Textile-Reinforced Mortars (TRM) vs. Fiber Reinforced Polymers (FRP) as Strengthening and Seismic Retrofitting Materials of Concrete and Masonry Structures

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SHEAR STRENGTHENING OF RC
FLEXURAL STRENGTHENING OF RC
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CONCLUSIONS

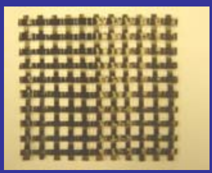
Some problems with FRP

- Poor behaviour 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
- Difficulty in contacting post-earthquake assessment of damage suffered by the concrete behind the FRP

Solution

Inorganic binders and fibres in the form of TEXTILES:

fiber meshes made of long woven, knitted or even unwoven tows or yarns in at least two (typically orthogonal) directions



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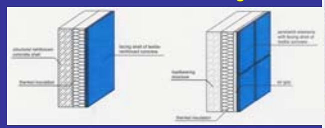
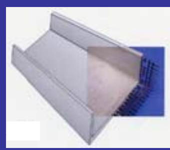
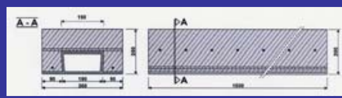
R & D of Textile-Reinforced Concrete (TRC) has progressed fast in the past few years (e.g. RILEM TC-TRC):

Reinforcement of exterior cladding elements





Thin-walled elements



Integrated formwork elements

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Past studies on the use of TEXTILES in the upgrading of RC:

Bond aspects, flexural and shear strengthening of beams
(first studies: Curbach / Ortlepp 2003 , Curbach / Brueckner 2003)

Main Conclusion: Properly designed textiles combined with inorganic binders have a good potential as strengthening materials of RC

Our research:

Textiles for:

- CONFINEMENT (plain and RC prisms, poorly detailed columns)
- SHEAR STRENGTHENING (including cyclic loading)
- FLEXURAL STRENGTHENING (beams)

- FLEXURAL / SHEAR STRENGTHENING OF MASONRY SUBJECTED TO IN-PLANE OR OUT-OF-PLANE LOADING

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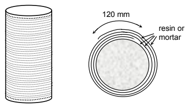
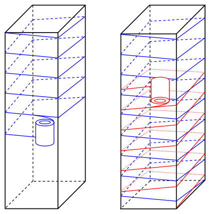
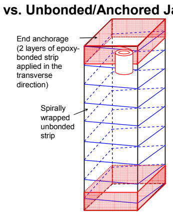
EXPERIMENTAL PROGRAM (44 uniaxial compression tests)



→ Mortar vs. Epoxy Resin (M, R)
→ Strength of Mortar (MI, MII)
→ No. of Layers (2, 3)

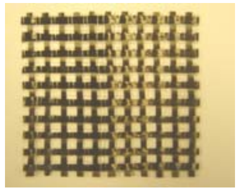
→ Mortar vs. Epoxy Resin (M, R)
→ No. of Layers (2, 4)
→ Bonded vs. Unbonded/Anchored Jacket

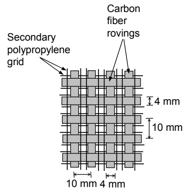




Spirally wrapped single strip is used to form each layer

MATERIALS

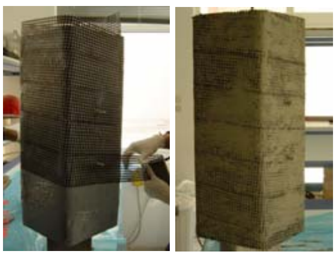




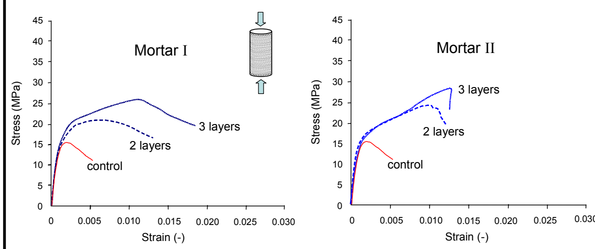
Carbon fibers , 160 g/m^2 , E = 225 GPa , f_t = 3350 GPa , tex 800

Nominal thickness (based on equivalent smeared distribution of fibers) = 0.047 mm

