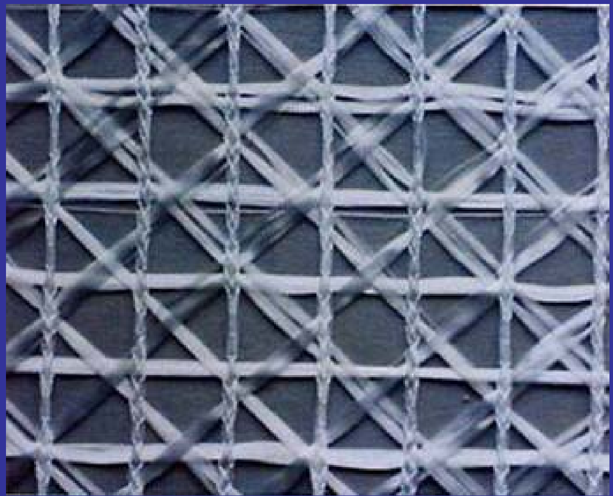
Fiber-Reinforced Polymers (FRPs): some problems with resins …

- Poor behavior of resins above T_g
- High cost of epoxies
- Inability to apply on wet surfaces or at low temperatures
- Lack of vapour permeability
- Incompatibility with substrate materials
- Difficult to perform post-earthquake assessment behind jackets

Solution proposed

Replacement of resin with mortar (e.g. Cement-based)
Use of TEXTILES → mechanical interlock between fibers and matrix





Textile-Reinforced Mortars – TRMs

Experimental Investigation

Aim:

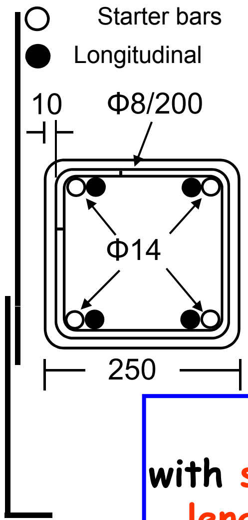
Seismic retrofitting of old-type non-seismically detailed RC columns, which suffer from limited deformation capacity due to splitting bond failure at lap-splice regions

Compare the effectiveness of TRM versus FRP jackets applied at the plastic hinge region of the specimens

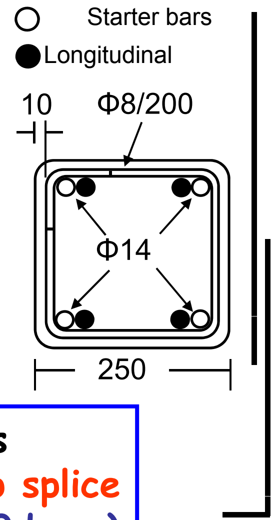
6 large scale flexure-dominated columns, cyclic uniaxial flexure with constant axial load (28% of compressive strength)

TEST SPECIMENS AND EXPERIMENTAL PARAMETERS

6 large-scale column specimens



6 Columns with lap splicing of longitudinal bars at the floor level



Lap splice length

- 3 columns with shorter lap splice lengths, (L20d_...)
- 3 columns with longer lap splice lengths, (L40d_...)

Tested without retrofitting, as controls

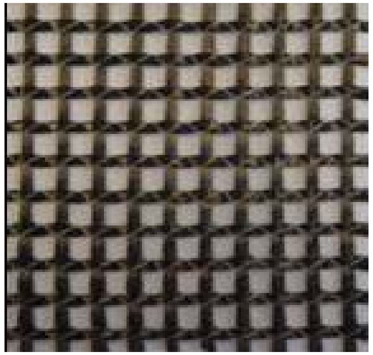
L20d_C	L40d_C

Retrofitted with a double-layered carbon fiber FRP jacket

L20d_R2	L40d_R2

Retrofitted with an equal (to its FRP counterparts) stiffness and strength carbon fiber TRM jacket comprising 4 layers

