

Ενίσχυση Κατασκευών με Προηγμένα Υλικά

Αθ. Τριανταφύλλου

Τμήμα Πολιτικών Μηχανικών



UNIVERSITY OF PATRAS
DEPARTMENT OF CIVIL ENGINEERING
STRUCTURAL MATERIALS LABORATORY
[<http://www.sml.civil.upatras.gr>]



ΠΕΡΙΕΧΟΜΕΝΑ

Εισαγωγή

Σκυρόδεμα

Περίσφιγξη: *Θλιπτική αντοχή και πλαστιμότητα*

Ενίσχυση σε Τέμνουσα

Ενίσχυση σε Κάμψη: *Δοκοί & πλάκες*

Τοιχοποιία

Δράση εντός επιπέδου

Δράση εκτός επιπέδου

Τοιχοπληρωμένα πλαίσια Ο/Σ

**Συνδυασμένη Αντισεισμική & Ενεργειακή
Αναβάθμιση Κτιρίων**

Συμπεράσματα

Ανάγκη για την ενίσχυση κατασκευών π.χ. λόγω σεισμικής αναβάθμισης, αλλαγής χρήσης, απομείωσης της ανθεκτικότητας

Ανάγκη χρήσης προηγμένων υλικών → Ινοπλισμένα Πολυμερή (ΙΟΠ)

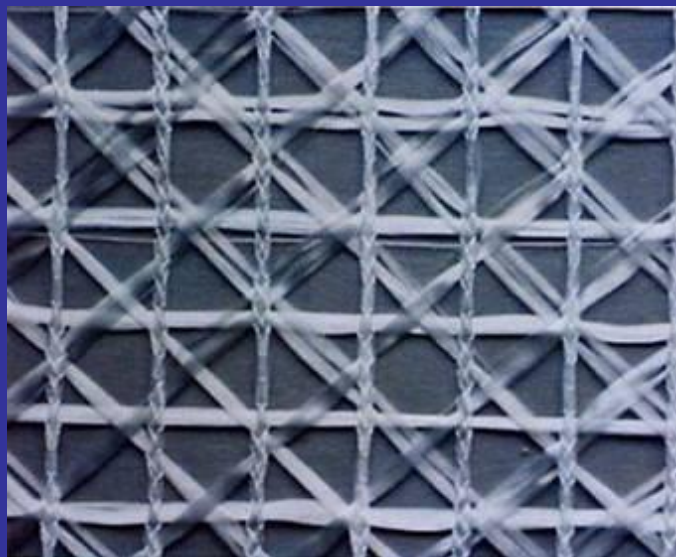
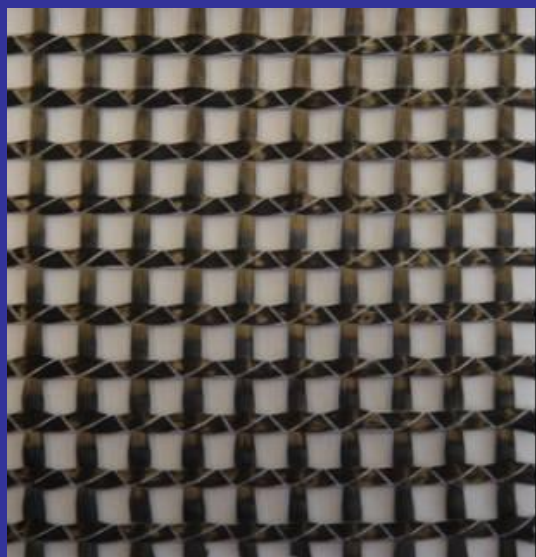
Fiber-Reinforced Polymers (FRP)



Ορισμένα προβλήματα των ΙΟΠ:

χαμηλή T_g , κόστος ?, υγρές επιφάνειες ?, χαμηλές θερμοκρασίες T ?, «αναπνοή» δομικών στοιχείων ?, ασυμβατότητα με υλικά ιστορικών κατασκευών, αποτίμηση βλαβών «πίσω» από μανδύες ?

