SERIES
Seismic Engineering Research Infrastructures for European Synergies
UNIVERSITY OF PATRAS • EUROPEAN COMMISSION • FRAMEWORK PROGRAMME 7

International Workshop:
"Role of research infrastructures in seismic rehabilitation"

Experimental behavior of non conforming full scale RC beam-column joints retrofitted with FRP

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Introduction

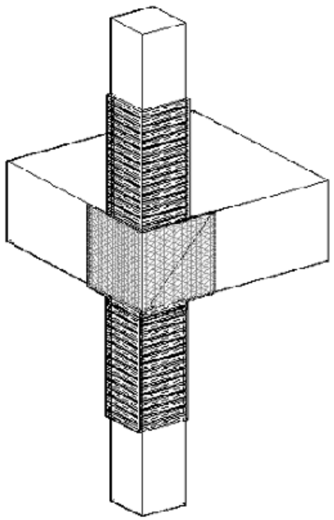
- ❖ Premature shear failure of beam-column joints is one of the main cause limiting the structural seismic capacity. Post earthquake inspections confirmed that partially confined (i.e. exterior) joints of RC existing buildings are the most vulnerable structural part due to the lack of adequate confinement, internal transverse stirrups and detailing.

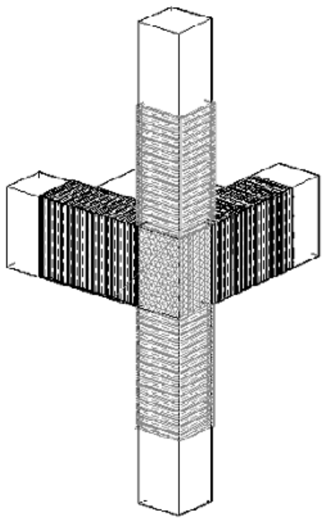
- ❖ Exterior joint FRP strengthening system may increase joint panel shear capacity and energy dissipation

Experimental program to investigate on the effectiveness of FRP beam column joints strengthening

Research goals

- Design of beam column joints typical of existing RC costruction (simulated design of existing RC building in the Mediterranean area);
- Test setup definition for T-shaped and X-shaped joints;
- Investigation on the beam column joints mechanical behavior and comparison with existing literature capacity models;
- Investigation on the effectiveness of different FRP strengthening layout;
- Model capacity development to predict the benefits provided by the FRP strengthening solution

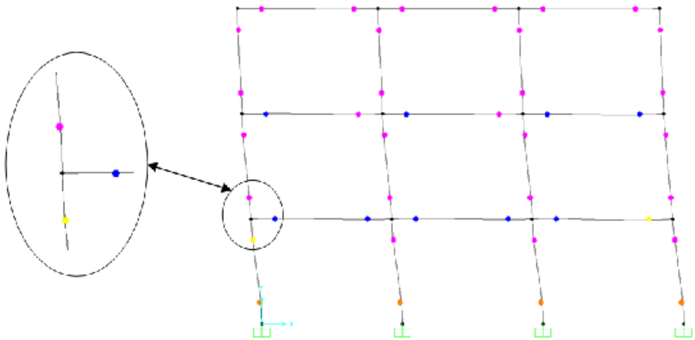


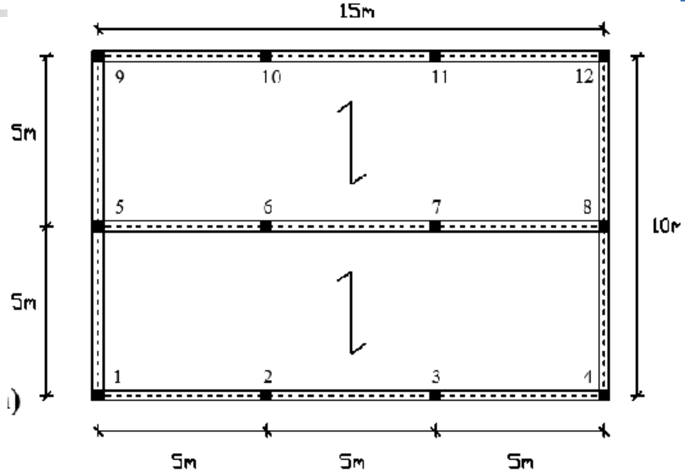


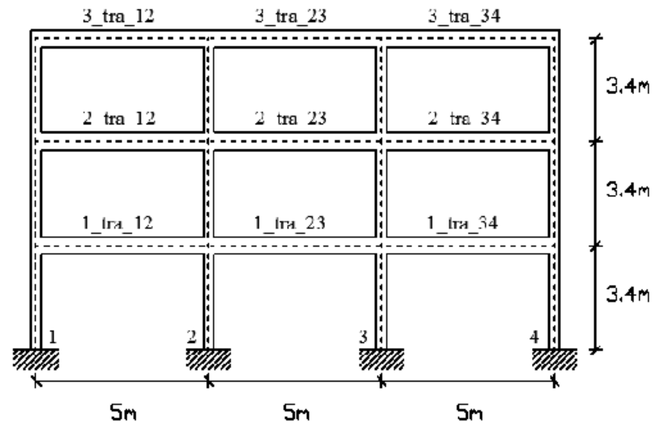
Specimens' design

- Simulated design:

-Design for gravity loads only
-Resisting frame in one direction
-Wrong strength hierarchy (weak column – strong beam



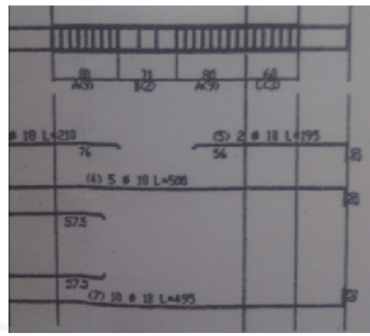




- Joint panel details according to obsolete codes:

- No stirrups in the joint panel
- Beam bars anchored in the joint panel (20 cm)

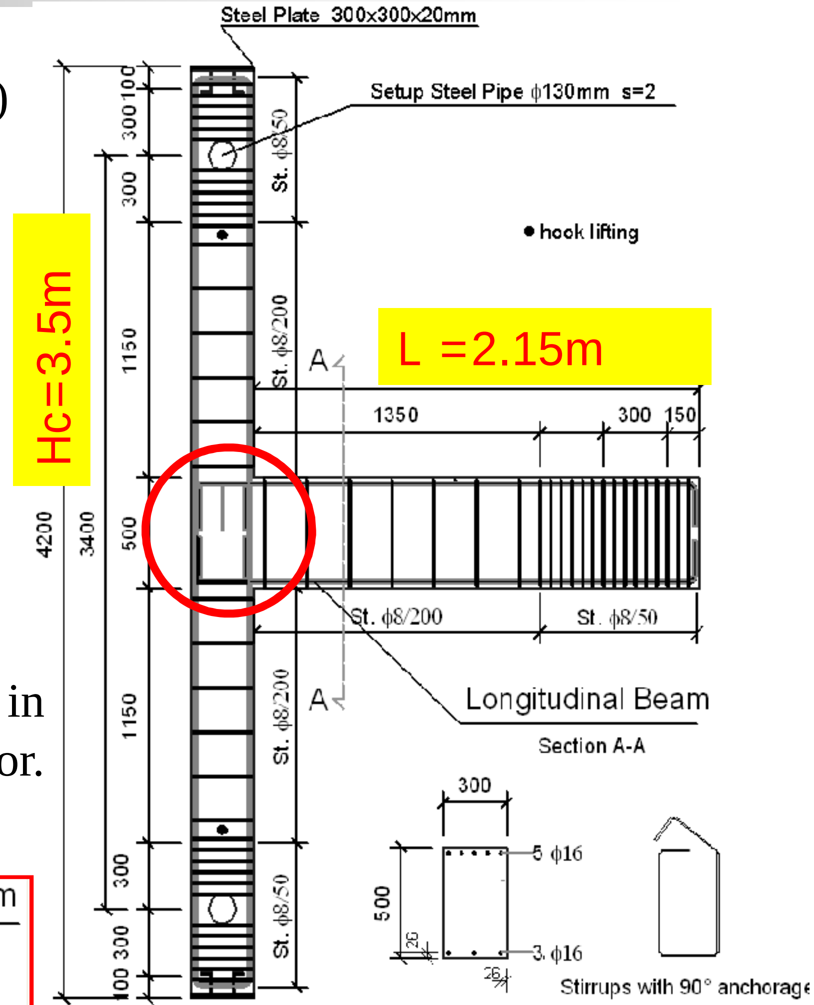
-Bending moment zero point on beam or columns in order to define subassemblies dimensions

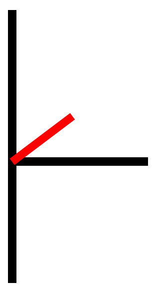


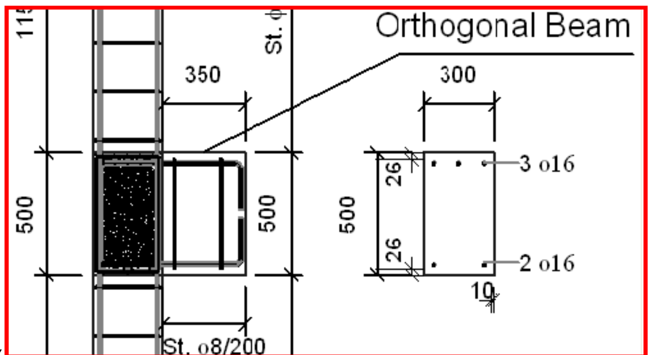
Specimens' design

- Poor quality concrete f_{cm} =16-19 MPa
- Deformed Steel (FeB44k) f_{ym} = 470 MPa

- Columns 30x30cm (4ϕ16, ρ =0,9%)
- Beams 30x50 cm, internal reinforcing:
  - 5ϕ16 (ρ =1.12%)top side
  - 3ϕ16 (ρ =0.67%)bottom side
- Stirrups ϕ8mm 20 cm spaced (beam and col.)
- Orthogonal beam is represented by a 35 cm stub in order to evaluate its influence on joint behavior. (designed taking into account only infill weight)







Specimens' design

- In order to predict subassemblies behavior linear and non linear analysis have been carried out taking in account test setup boundary conditions