L20d_M4	L40d_M4



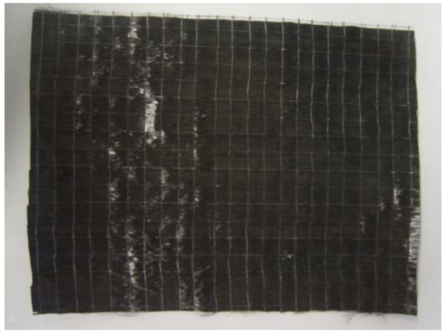
ρ = 348 g/m^2

t = 0.095 mm

TRM - 4 layers

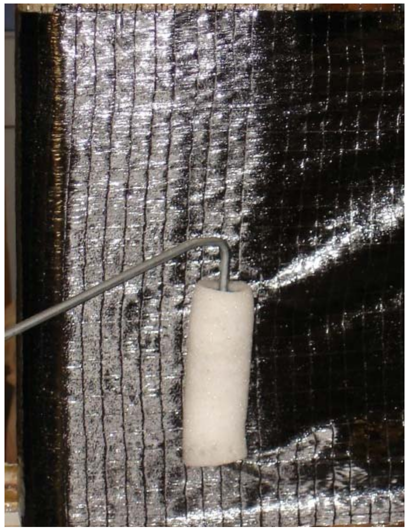
EQUIVALENT CONFINING SYSTEMS

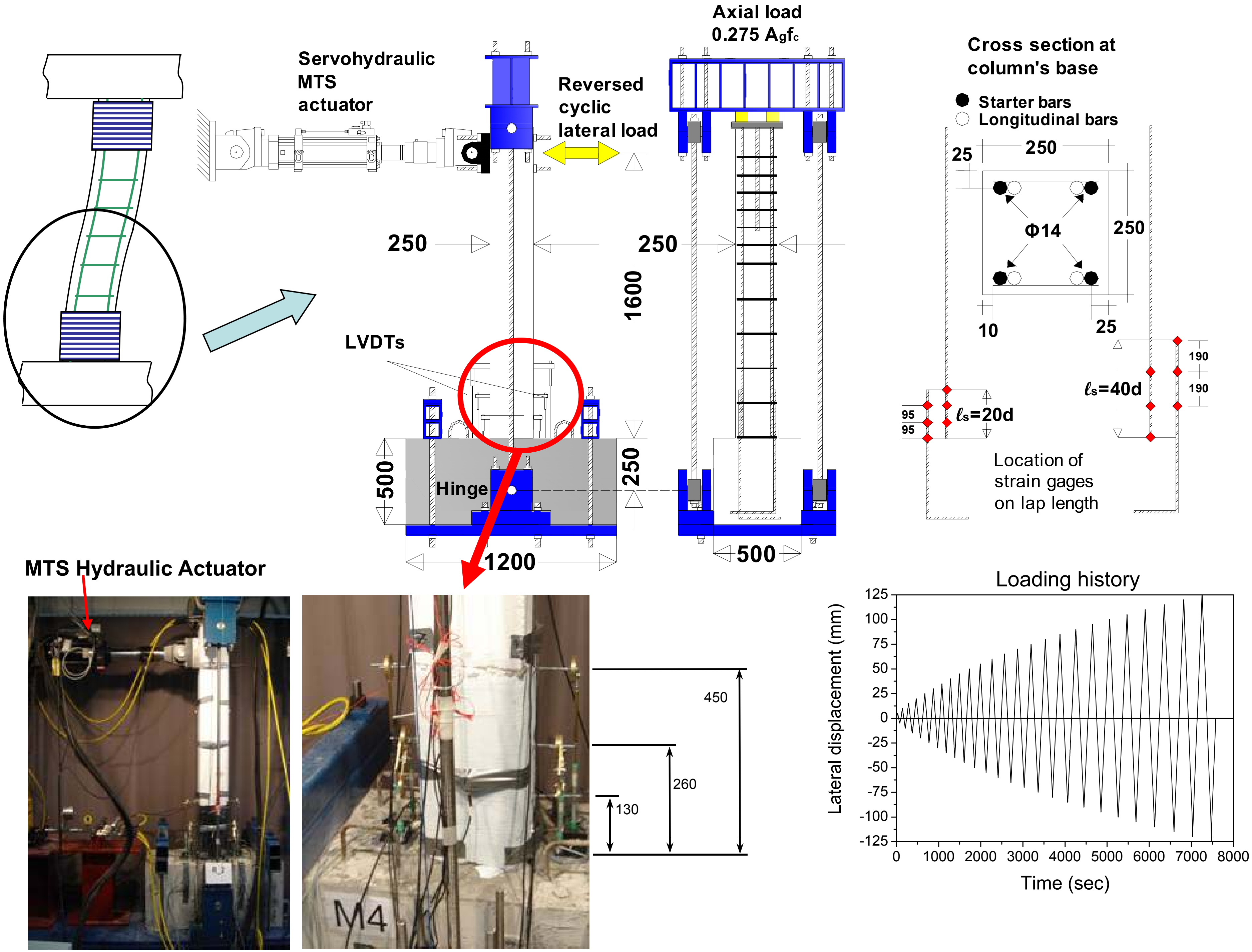
FRP - 2 layers



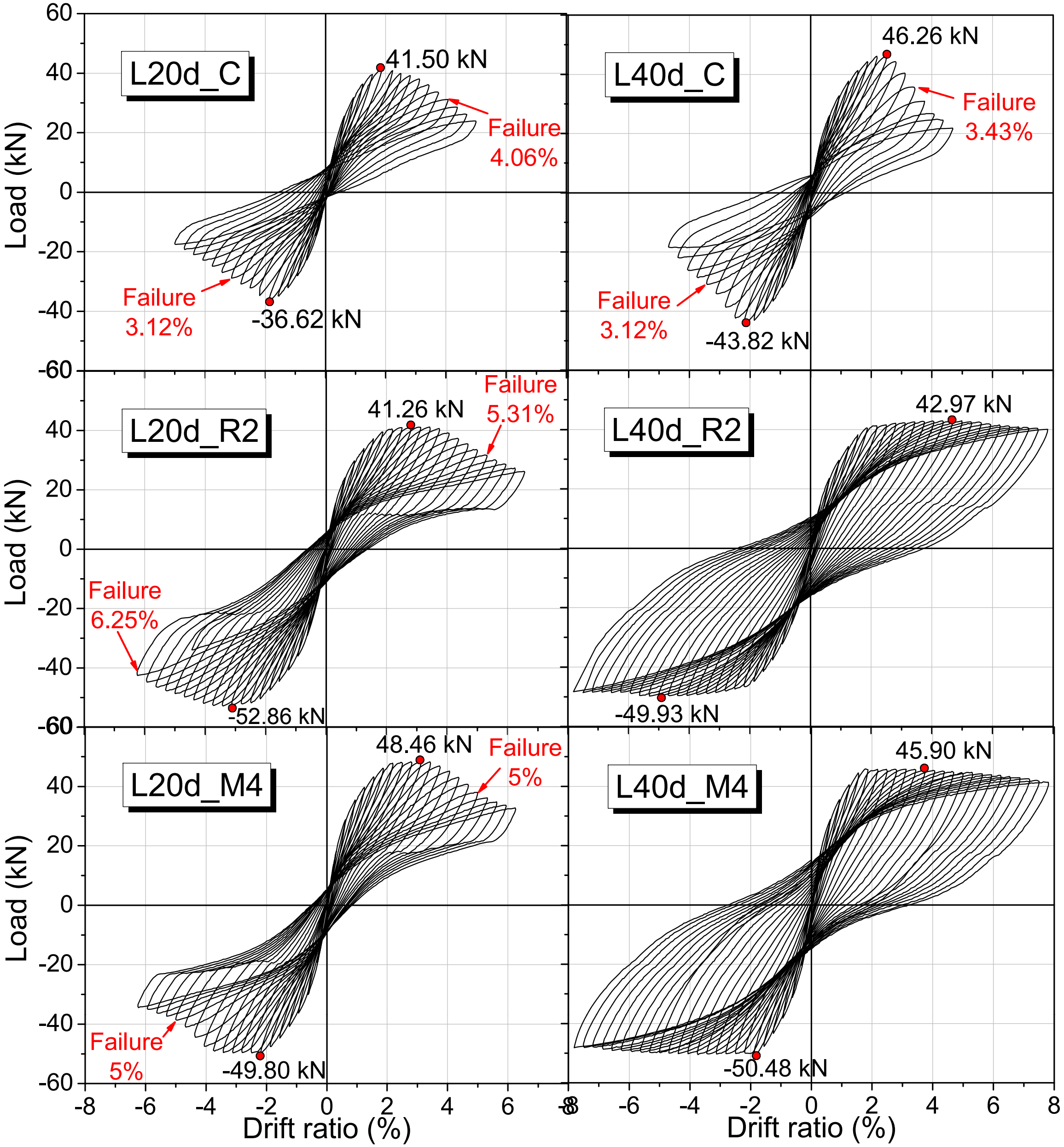
ρ = 300 g/m^2

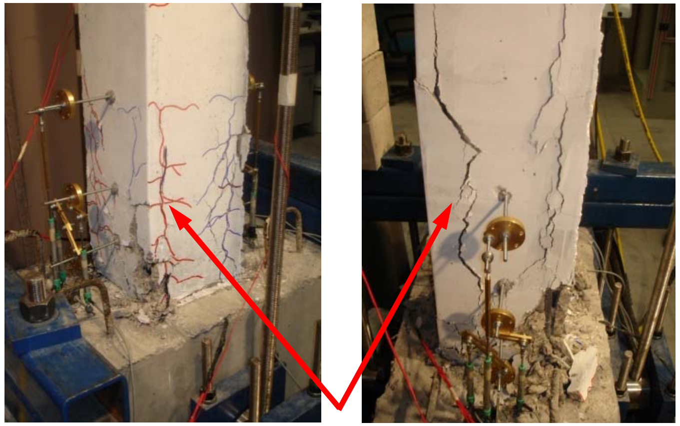
t = 0.17 mm




Servohydraulic
MTS