Χρήση κονιάματος αντί ρητίνης σε συνδυασμό με Πλέγματα Ινών



Textile-Reinforced Mortars – TRM

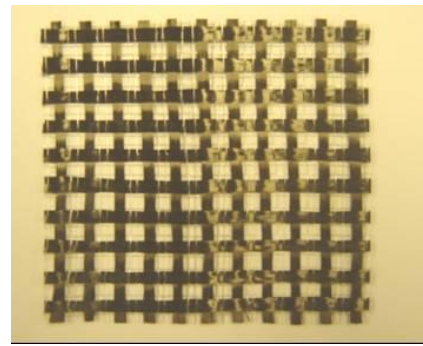
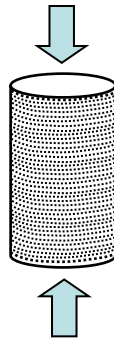
(UPAT ... 2006)

Other names: TRC (Germany) , FRCM (USA → 2012)

Ινοπλέγματα σε **Ανόργανη Μήτρα (IAM)**

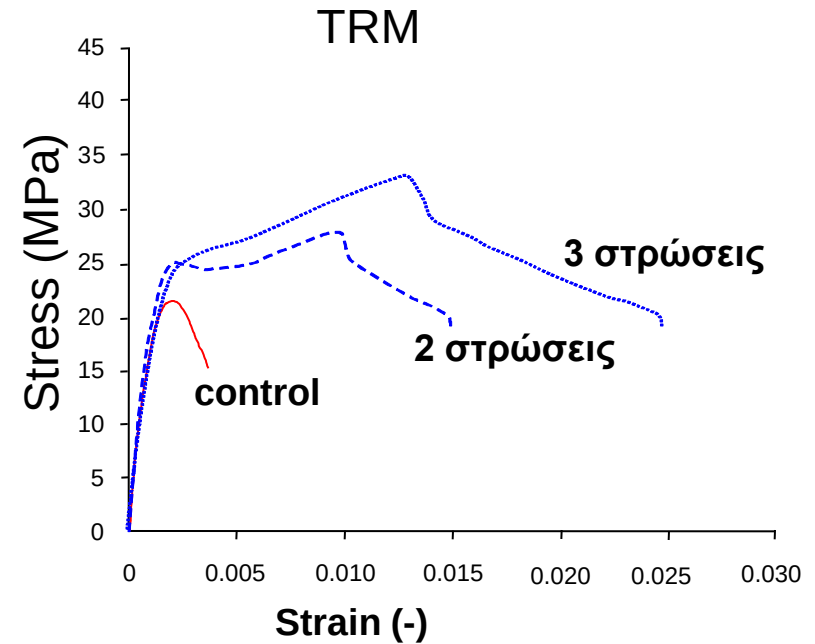
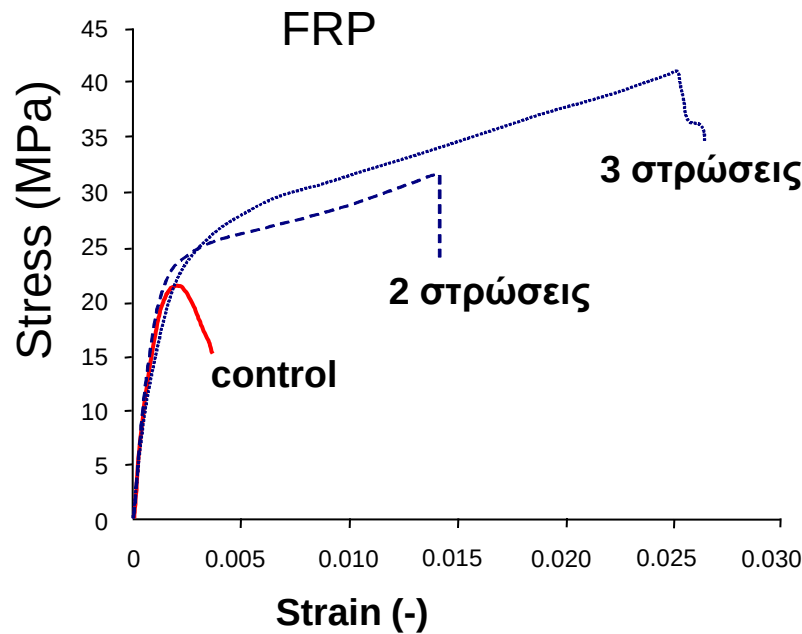