Subassemblies failure sequences

1. Joint panel shear failure

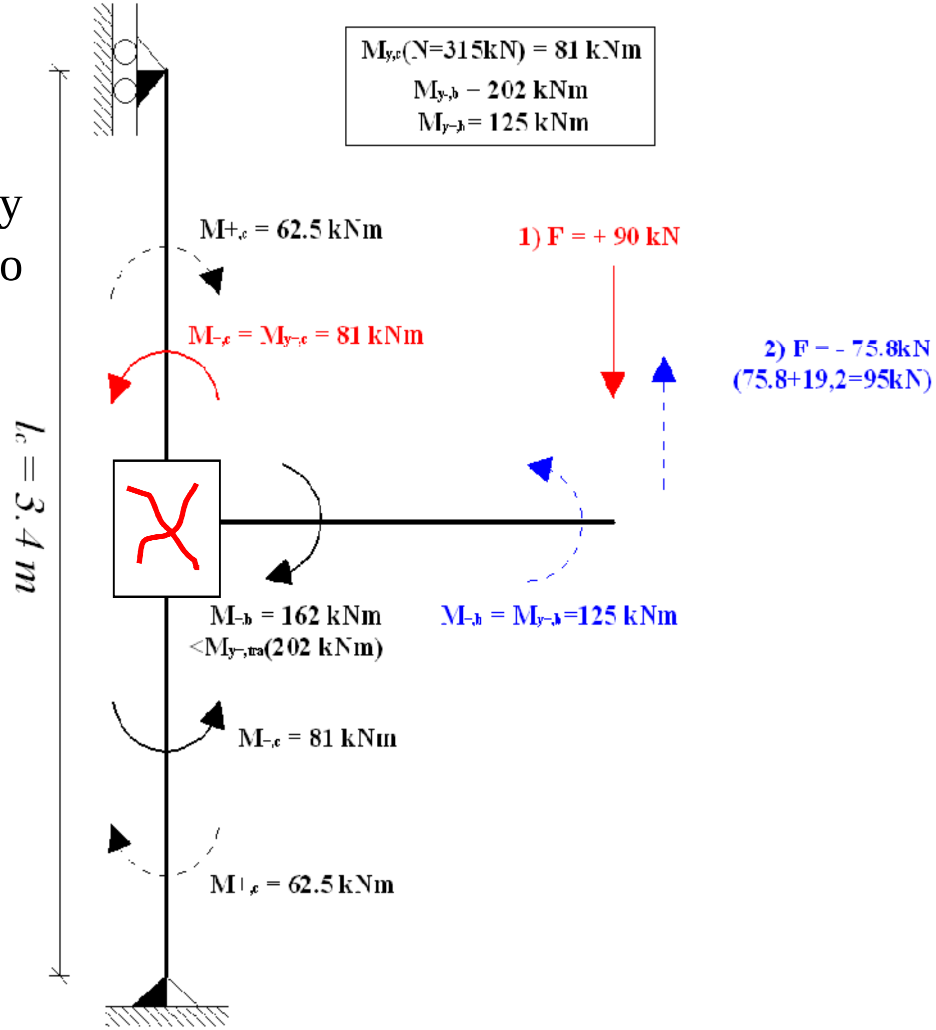
- Joint shear capacity (according to Priestley 1997) V_j ($p_t = 0{,}42\sqrt{f_{cm}}$) corresponding to external force F =73.6 kN (V_c= 38.9 kN)

2. Top column yielding

- Top column bar yielding; external force F =90 kN (Vc=47 kN)

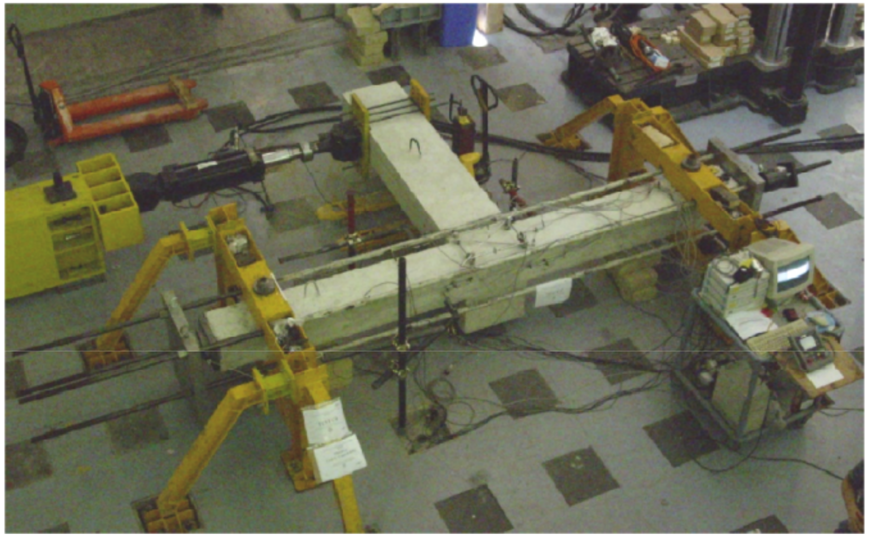
3. Beam yielding

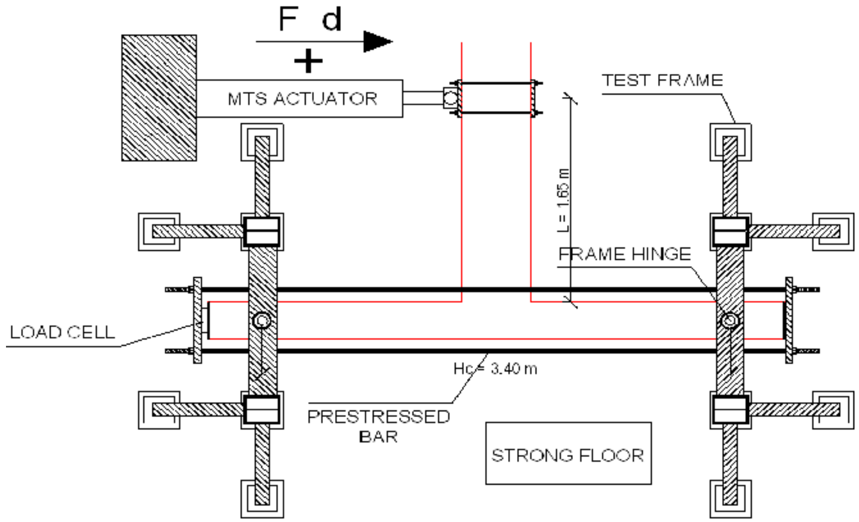
- Beam bars yielding (bottom side - due to preload representative of gravity loads); external force F = -95 kN (Vc=50.2 kN)



Test Setup

- Beam-column subassembly horizontally placed on a plane parallel to the strong floor

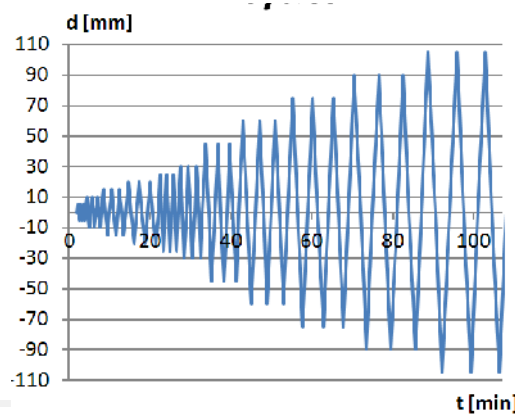




- Two rigid frames to constrain column ends by means of two steel hinges
- Constant axial load ($\nu = 0.21$) by mean of four prestressed steel bars
- Load History:

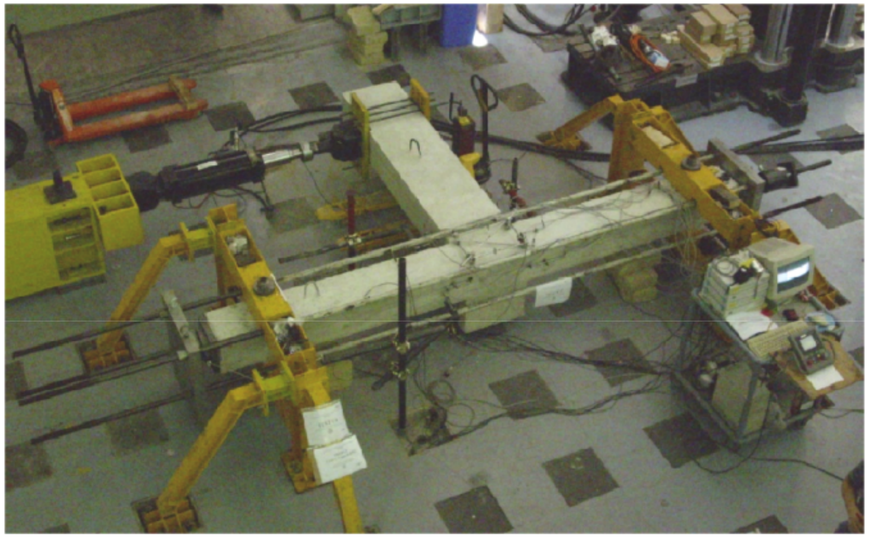
• preload of 19.2 kN to simulate gravity loads

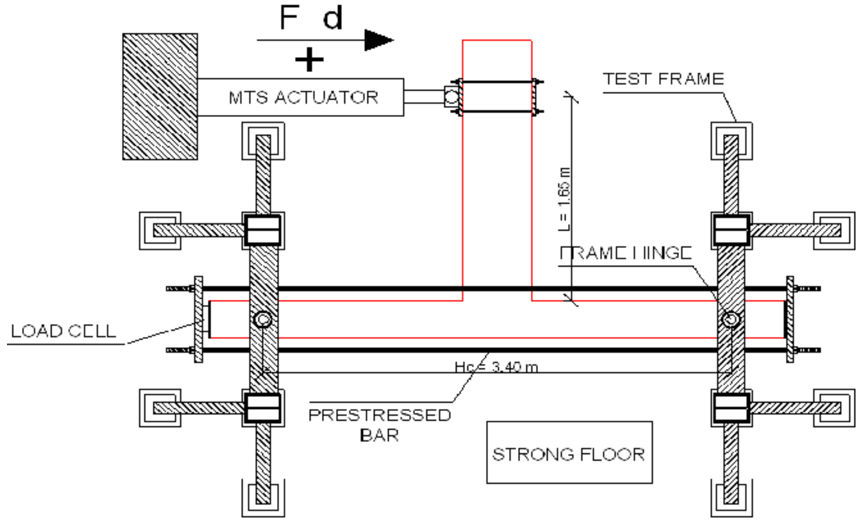
• cyclic displacement loading (3 ripetition per cycle)



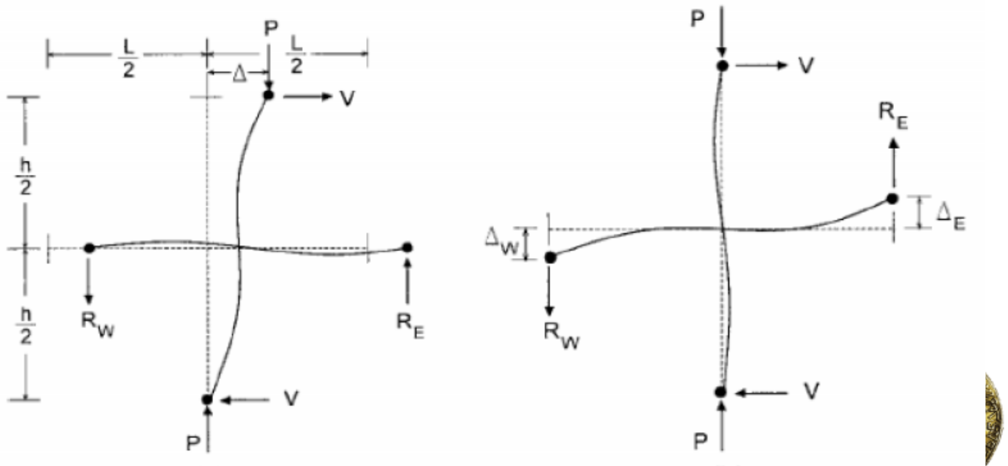
Test Setup

- Beam-column subassembly horizontally placed on a plane parallel to the strong floor



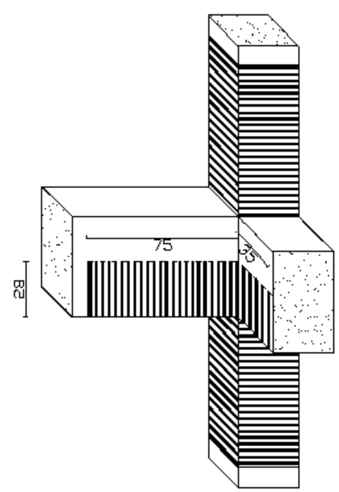


The test setup may effectively reproduce seismic actions on a beam-column subassembly unless P-D effects due to column axial load is neglected, Park, 1992.