actuator
Reversed
cyclic
lateral load
Axial load
0.275 AgfC
250
250
1600
LVDTs
500
Hinge
250
1200
500
Cross section at
column's base
Starter bars
Longitudinal bars
25
250
250
Φ14
10
25
95
95
ℓs=20d
ℓs=40d
190
190
Location of
strain gages
on lap length
MTS Hydraulic Actuator
M4
450
260
130
Loading history
Lateral displacement (mm)
Time (sec)
125
100
75
50
25
0
-25
-50
-75
-100
-125
0
1000
2000
3000
4000
5000
6000
7000
8000

Columns with Lap-Spliced Bars – L20d_... and L40d_...





Longitudinal splitting cracks

L20d_

Strength increase :

20% (FRP jacket) 26% (TRM jacket)

Deformability increase :

x1.65 (FRP jacket) x1.39 (TRM jacket)

L40d_

Strength increase :

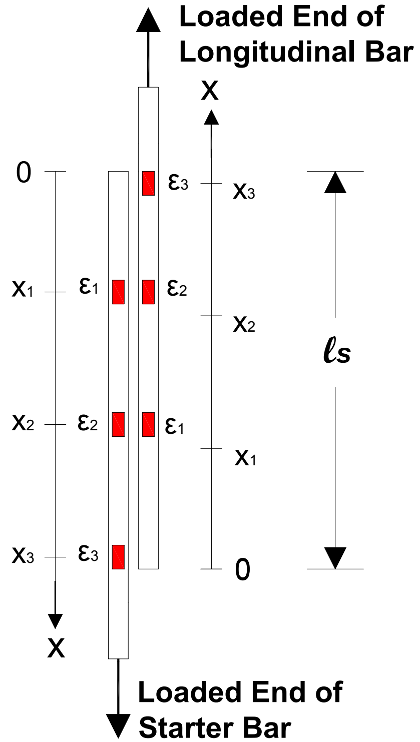
3% (FRP jacket) 7% (TRM jacket)