Mortar	Flexural Strength (MPa)	Compressive Strength (MPa)
Mortar I		
7 days	2.68	7.59
28 days	3.28	8.56
Mortar II		
7 days	3.02	27.45
28 days	4.24	30.61



Mortar Strength (cylinders)



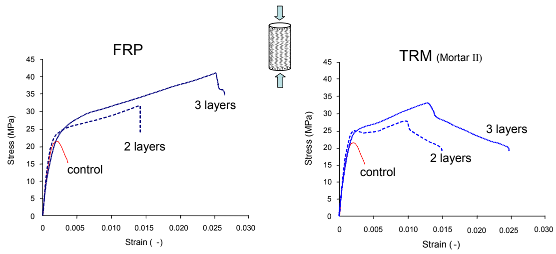
Strength increase

57% (2 layers) 77% (3 layers)

Strain increase

x5.4 (2 layers) x6.1 (3 layers)

Resin vs. Mortar (cylinders)



FRP	TRM
Strength increase	**Strength increase**
53% (2 layers) 92% (3 layers)	**25% (2 layers) 49% (3 layers)**
Strain increase	**Strain increase**
x8.3 (2 layers) x12.7 (3 layers)	**x4.9 (2 layers) x5.4 (3 layers)**

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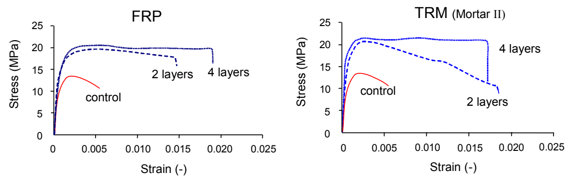
Resin vs. Mortar (prisms)



FRP	TRM
Strength increase	**Strength increase**
29% (2 layers) 47% (4 layers)	**39% (2 layers) 51% (4 layers)**
Strain increase	**Strain increase**
x6.2 (2 layers) x10.1 (4 layers)	**x5.9 (2 layers) x8.8 (4 layers)**

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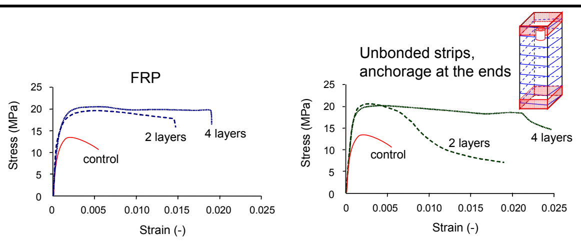

FRP	Unbonded strips
Strength increase	**Strength increase**
29% (2 layers) 47% (4 layers)	**39% (2 layers) 45% (4 layers)**
Strain increase	**Strain increase**
x6.2 (2 layers) x10.1 (4 layers)	**x4.0 (2 layers) x8.8 (4 layers)**

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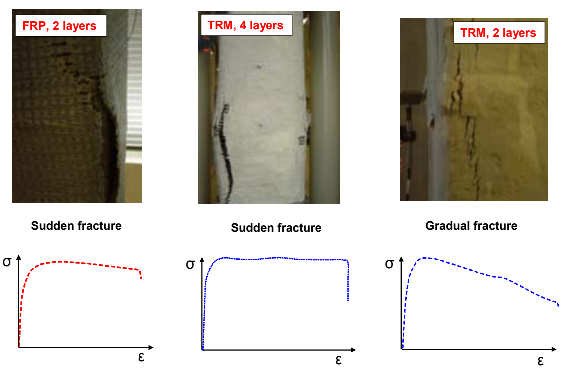
Failure mode : Jacket fracture at the corners



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Effectiveness of TRM vs. FRP

Cylinders

Strength increase : 0.82 - 0.77

Strain increase : 0.59 - 0.42

Effectiveness of TRM vs. FRP

Prisms

Strength increase : 1.09 – 1.03

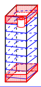
Strain increase : 0.95 - 0.87

Effectiveness of Unbonded / End-anchored vs. Bonded (FRP)

Prisms

Strength increase : 1.08 - 0.98

Strain increase : 0.64 - 0.87



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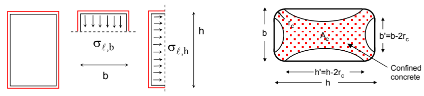
SIMPLE ANALYTICAL MODEL