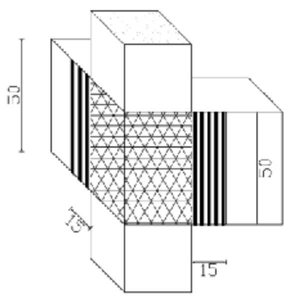


Test Matrix

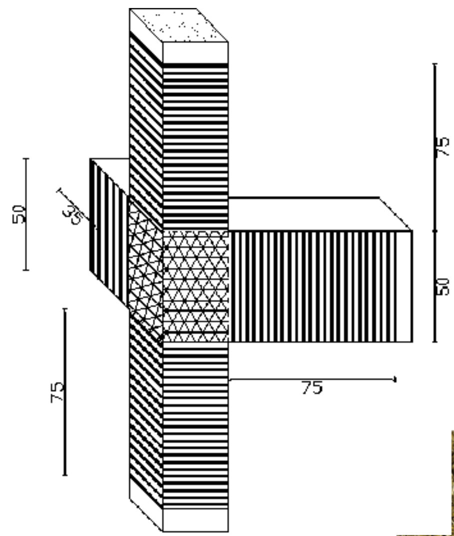
Name	Specimen description	f_{cm}	ρ_{FRP} (joint panel)
[-]	[-]	[MPa]	[%]
T_C	as-built	16.38	-
T_C3	as-built	16.30	-
T_FRP	"Light" CFRP Strengthening (scheme 1)	14.84	0.0176
T_FRP2	"Strong" FRP Strengthening (scheme 2a)	17.74	0.0176
T_FRP3	"Strong" FRP Strengthening (scheme 2b)	n.a.	0.0352



"Light" CFRP strengthening (Scheme 1)



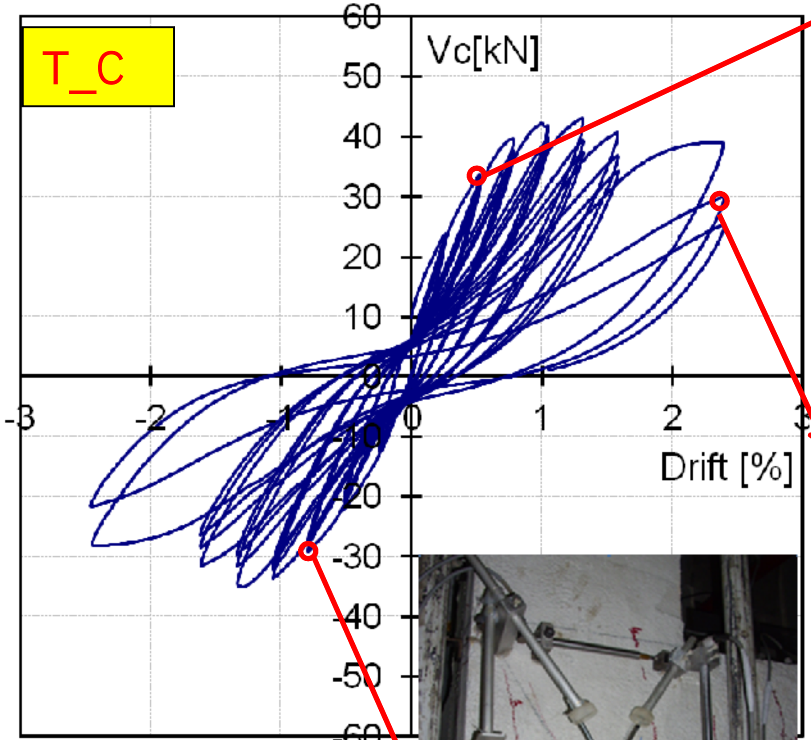
"Strong" CFRP strengthening (Scheme 2)

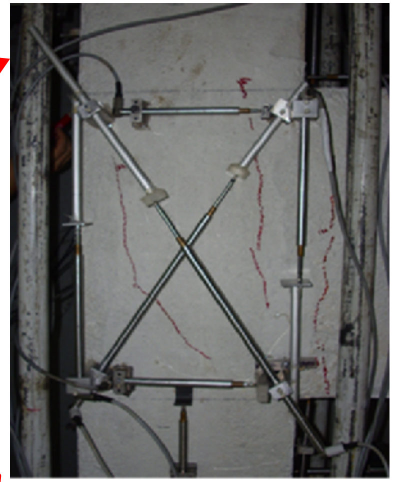


$\nu = N/(A_c \cdot f_{cm}) = 0.21$

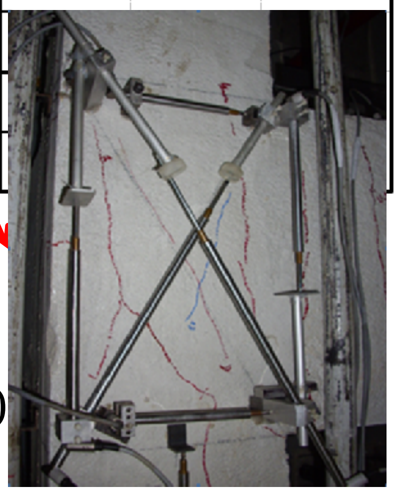
Test Results: As built specimens

- **Crack pattern and failure mode**

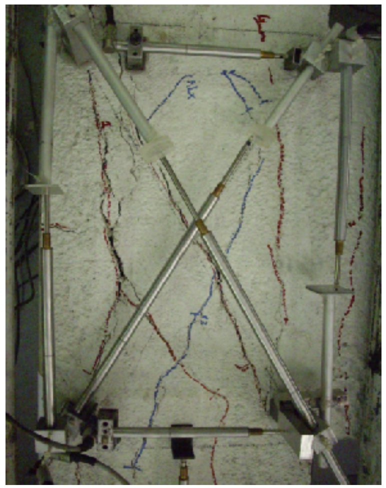




3° Cycle
First Diagonal Crack
(Drift =0.52%,
Vc = 33.2 kN)

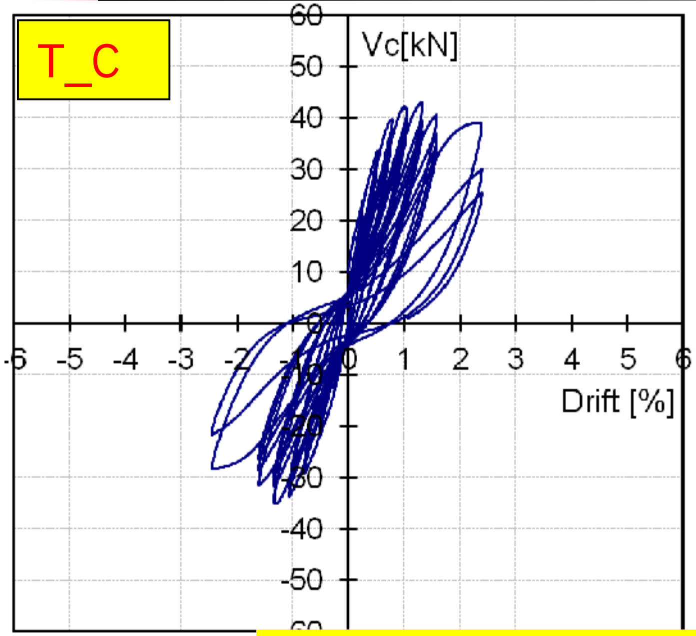


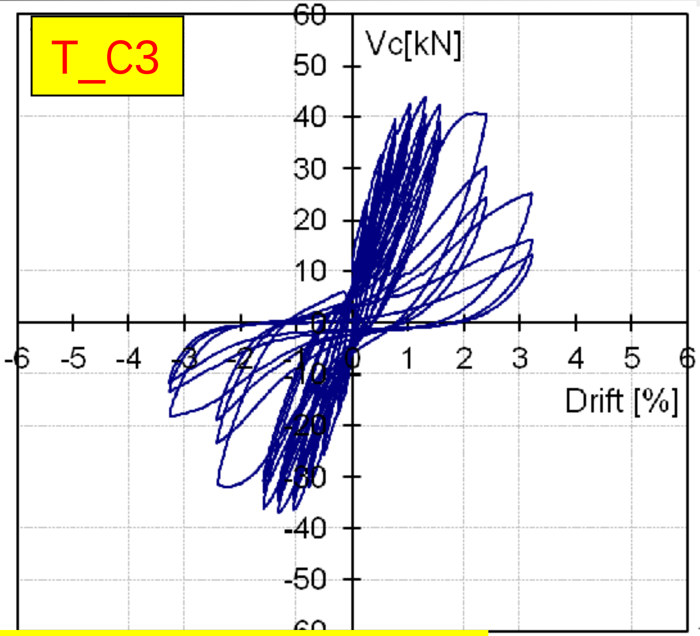
5° Cycle
Diagonal cracking
for negative load
(Drift =0.70%, V_c = -29.7 kN)



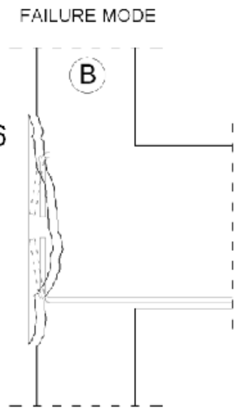
7° Cycle (Drift=2.4%, Vc =25.2kN)
extensive damage