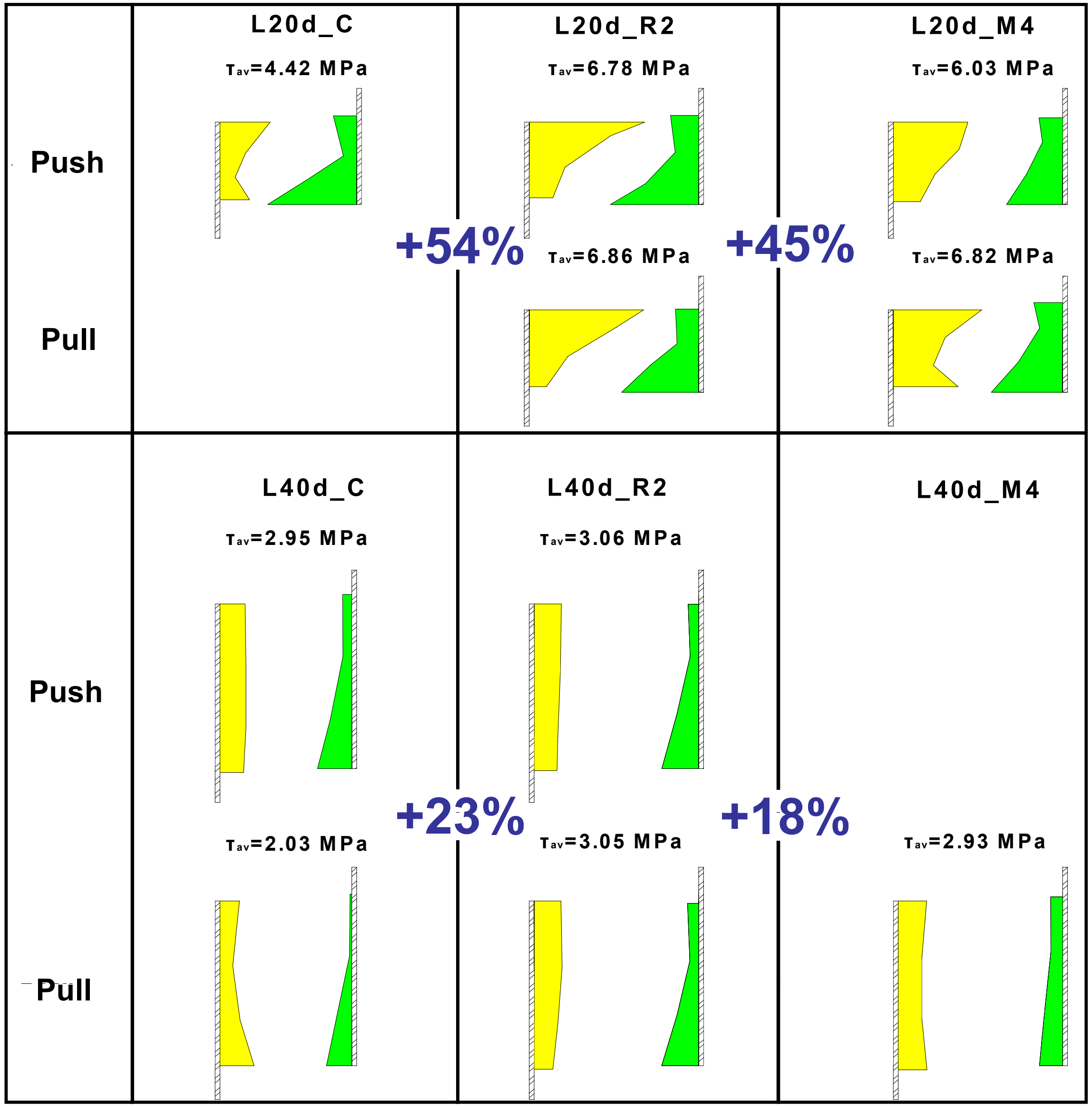
Deformability increase :

x2.5 (FRP jacket) x2.5 (TRM jacket)

BOND STRESS DISTRIBUTION (at peak resistance) along the lap length and AVERAGE BOND STRENGTH of the lap splice

$$\tau_i = \frac{d_b E_s}{4}\left(\frac{\varepsilon_i - \varepsilon_{i-1}}{x_i - x_{i-1}}\right)$$





Analytic Investigation-

Modelling

Bond Models of ACI and *fib*

Main parameters that affect the **bond strength between concrete and spliced bars** in tension include: the concrete cover, the splice length, the compressive strength of concrete, the splice bar diameter, the reinforcing bar geometry and **concrete confinement**.