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \left(\frac{\sigma_{\ell u}}{f_{co}} \right)^m \qquad k_1 = \alpha_1 k_{1,R}$$

$$\varepsilon_{ccu} = \varepsilon_{co} + k_2 \left(\frac{\sigma_{\ell u}}{f_{co}} \right)^n \qquad k_2 = \alpha_2 k_{2,R}$$

α_1 : effectiveness coeff. for strength

α_2 : effectiveness coeff. for strain



$$\sigma_\ell = \frac{\sigma_{\ell,h} + \sigma_{\ell,b}}{2} = \frac{1}{2}\alpha \left(\frac{2t_j}{h} E_j \varepsilon_j + \frac{2t_j}{b} E_j \varepsilon_j \right) = \alpha \frac{(b+h)}{bh} t_j E_j \varepsilon_j \Rightarrow \boxed{\sigma_{\ell u} = \alpha \frac{(b+h)}{bh} t_j f_j}$$

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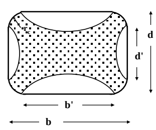
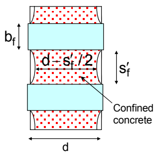
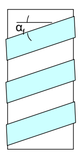
$$\alpha = \alpha_n \times \alpha_s \times \alpha_a \le 1$$



$$\alpha_n = \frac{A_e}{A_g} = 1 - \frac{b'^2 + d'^2}{3A_g\left(1 - \frac{A_s}{A_g}\right)}$$



$$\alpha_s = \frac{\left(1 - \frac{s'_f}{2d}\right)^2}{1 - \frac{A_s}{A_g}}$$



$$\alpha_a = \frac{1}{1 + (\tan\alpha_f)^2}$$

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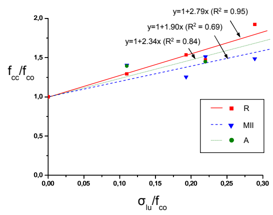

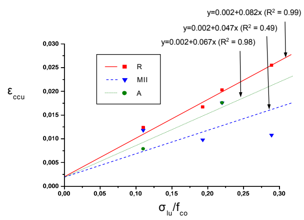

TRM vs. FRP : α_1 = 0.68 , α_2 = 0.57

Unbonded & end-anchored vs. FRP : α_1 = 0.84, α_2 = 0.82

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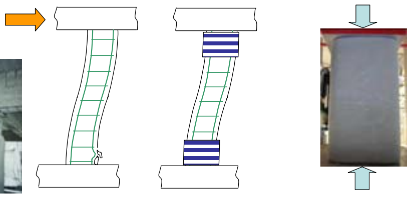
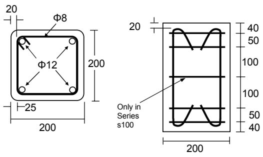
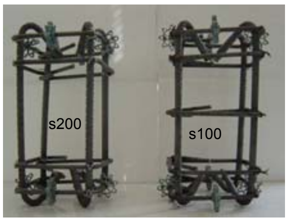
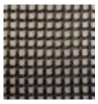
CONFINEMENT TO DELAY REBAR BUCKLING IN COLUMNS



Series U (no steel) , s200 , s100

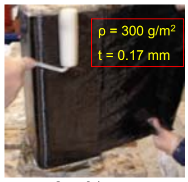






ρ = 348 g/m²
t = 0.095 mm
tex 1600

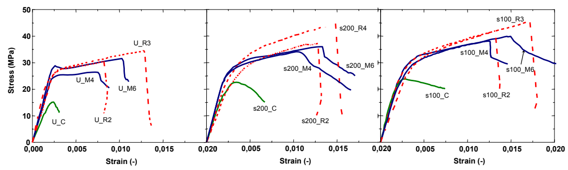
4 or 6 layers



2 or 3 layers

THE TWO SYSTEMS ARE “EQUIVALENT”