Test Results: As built specimens

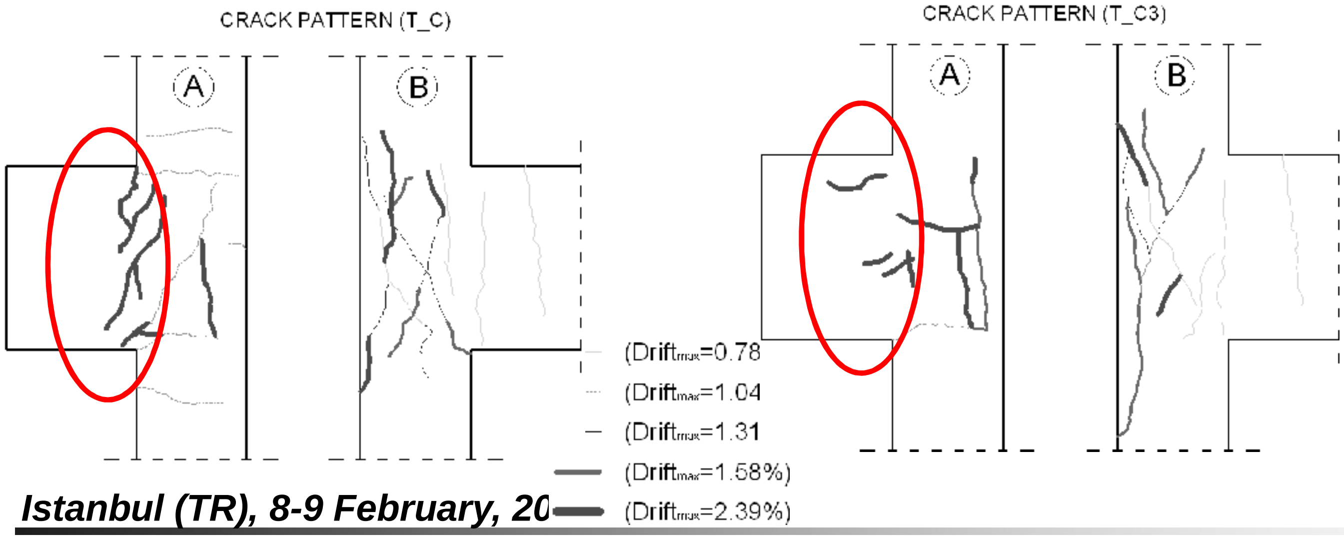




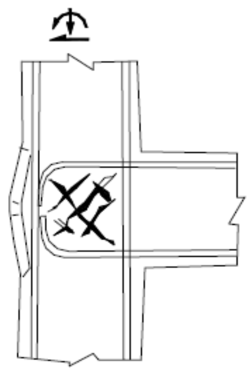
Failure mode



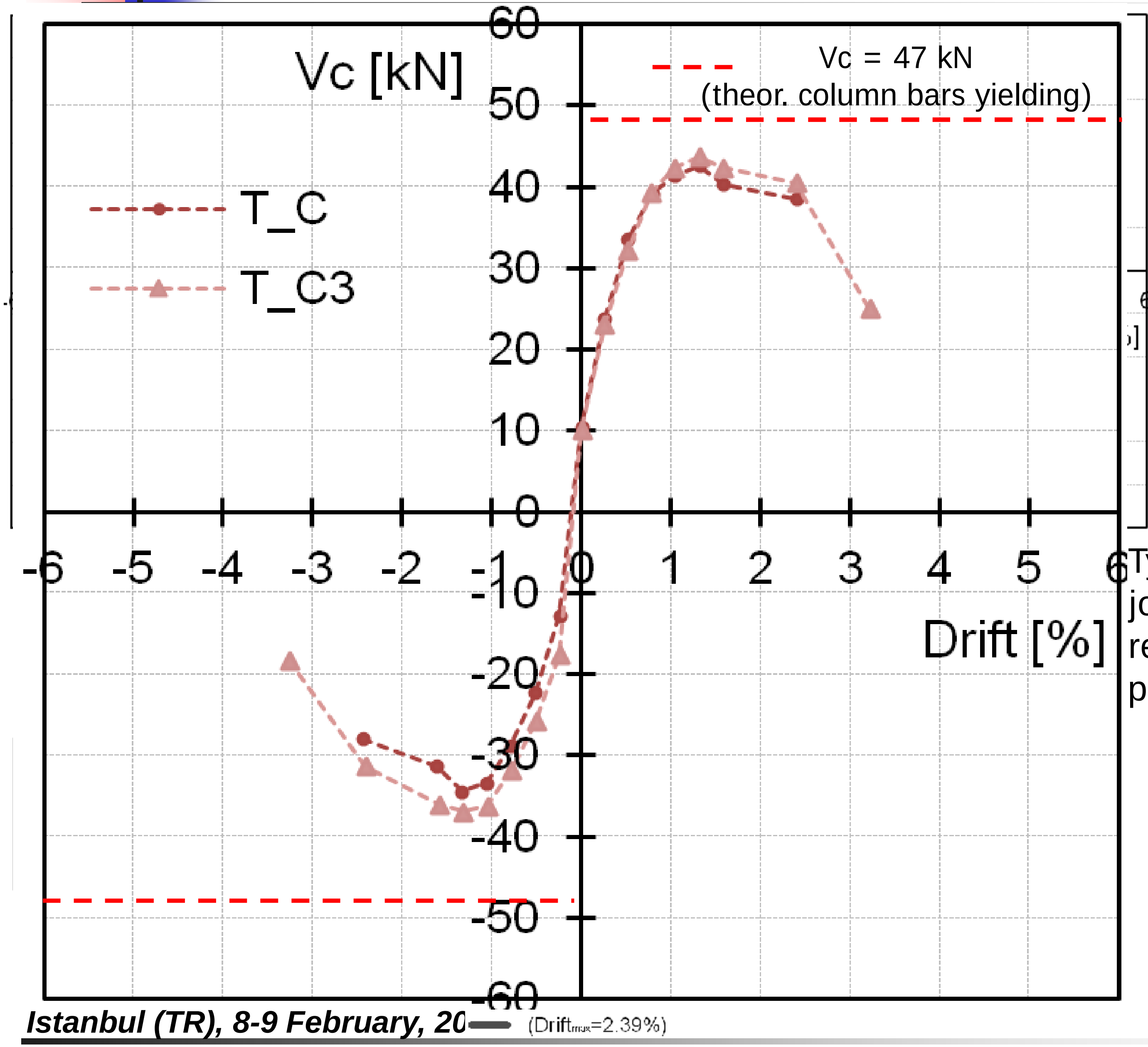
Similar behavior and crack pattern



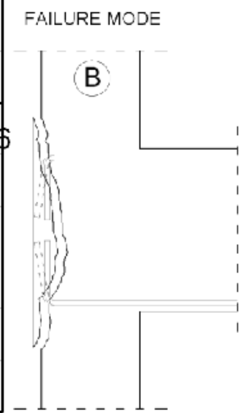
Typical failure mode of T-joints with beam reinforcement bent into the panel (Pampanin et al. 2002)



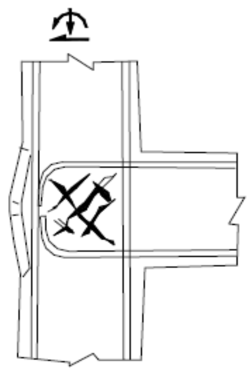
Test Results: As built specimens



Failure mode



Typical failure mode of T-joints with beam reinforcement bent into the panel (Pampanin et al. 2002)



Test Results: T_C3

T_C3

Exp. - theor. comparison

- - - - $V_c\left(p_t = 0.29\sqrt{f_c}\right)$

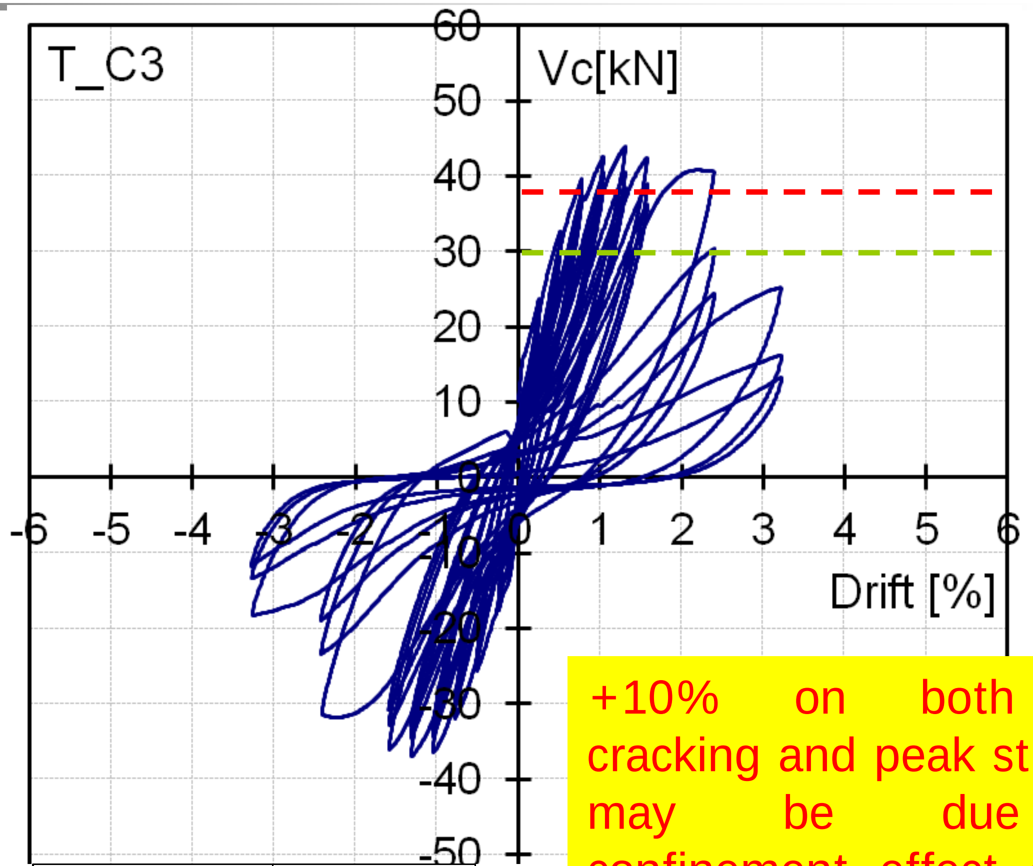
Deformed bars,
k = 0.29 (Priestley 1997) first cracking
k = 0.30 NTC'08

- - - - $V_c\left(p_t = 0.42\sqrt{f_c}\right)$

Deformed bars, strength peak
k = 0.42 (Priestley 1997)

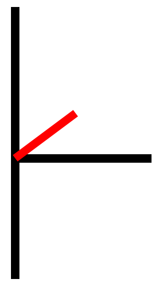
$$p_t = \left| \frac{f_a}{2} - \sqrt{\left(\frac{f_a}{2}\right)^2 + v_j^2} \right| \leq k\sqrt{f_c}$$