ΠΕΡΙΣΦΙΓΞΗ- άοπλο σκυρόδεμα



$$\rho = 160 \text{ g/m}^2$$

$$t_{\text{fib}} = 0.047 \text{ mm}$$

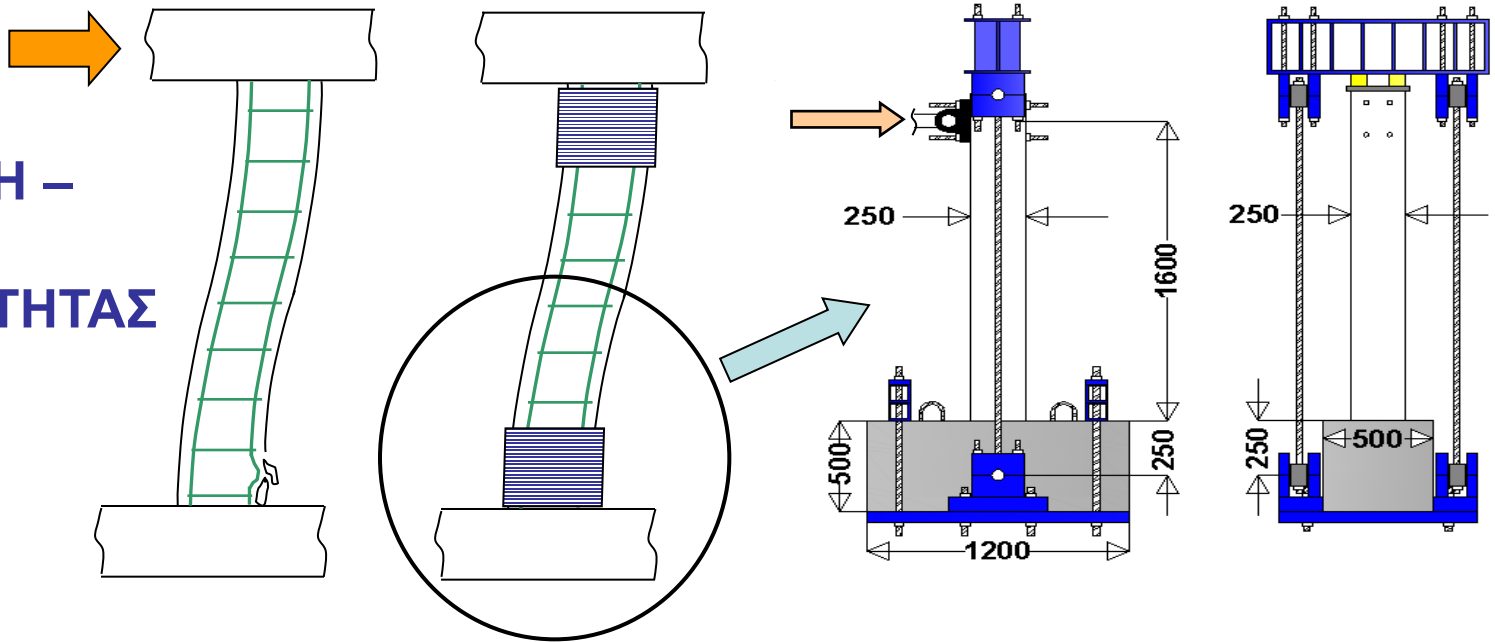


Αποτελεσματικότητα TRM / FRP:

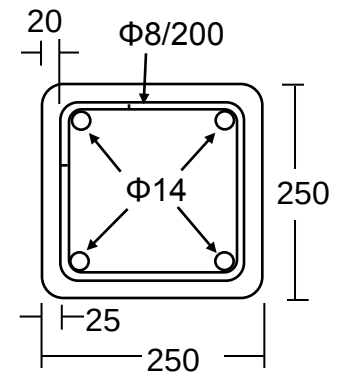
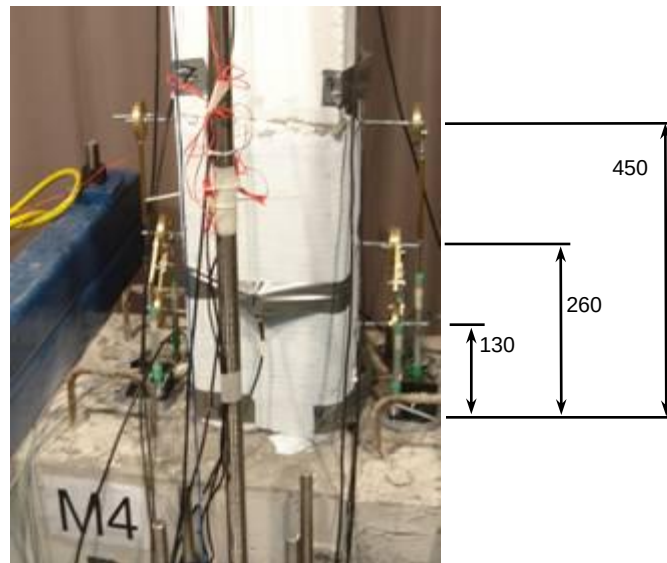
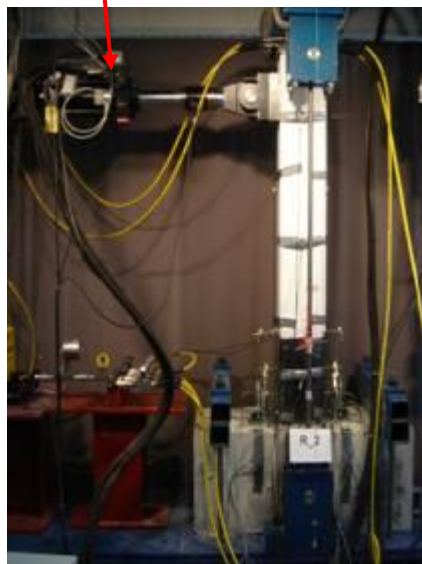
Αντοχή : 80%