Zuo and Darwin (2000) - ACI 408R-03 (2003) :

$$\tau_{max} = \frac{1}{\pi d_b \ell_s}[(1.44\ell_s(c_{min}+0.5d_b)+56.3A_b)(0.1\frac{c_{max}}{c_{min}}+0.9)f_c^{1/4}+K_{tr,s}f_c^{3/4}]$$

No jacket:
Predicted/Experimental = **0.92**

$$K_{tr,s} = k_s(N_s s_h \frac{A_{sw}}{s_h})+743.6$$

, with $k_s = \frac{0.354 t_r t_d}{n_s}$

Lettow and Eligehausen (2006) – New Model Code *fib* :

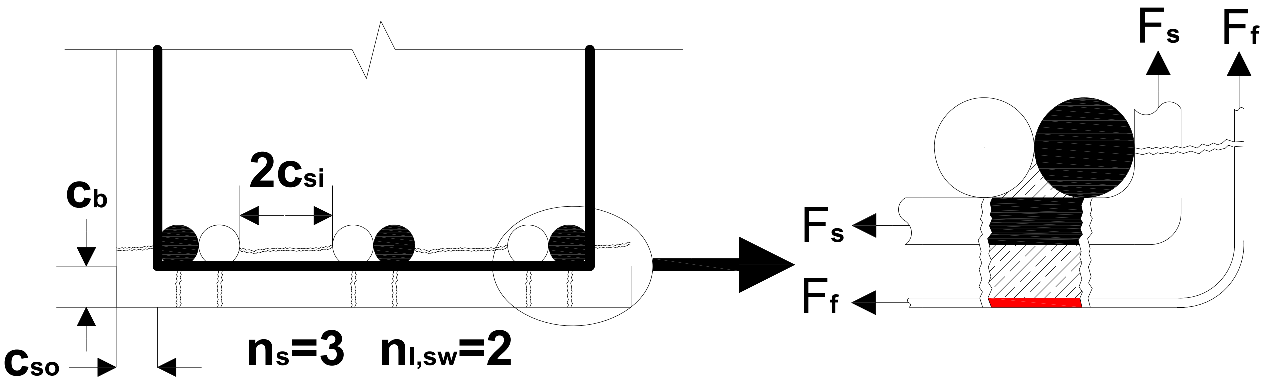
$$\tau_{max} = \frac{d_b}{4\ell_s}[24.2(\frac{\ell_s}{d_b})^{0.55}(f_c)^{1/4}(\frac{c_d}{d_b})^{1/3}(\frac{c_{max}}{d_b})^{0.1}(\frac{20}{d_b})^{0.2}(1+K_{tr,s})]$$

No jacket:
Predicted/Experimental = **0.96**

$$K_{tr,s} = k_s(\frac{A_{sw} n_{l,sw}}{s_h})$$

, with $k_s = \frac{10}{d_b n_s}$

Bond Strength of FRP and TRM Confined Concrete



A modified term $K_{tr,t}$ is proposed, which accounts for the total confinement applied by both the contribution of stirrups and FRP or TRM jackets:

$$K_{tr,t} = K_{tr,s} + K_{tr,j} = \text{Linear Function of } k_s(A_{sw}/s_h) + k_f 2nt_f$$

$$k_f = k_s h_f \frac{E_f}{E_s} \frac{\varepsilon_{f,ef}}{\varepsilon_{sw}}$$

[Zuo and Darwin (2000)]

$$k_f = k_s \frac{E_f}{E_s} \frac{\varepsilon_{f,ef}}{\varepsilon_{sw}}$$

[Lettow and Eligehausen (2006)]

The proposed parameter $K_{tr,j}$ takes into account :