CONTROL **FRP** **TRM**

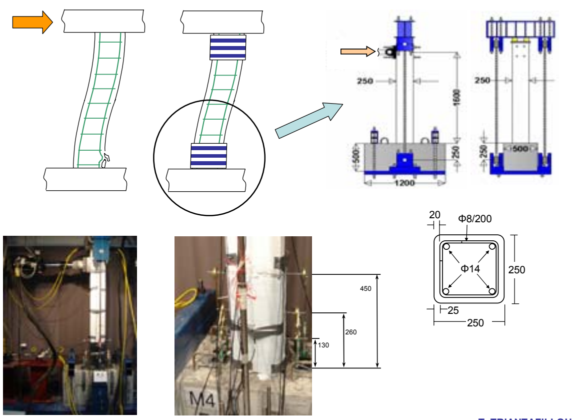


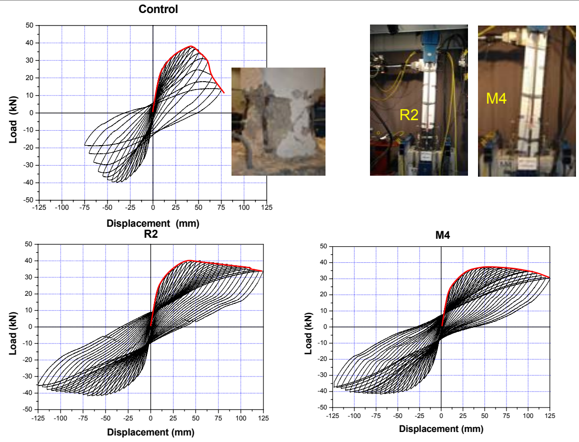
Jacket effectiveness
$$K_\sigma = \frac{\sigma_{max,c} - \frac{A_s}{A_g} f_y}{\sigma_{max,o} - \frac{A_s}{A_g} f_y} \qquad K_\varepsilon = \frac{\varepsilon_{u,c}}{\varepsilon_{u,o}}$$

TRM vs. FRP: $\frac{K_{\sigma,TRM}}{K_{\sigma,FRP}}$ $\frac{K_{\varepsilon,TRM}}{K_{\varepsilon,FRP}}$

0.85-0.90 0.87-0.93

Cyclic Testing of Poorly Detailed Columns





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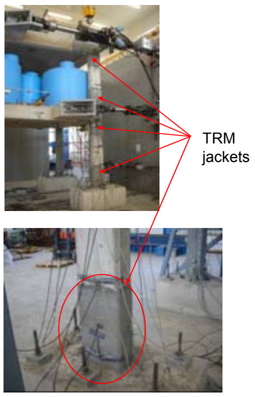
2/3 SCALE TESTING OF 2-STOREY BUILDING

Tested at 0.3g before retrofitting

TRM jackets have performed extremely well !!

Tested at 0.45g after retrofitting



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Ultimate chord rotation (EC8)

$$\theta_u = k0.016\left(0.3^{\nu}\right)\left[\frac{max(0.01,\omega')}{max(0.01,\omega)}f_c\right]^{0.225}\left(\frac{L_V}{h}\right)^{0.35}25^{c}\left(1.25^{100\rho_d}\right)$$

$$c = a\rho_{sx}\frac{f_{yw}}{f_c} + a_f\,\rho_{fx}\frac{f_{fe}}{f_c}$$

$$\alpha_f = \beta\left[1 - \frac{(b-2R)^2 + (h-2R)^2}{3bh}\right]$$

$$\beta = \frac{K_{\varepsilon,TRM}}{K_{\varepsilon,FRP}}$$

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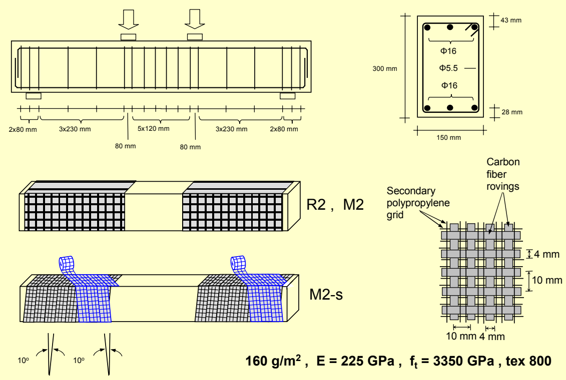
EXPERIMENTAL PROGRAM