Παραμόρφωση : 60%

ΠΕΡΙΣΦΙΓΞΗ – ΑΥΞΗΣΗ ΠΛΑΣΤΙΜΟΤΗΤΑΣ

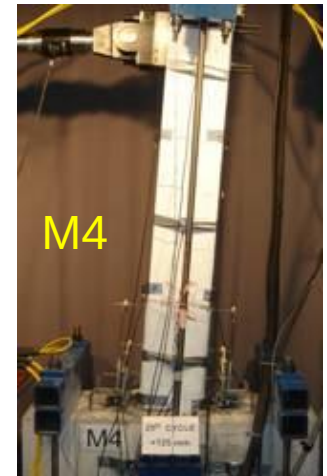
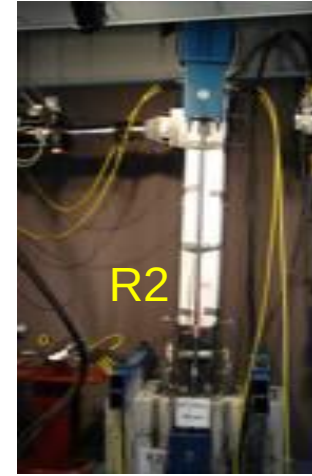
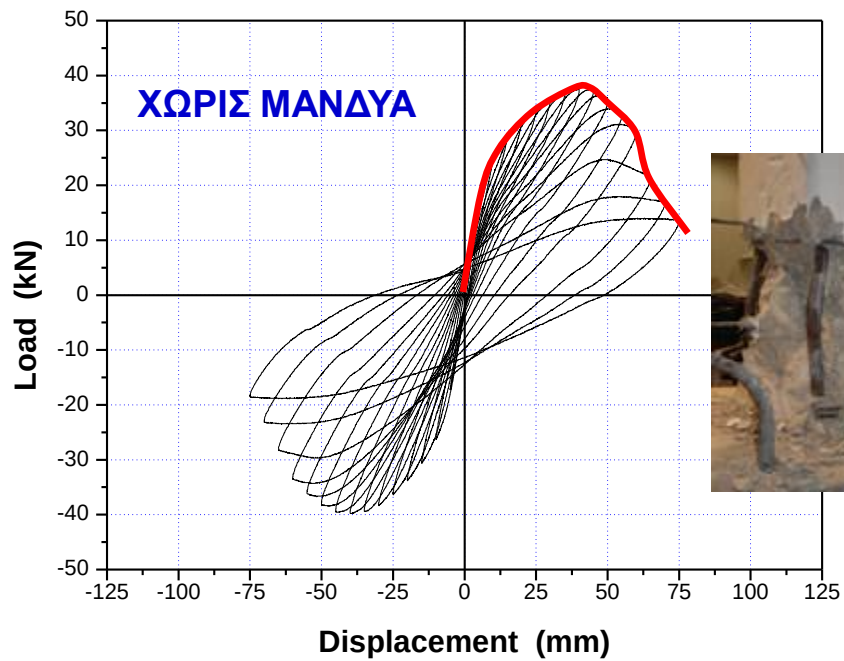


MTS Hydraulic Actuator



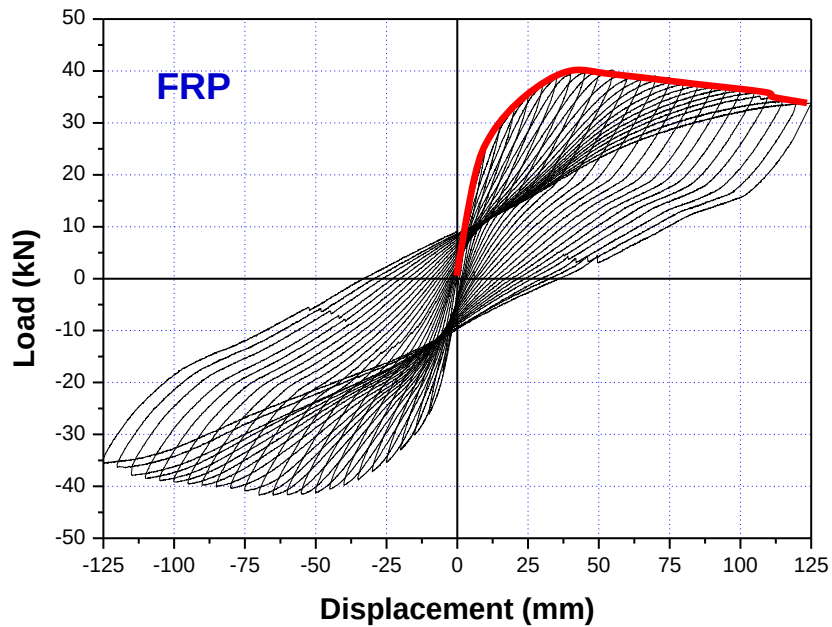
Non-seismically detailed
old-type RC column