- The area of external FRP or TRM reinforcement ($2nt_f$) in the splice region
- The effect of the modulus of elasticity of the jacket's composite material (E_f)
- The average effective strain of the jacket in the circumferential direction ($\varepsilon_{f,ef}$)

$$K_{tr,j} = 2nt_f \frac{E_f}{E_s} \frac{\varepsilon_{f,ef}}{\varepsilon_{sw}}$$

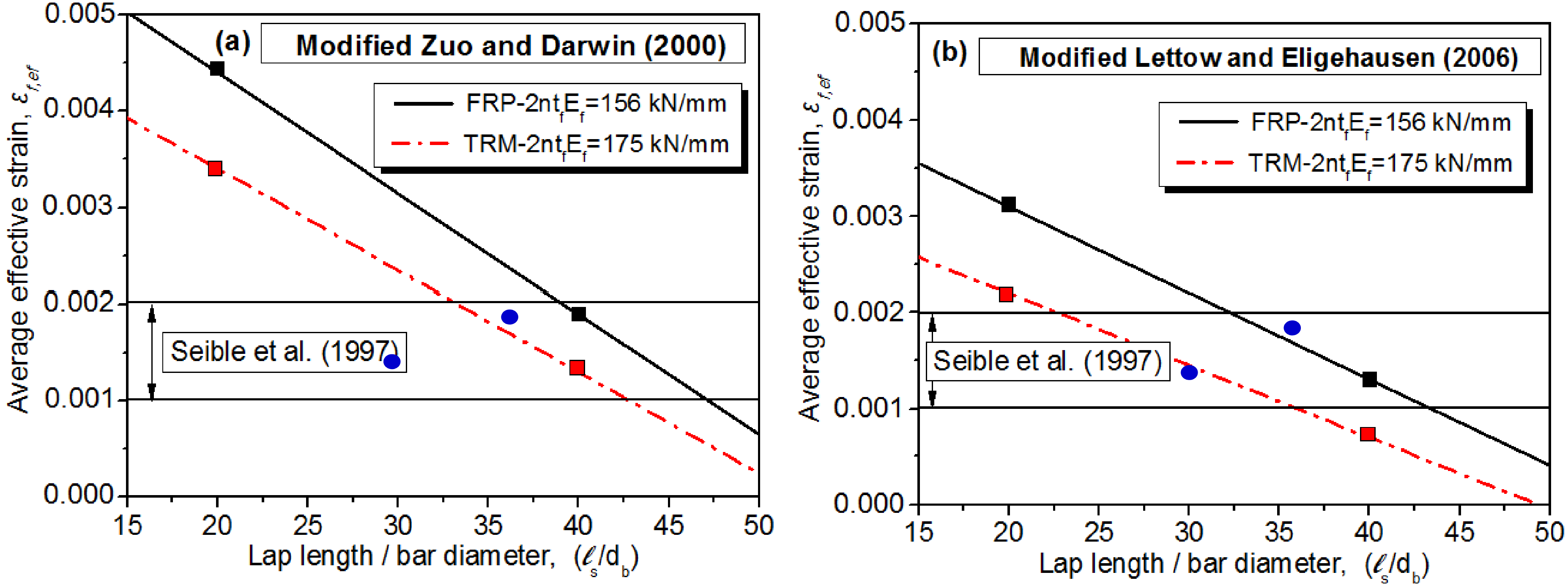
$\varepsilon_{f,ef}$ → UNKNOWN

ε_{sw}: Average effective strain of the stirrups in the circumferential direction