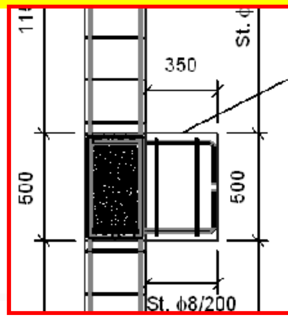
$$f_a = \frac{N_c}{b_j \cdot h_c} \qquad v_j = \frac{V_{jh}}{b_j \cdot h_c}$$



+10% on both first cracking and peak strength may be due to confinement effect of the orthogonal beam

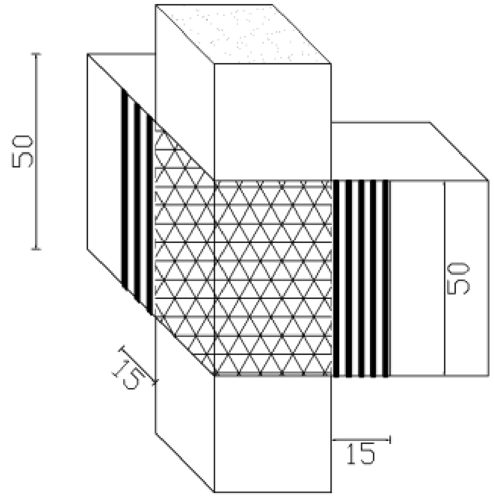
		First Cracking		$p_t=(0.29\sqrt{f_{cm}})$		Peak		$p_t=(0.42\sqrt{f_{cm}})$	
Spec.	A_j	V_c	Drift	V_c	ΔV_c	V_c	Drift	V_c	ΔV_c
[-]	[mm²]	[kN]	[%]	[kN]	[%]	[kN]	[%]	[kN]	[%]
T_C	74400	33.2	0.52	30.4	8.9	42.6	1.31	39.0	9.3
T_C3	74400	32.2	0.51	30.2	6.6	43.8	1.32	39.4	11.1

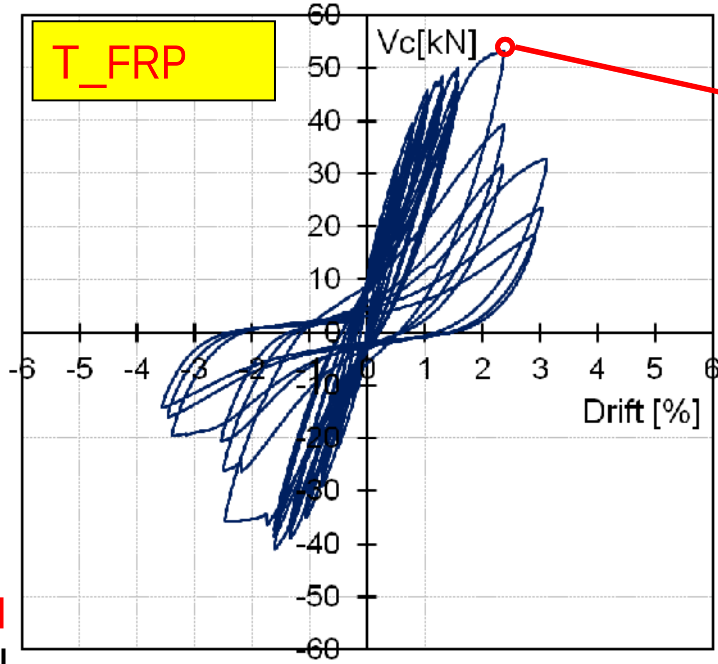


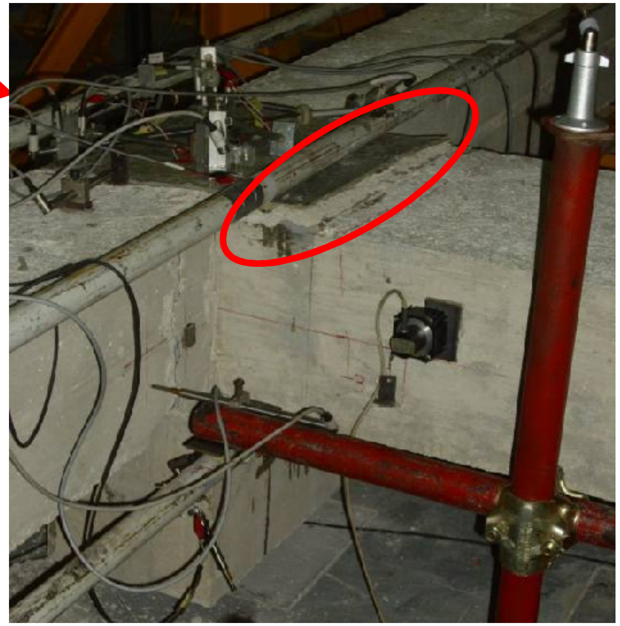


Test Results: FRP strengthened spec.

"Light" CFRP strengthening (Scheme 1)





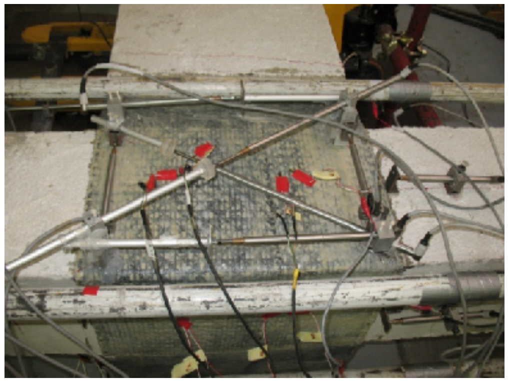


FRP end debonding starting from U-wrap free end

- 6° cycle (Drift = 2.37%, Vc = 53.15 kN)

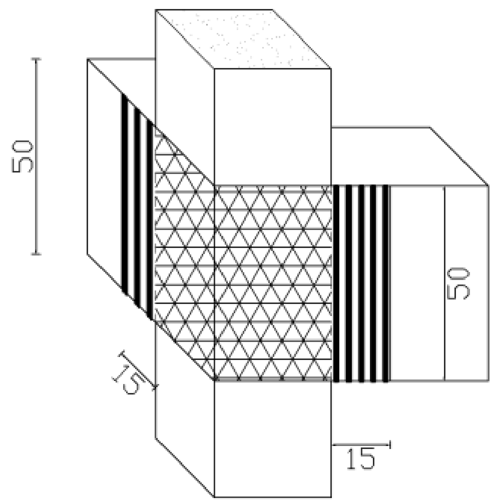
1 ply CFRP quadriaxial laminates on joint panel extended 15 cm on beam

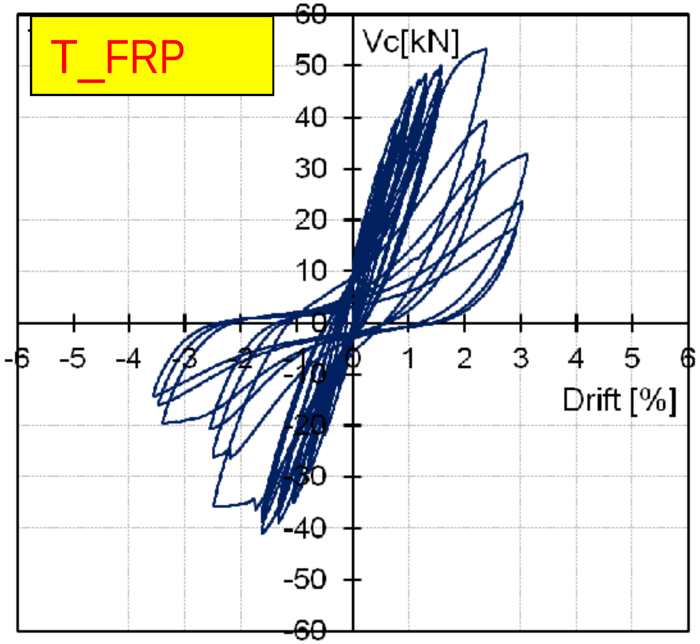
1 ply uniaxial CFRP laminates - U-shaped wrapping 15 cm on beam end



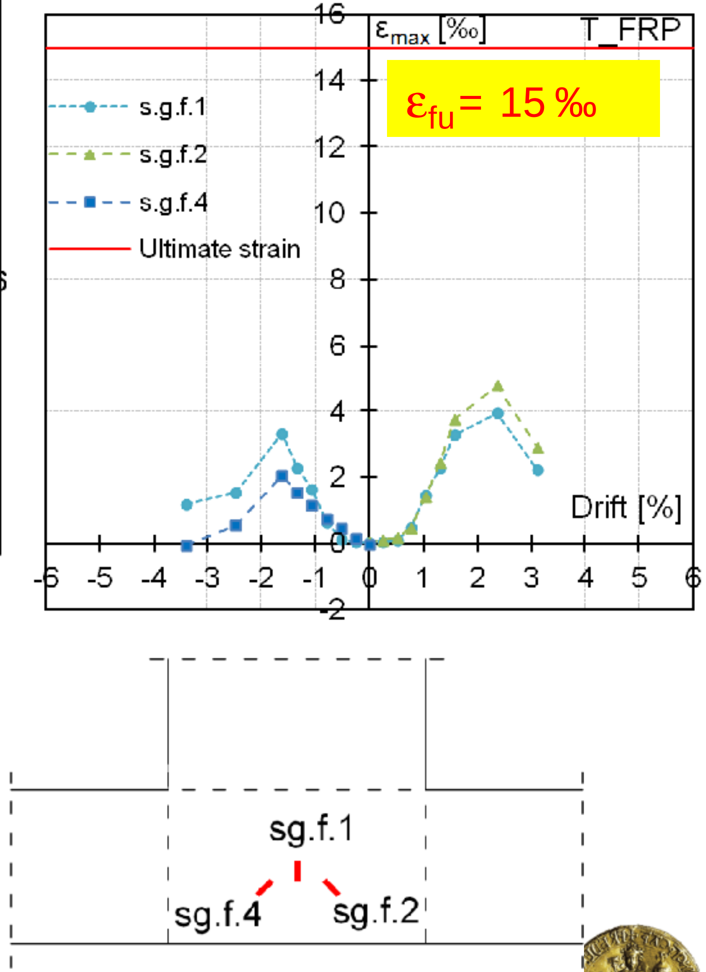
Test Results: FRP strengthened spec.