Control

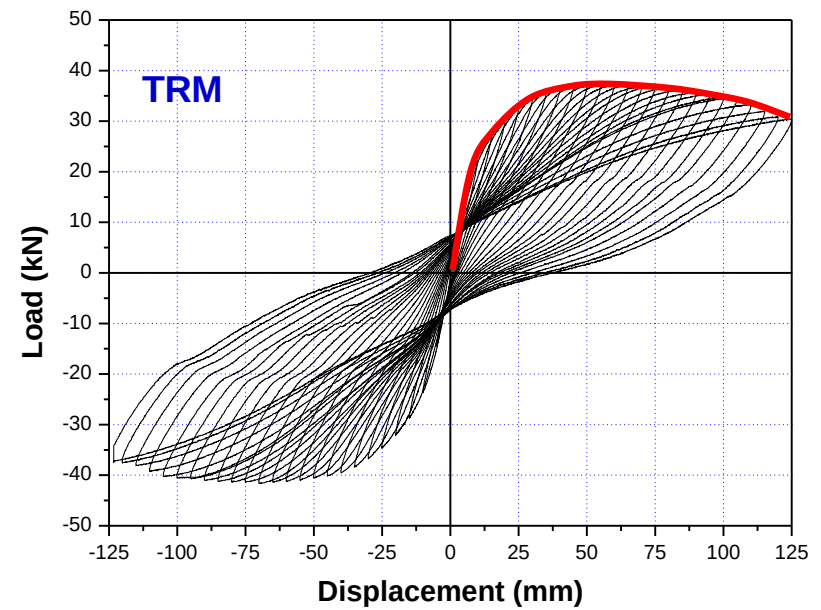


[video](#)

R2



M4



ΔΙΩΡΟΦΟ ΚΤΗΡΙΟ ΣΕ ΚΛΙΜΑΚΑ 2/3

[video](#)



Δοκιμή 0.3g πριν την ενίσχυση

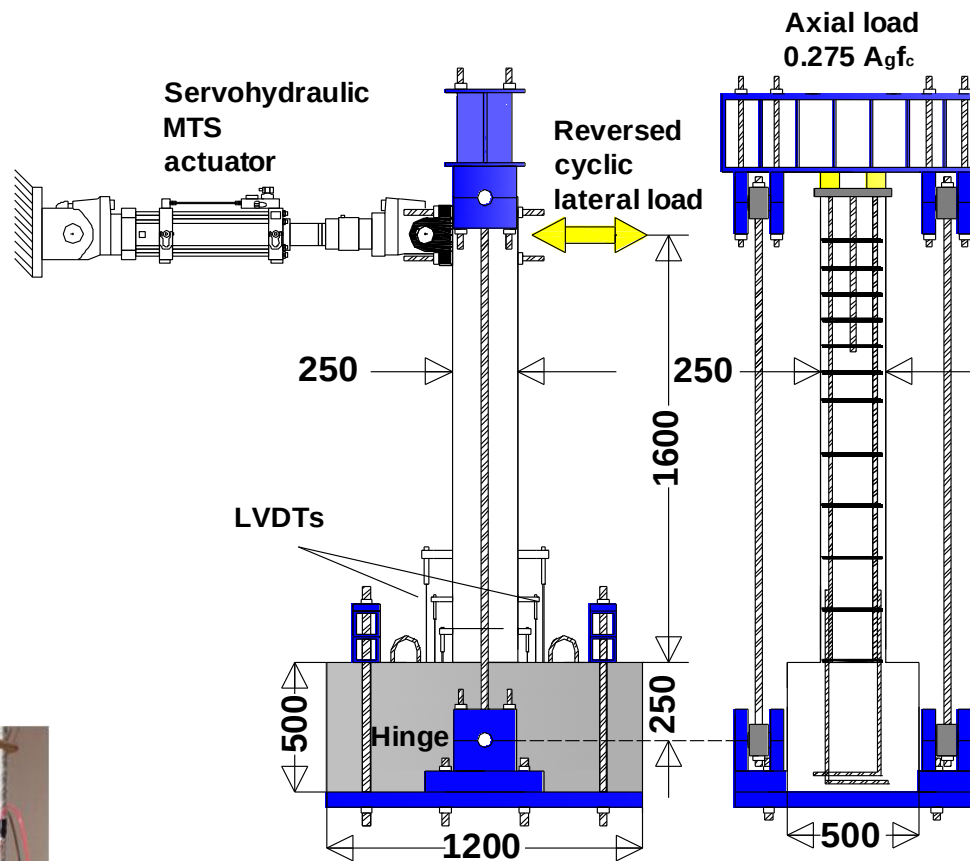
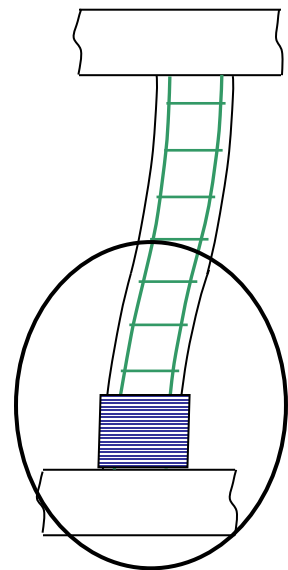
Εξαιρετική συμπεριφορά
μανδυνών TRM