160 g/m^2 , E = 225 GPa , f_t = 3350 GPa , tex 800

Nominal thickness = 0.047 mm

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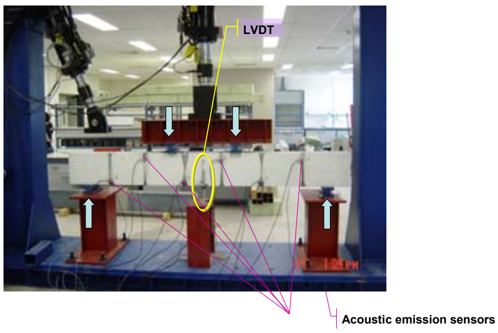
Monotonic Testing



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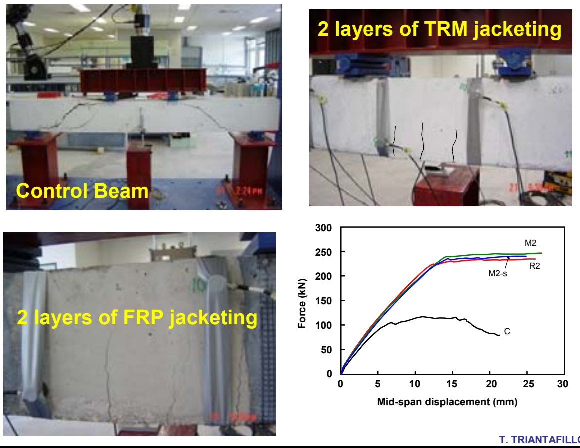

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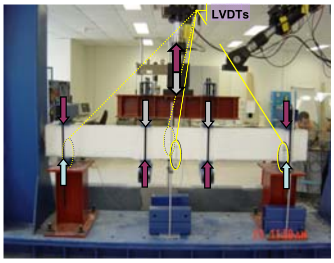
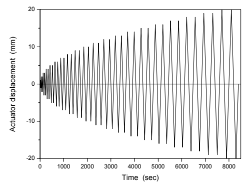
Cyclic Testing





2 cycles at a series of progressively increasing (by 1 mm) displacement amplitudes (rate = 0.2 mm/sec)

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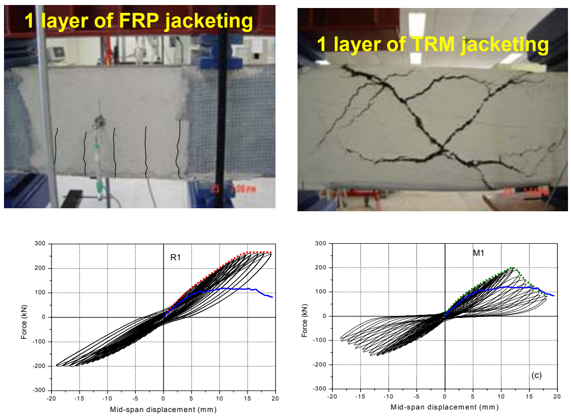

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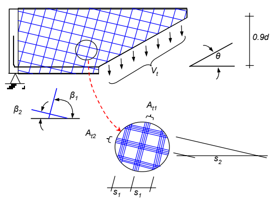
SIMPLE ANALYTICAL MODEL



$$V_t = \sum_{i=1}^{2} \frac{A_{ti}}{s_i} \sigma_{te,i}\, 0.9d(\cot\theta + \cot\beta_i)\sin\beta_i$$

effective stress of TRM in direction i = $k\sigma_{fe,i}$

In this study, the effectiveness of TRM vs. FRP is k = 0.50-0.57

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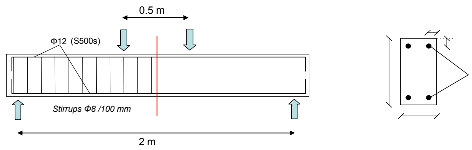
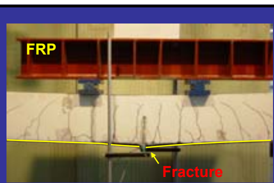
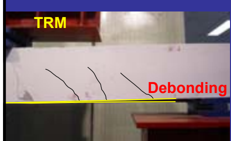
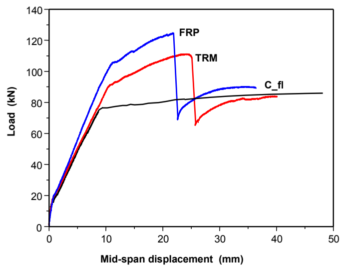