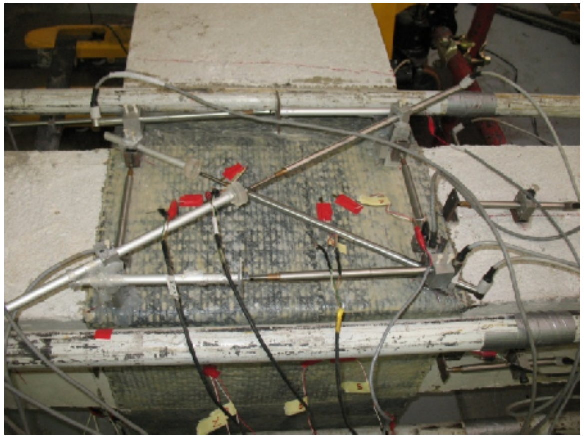
"Light" CFRP strengthening (Scheme 1)





Strain on FRP panel



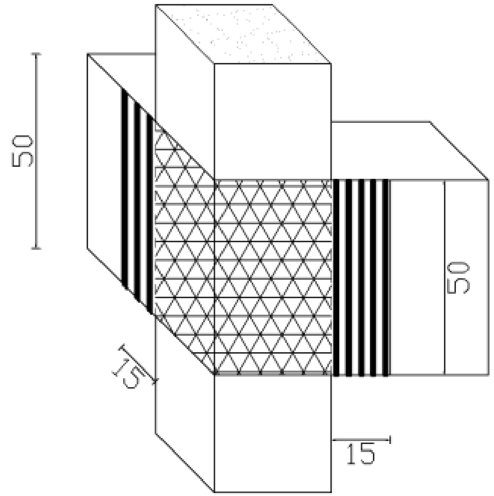


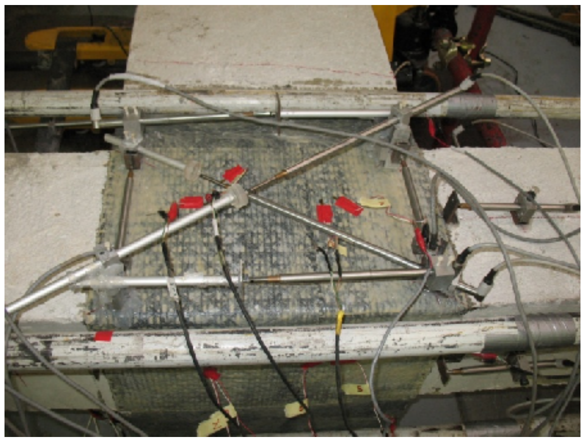
Maximum strain recorded on FRP panel:

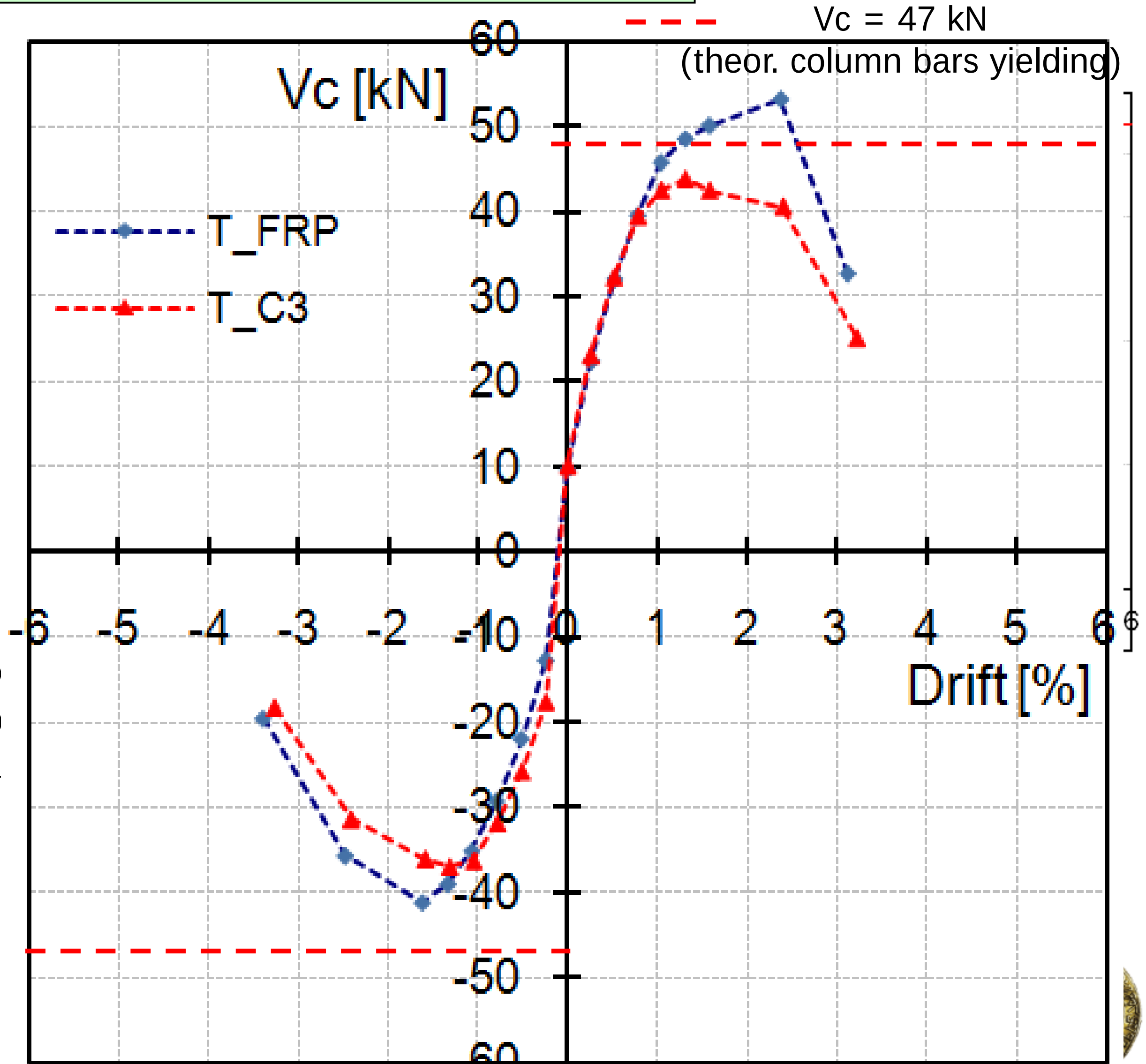
$\varepsilon_{f,max}$ = 4.7 ‰

Test Results: FRP strengthened spec.

“Light” CFRP strengthening (Scheme 1)







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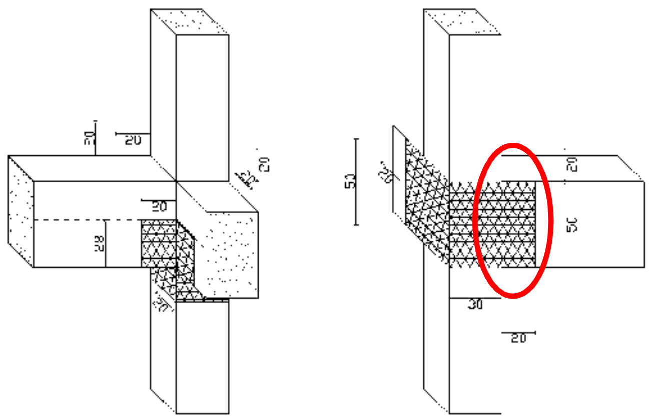
Test Results: FRP strengthened spec.

“Strong” CFRP strengthening (Scheme 2a)

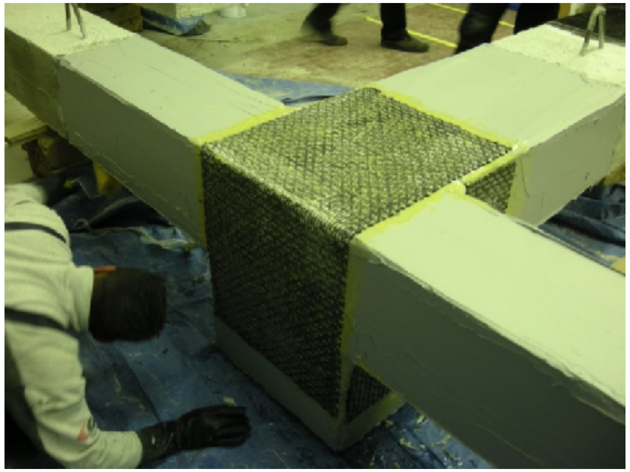
T_FRP_2

1) 1 Layer CFRP Quadriaxial Sheet

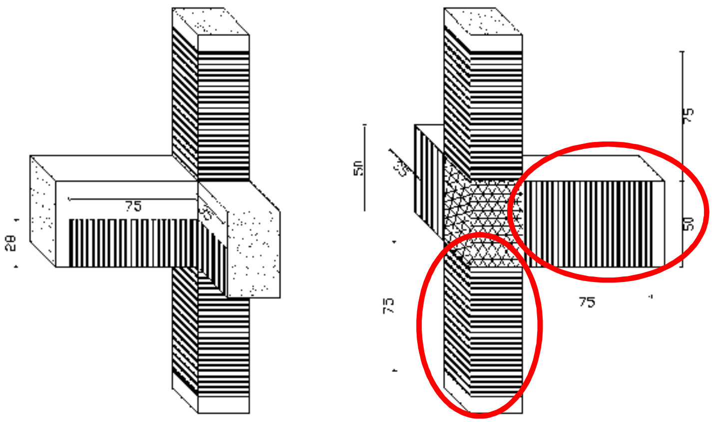


1 ply CFRP quadriaxial laminates on joint panel extended 20 cm on beam

1 ply L-shaped CFRP quadriaxial laminates to connect beam and column

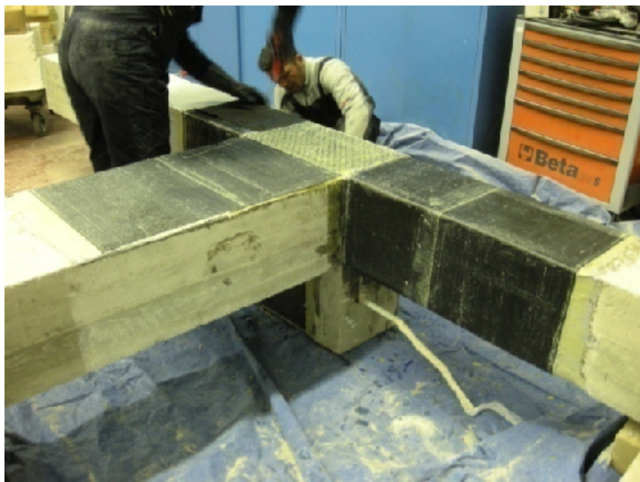


2) 1 Layer CFRP Uniaxial Sheet



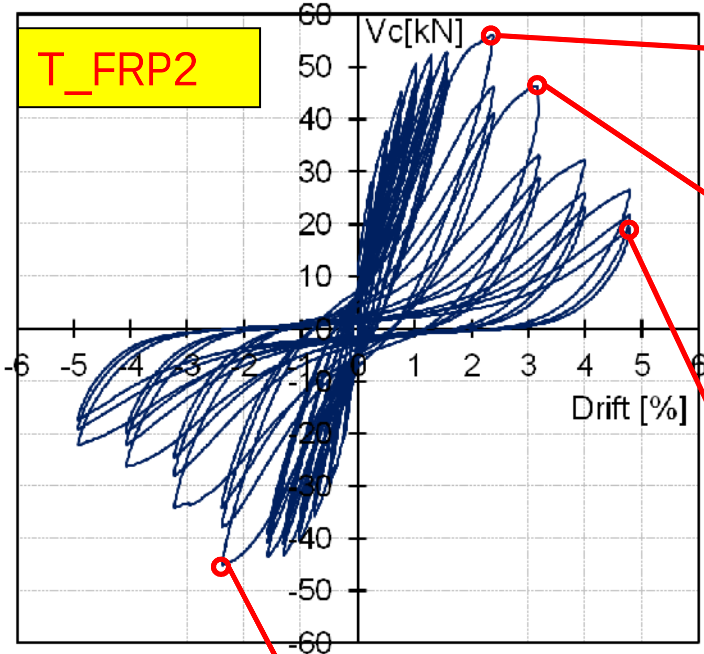
1 ply uniaxial CFRP laminates – column confinement 75 cm