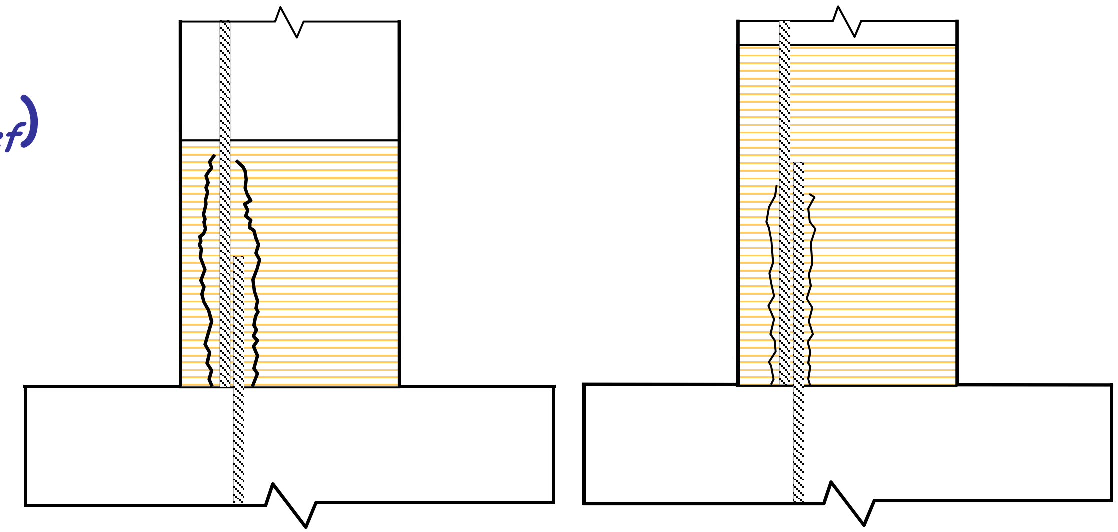
Reference	**Specimen Type**	ε_{sw}	ε_{yw}	$\varepsilon_{sw} / \varepsilon_{yw}$
Cairns and Arthur (1979)	Columns	0.0010	0.0017	0.60
Lukose et al. (1982)	Beams	0.0014	0.0023	0.63
Paulay (1982)	Columns	0.0015	0.0015	1.00
Panahshani et al. (1992)	Beams	0.0011	0.0023	0.48
Valluvan et al. (1993)	Columns	0.0016	0.0024	0.66
Saadatmanesh et al. (1997b)	Columns	0.0010	0.0018	0.55
Azizinamini et al. (1999)	Beams	0.0015	0.0021	0.71
Haroun et al. (1999)	Columns	0.0016	0.0022	0.73
Ma and Xiao (1999)	Columns	0.0015	0.0015	1.00
Melek and Wallace (2004)	Columns	0.0012	0.0024	0.50
		0.00134		

$\varepsilon_{sw}=0.0013$

The jacket's average effective strain $\varepsilon_{f,ef}$ is determined based on the experimentally measured bond strength



Higher activation (high $\varepsilon_{f,ef}$) of FRP or TRM jackets for short lap lengths !



Proposed Equations (more data needed !)

Modified Zuo and Darwin (2000) model (*ACI*):

$$\varepsilon_{f,ef} = 0.0069 - 12.5 \cdot 10^{-5}(\ell_s / d_b)$$ for FRP Jackets

$$\varepsilon_{f,ef} = 0.0055 - 10.5 \cdot 10^{-5}(\ell_s / d_b)$$ for TRM Jackets

Modified Lettow and Eligehausen (2006) model (*fib*):

$$\varepsilon_{f,ef} = 0.0049 - 9 \cdot 10^{-5}(\ell_s / d_b)$$ for FRP Jackets

$$\varepsilon_{f,ef} = 0.0037 - 7.5 \cdot 10^{-5}(\ell_s / d_b)$$ for TRM Jackets

CONCLUSIONS

The (limited) test data obtained in this study confirm that TRM jackets are nearly as effective as FRP jackets in confining lap-spliced regions. Both composite materials enhanced the global response of columns in terms of strength and deformation capacity

Existing well-known models (ACI, *fib*), which predict well the bond strength at lap splices without jacketing, were extended in this study to account for the confinement provided by external jackets, by introducing basic characteristics of the jackets

Calibration of the modified models with test results leads to the conclusion that the jacket effective strain at peak resistance of the columns decreases as ℓ_s/d_b increases

The proposed models (possibly modified when more data become available) can be used to design the thickness of jackets at lap splices so that steel yielding will preced bond failure of the rebars

THANK YOU FOR YOUR ATTENTION