Epoxy-bonded textile (FRP)

TRM







50% increase in strength

35% increase in strength

Effectiveness of TRM vs. FRP

Strength : 0.70

Ductility : 1.30

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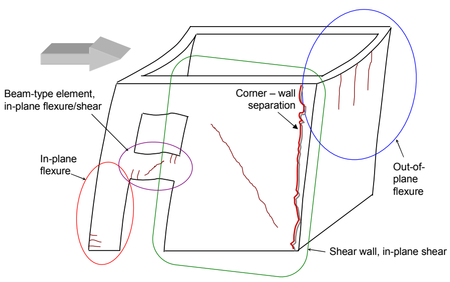
STRENGTHENING OF MASONRY



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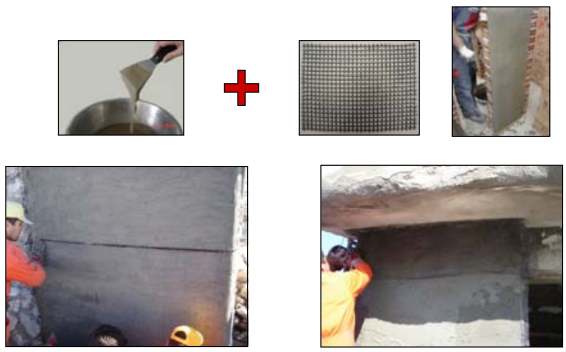
Textile-reinforced mortars – TRM