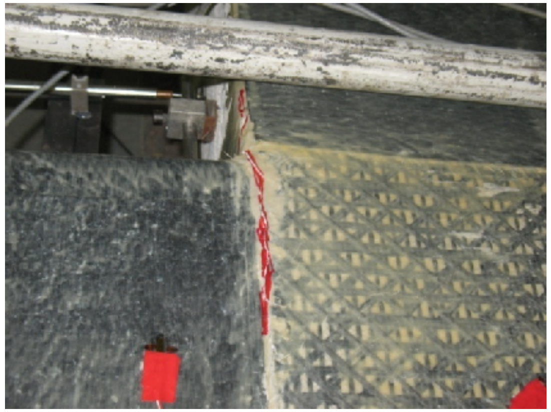
1 ply uniaxial CFRP laminates – U-shaped wrapping 75 cm



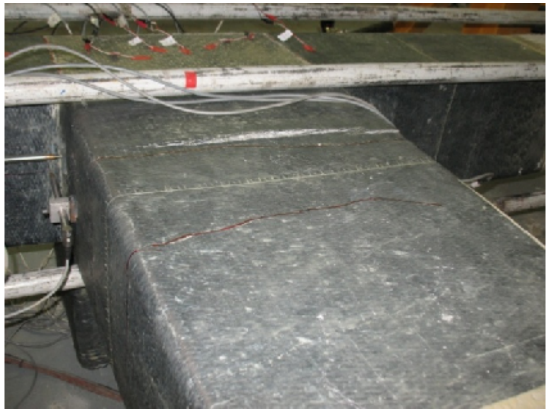
Test Results: FRP strengthened spec.

"Strong" CFRP strengthening (Scheme 2a)

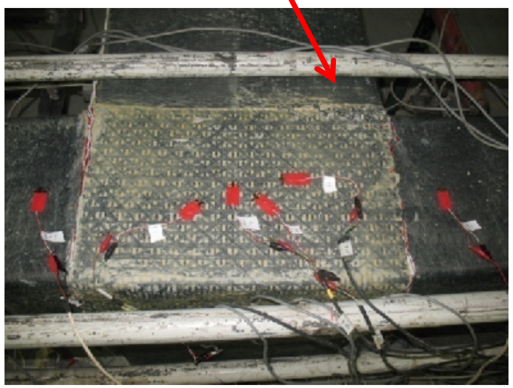




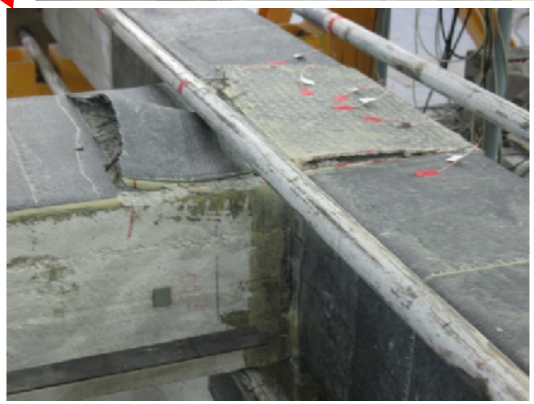
7° Cycle
First Debonding
(Drift =2.38%, V_c = 56.1 kN)



8° Cycle
End Debonding
(Drift =3.18%, V_c = 46.0 kN)



7° Cycle
Quadriaxial fibers cut
(Drift=2.39%, V_c = 44.9 kN)



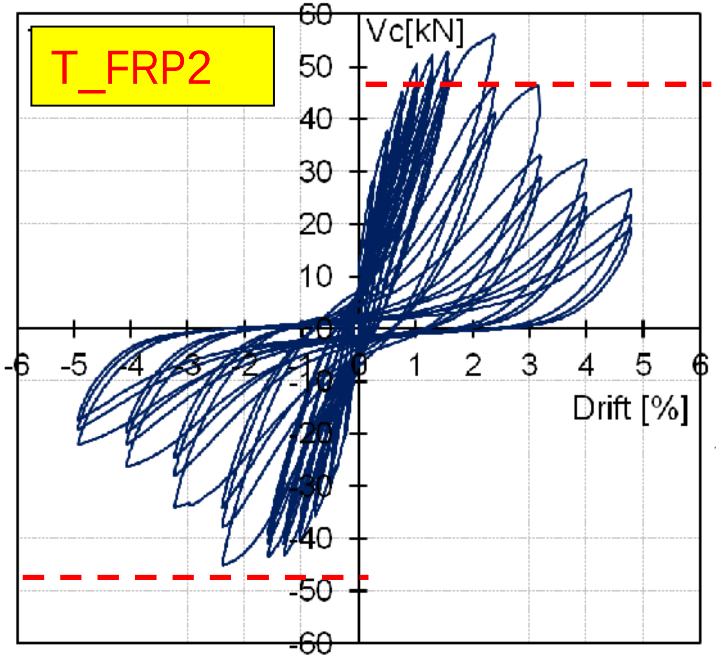
10° Cycle
Final damage
(Drift =4.8%, V_c = 19.1 kN)

Test Results: FRP strengthened spec.

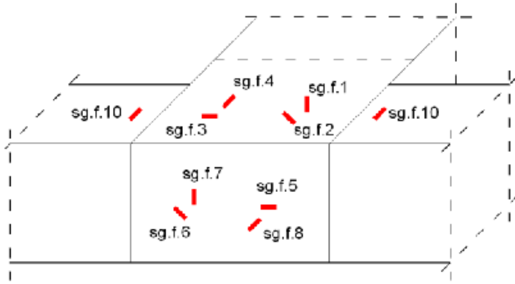
T_FRP2

Test Results: FRP strengthened spec.

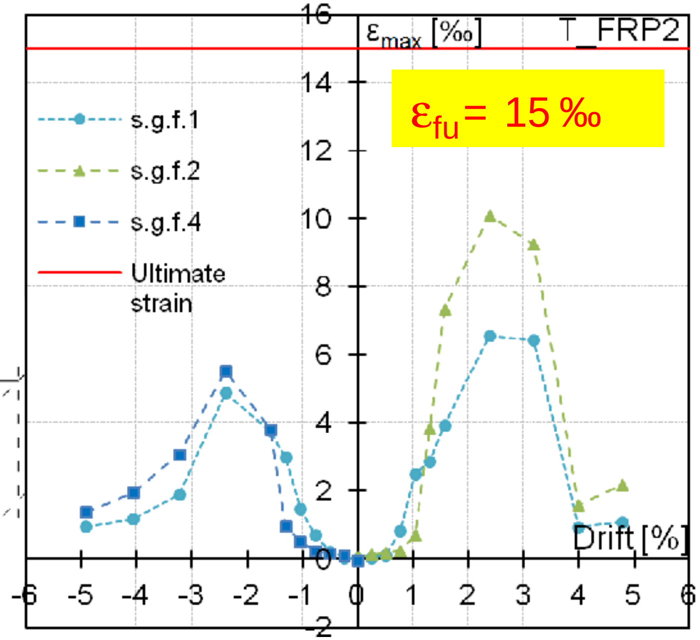
"Strong" CFRP strengthening (Scheme 2a)



Vc = 47 kN (theor. column bars yielding)