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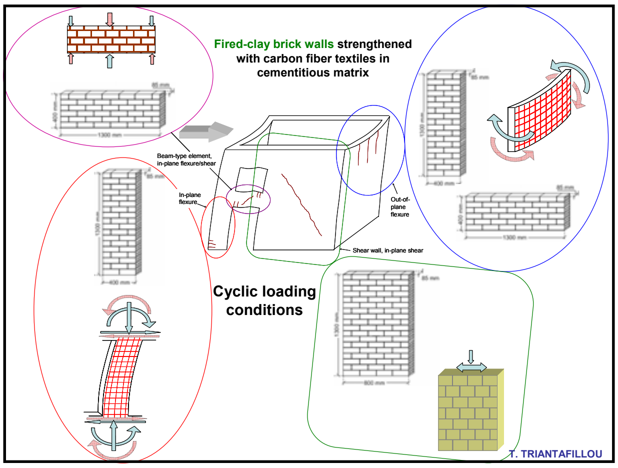
Fired-clay brick walls strengthened with carbon fiber textiles in cementitious matrix
Beam-type element, in-plane flexure/shear
In-plane flexure
Out-of-plane flexure
Shear wall, in-plane shear
Cyclic loading conditions
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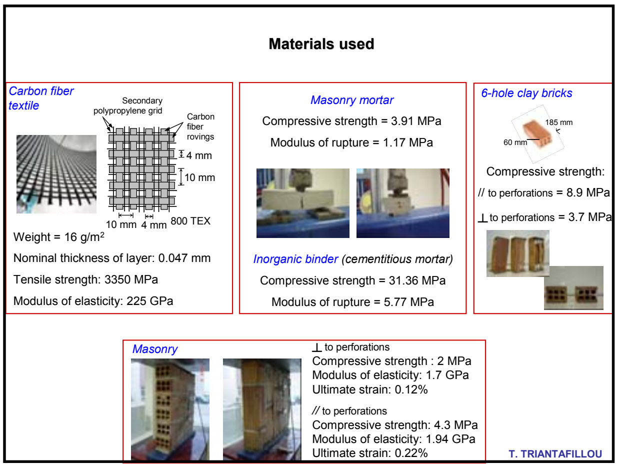
Materials used
Carbon fiber textile
Secondary polypropylene grid
Carbon fiber rovings
4 mm
10 mm
10 mm 4 mm
800 TEX
Weight = 16 g/m²
Nominal thickness of layer: 0.047 mm
Tensile strength: 3350 MPa
Modulus of elasticity: 225 GPa
Masonry mortar
Compressive strength = 3.91 MPa
Modulus of rupture = 1.17 MPa
Inorganic binder (cementitious mortar)
Compressive strength = 31.36 MPa
Modulus of rupture = 5.77 MPa
6-hole clay bricks
185 mm
60 mm
Compressive strength:
// to perforations = 8.9 MPa
⊥ to perforations = 3.7 MPa
Masonry
⊥ to perforations
Compressive strength : 2 MPa
Modulus of elasticity: 1.7 GPa
Ultimate strain: 0.12%
// to perforations
Compressive strength: 4.3 MPa
Modulus of elasticity: 1.94 GPa
Ultimate strain: 0.22%
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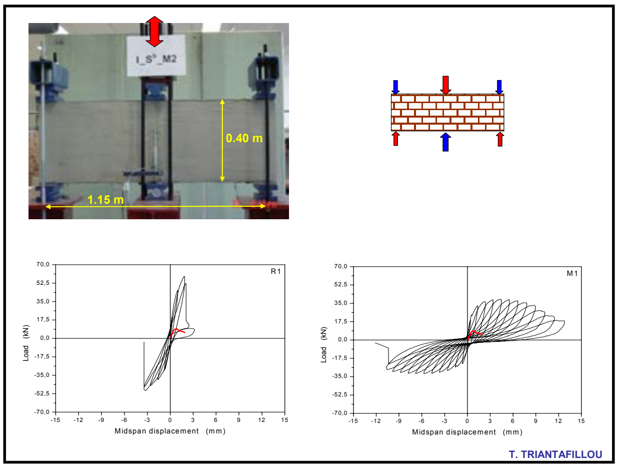
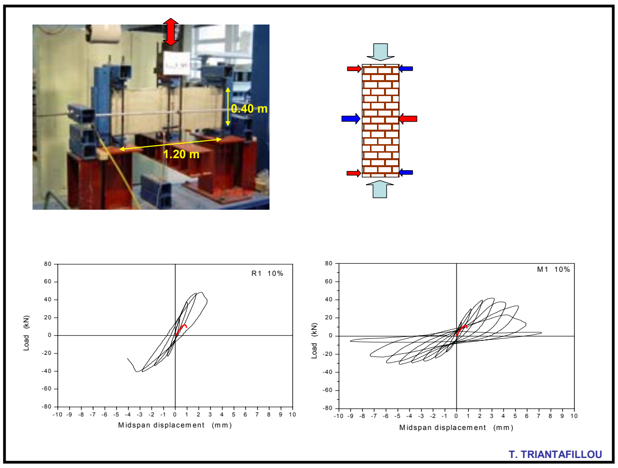
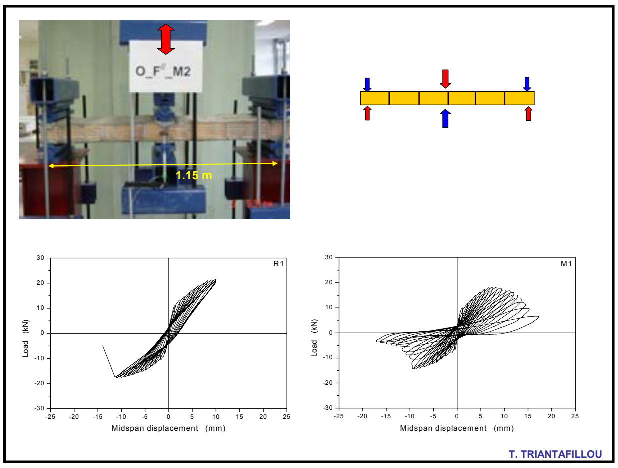
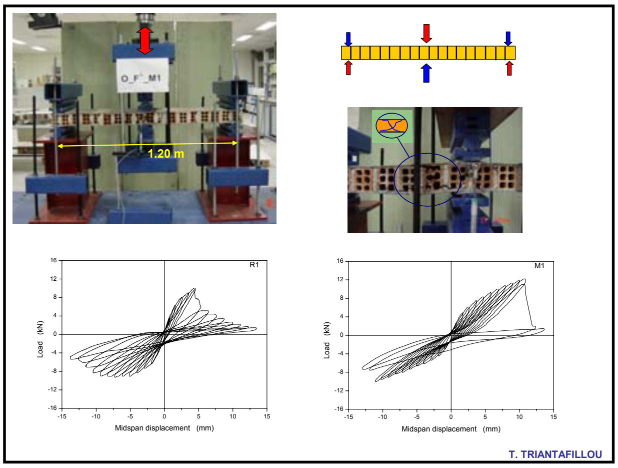
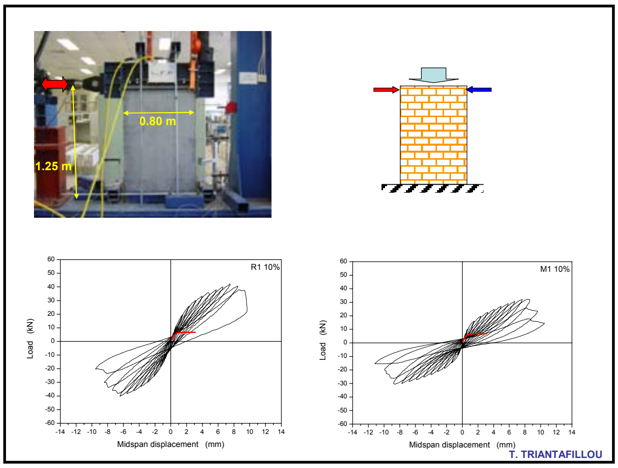

0.40 m
1.15 m
R1
M1
Load (kN)
Midspan displacement (mm)
T. TRIANTAFILLOU


0.40 m
1.20 m
R1 10%
M1 10%
Load (kN)
Midspan displacement (mm)
T. TRIANTAFILLOU


1.15 m
R1
M1
Load (kN)
Midspan displacement (mm)
T. TRIANTAFILLOU


1.20 m
R1
M1
Load (kN)
Midspan displacement (mm)
T. TRIANTAFILLOU


0.80 m
1.25 m
R1 10%
M1 10%
Load (kN)
Midspan displacement (mm)
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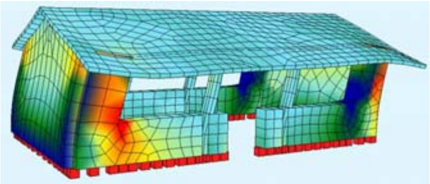
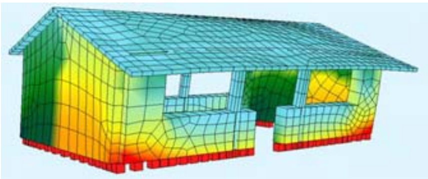
RESULTS OF ANALYSIS



SEISMIC LOADING - LONGITUDINAL



SEISMIC LOADING - TRANSVERSE

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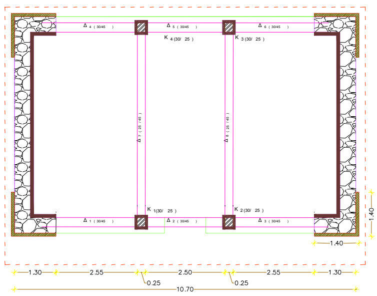
DESIGN OF THE RETROFITTING



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INTRODUCTION & BACKGROUND
CONFINEMENT OF RC
SHEAR STRENGTHENING OF RC
FLEXURAL STRENGTHENING OF RC
MASONRY
CONCLUSIONS

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CONCLUSIONS

Strengthening with FRP : very effective, easy to apply, some problems with resins

Strengthening with Textile Reinforced Mortar (TRM) : extremely effective, results in more ductile failure modes !

Modelling: straightforward procedure, by introducing effectiveness coefficients

The mortar plays an important role !

TRM is a very promising solution !

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FRP HAVE BEEN AND WILL CONTINUE TO BE QUITE SUCCESSFUL !!

TRM SHOW THE WAY FOR EVEN MORE APPLICATIONS OF CONTINUOUS FIBER REINFORCEMENT IN STRUCTURAL UPGRADING

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