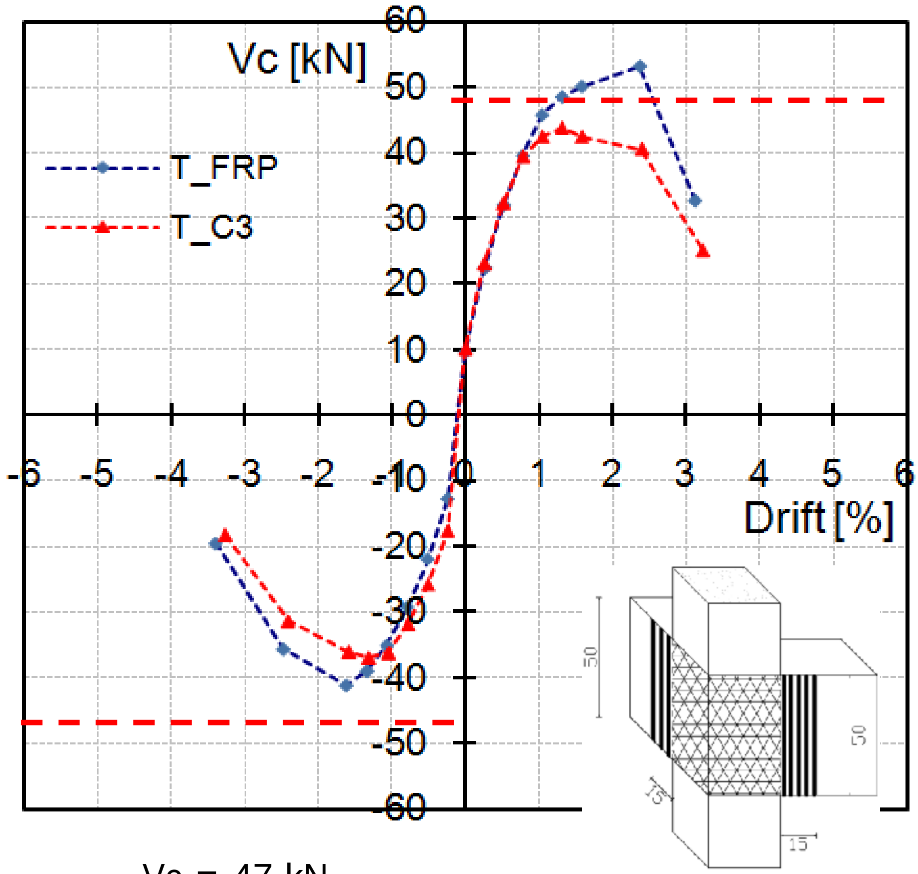
Strain on FRP panel



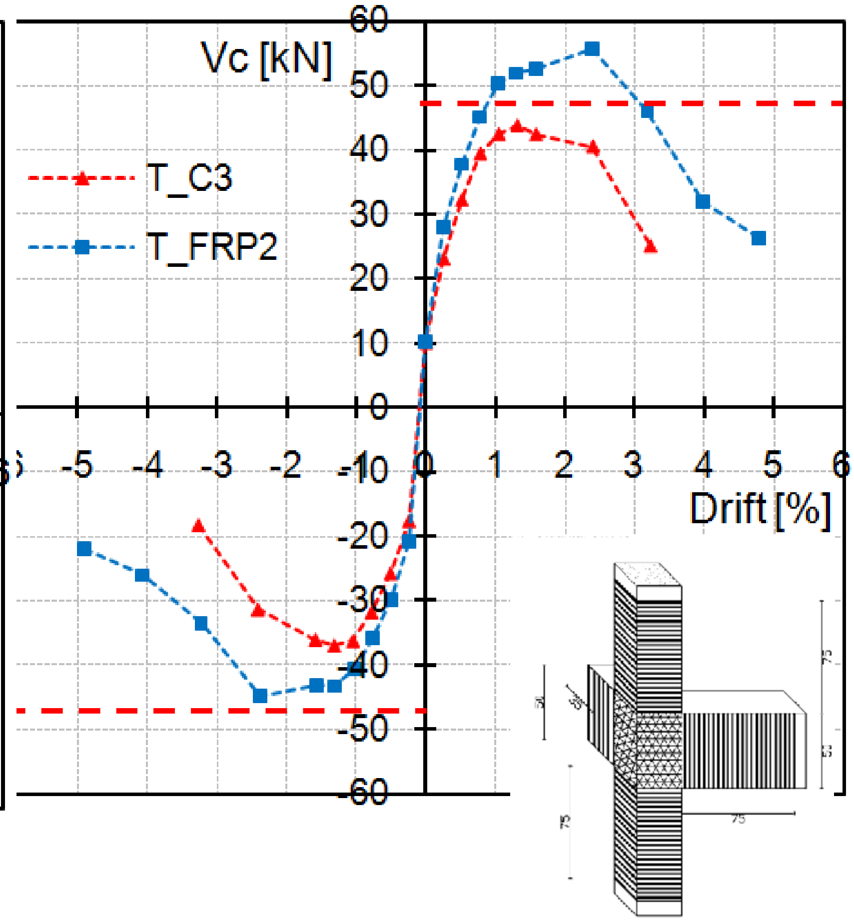
Maximum strain recorded on FRP panel: $\varepsilon_{f,max}$ = 10.2 ‰

Test Results: FRP strengthened spec.

T_C3 vs. T_FRP



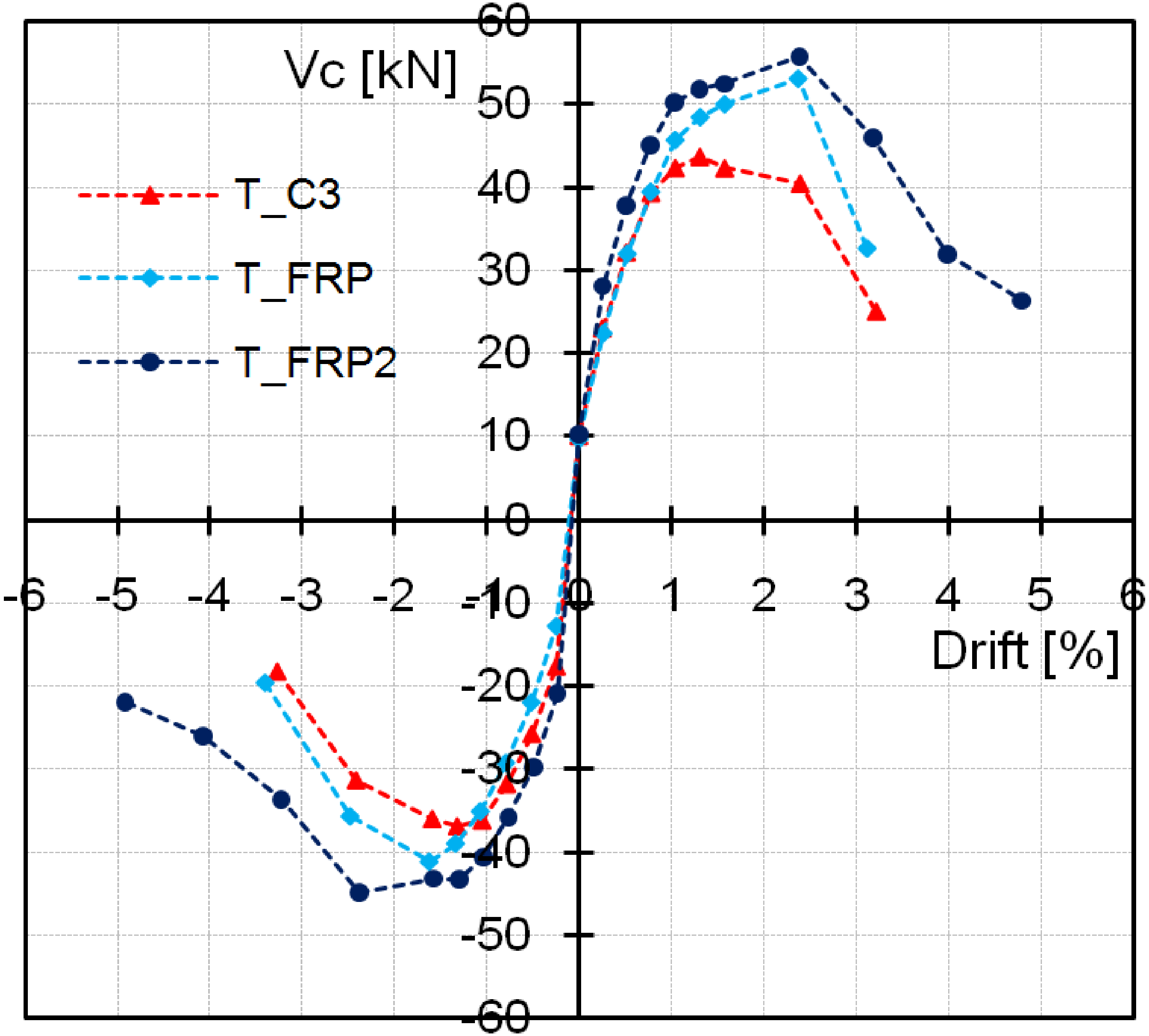
T_C3 vs.T_FRP2



Vc = 47 kN (theor. column bars yielding)

- Column rebar yielding before joint shear failure
- The subassembly maximum strength has been attained
- Significant ductility increase on T_FRP2

Test Results: FRP strengthened spec.



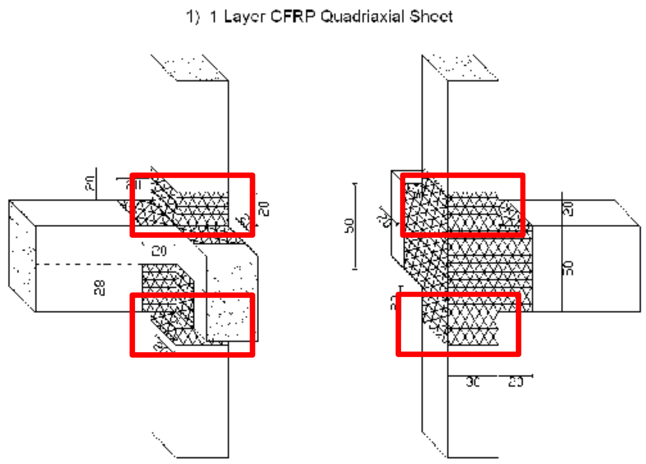
Conclusive remarks

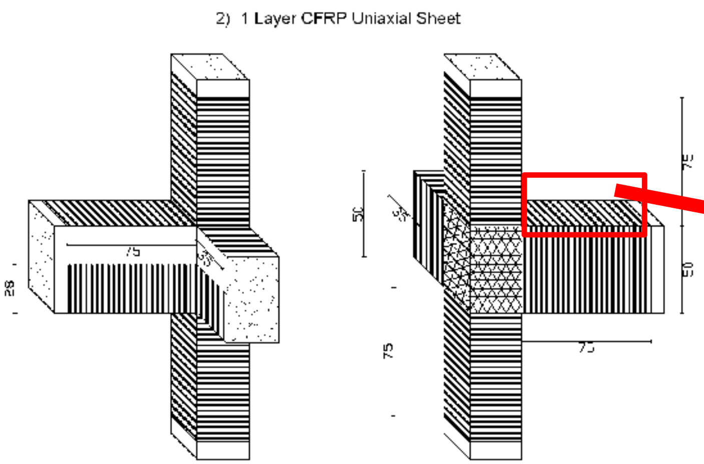
Spec.	f_{cm}	Load sign	$V_{c,MAX}$	Strength increase	Drift at failure	Ult. drift increase	Energy	Energy increase	ε_{FRP} (deb.)
[-]	[MPa]	[-]	[kN]	[%]	[%]	[%]	[kN*mm]	[%]	[‰]
T_C	16.4	+	42.6	-	n.a.		n.a.	-	-
		-	34.4	-	n.a.				
T_C3	16.3	+	43.7	-	2.7		10237	-	
		-	36.9	-	2.5				
T_FRP	14.8	+	53.2	21.5	2.8	2.6	11420	12	4.7
		-	41.1	11.5	2.6	3.6			
T_FRP2	17.7	+	56.1	28.3	3.3	21.2	12225	19	10.2
		-	45.2	22.5	3.1	20.9			

- Joint panel tensile failure was attained on control specimens
- Control specimens' strength capacity slightly higher (+10%) than theoretical predictions (Priestley 1997) – confinement effect of orthogonal beam
- "Light" CFRP strengthening significantly increased the subassembly strength (+20%); negligible ultimate drift increase (+3%) due to FRP debonding ($\varepsilon_{f,max}$ = 4.7 ‰); energy dissipation capacity increase +12%
- "Strong" CFRP strengthening allowed to fully exploit the subassembly strength (+28%, maximum increase due to column rebars yielding); ultimate drift increase (+20%)- FRP strain at debonding ($\varepsilon_{f,max}$ = 10.2 ‰); energy dissipation capacity increase +19%

Future development

T_FRP_3





2 plies CFRP quadriaxial laminates on joint panel extended 20 cm on beam

1 ply L-shaped CFRP quadriaxial laminates to connect beam and column

1 ply uniaxial CFRP laminates – column confinement 75 cm

1 ply uniaxial CFRP laminates – full wrapping 75 cm (except for slab thickness)

"Strong" CFRP strengthening (Scheme 2b)