Δοκιμή 0.45g μετά την ενίσχυση



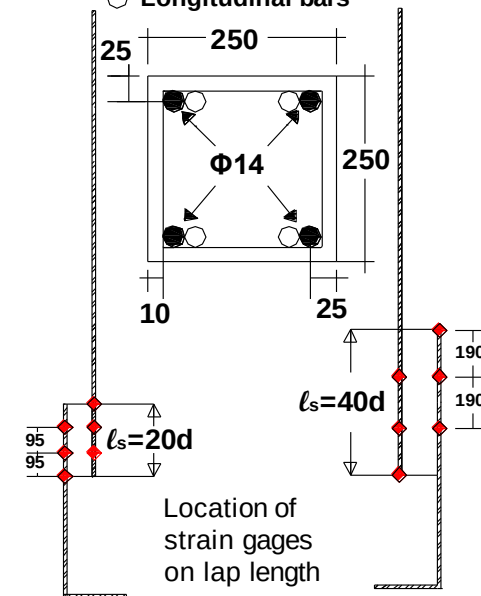
Μανδύες
TRM





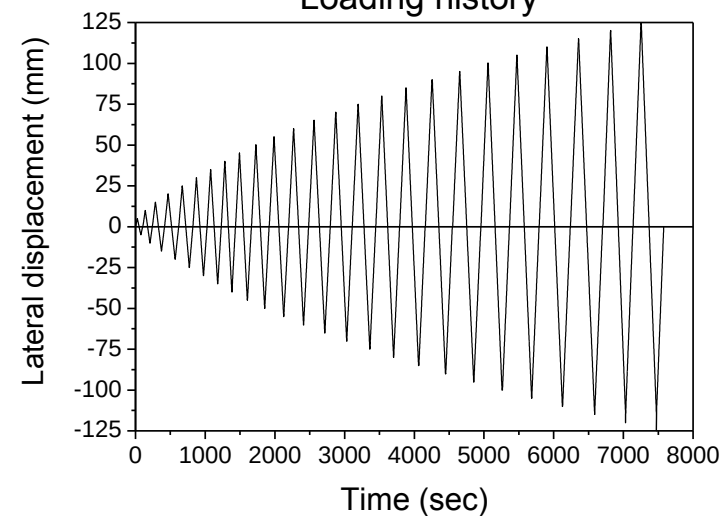
Cross section at column's base

- Starter bars
- Longitudinal bars



ΠΕΡΙΣΦΙΓΞΗ ΣΕ
«ΜΑΤΙΣΕΙΣ»

Loading history





$$\rho = 348 \text{ g/m}^2$$

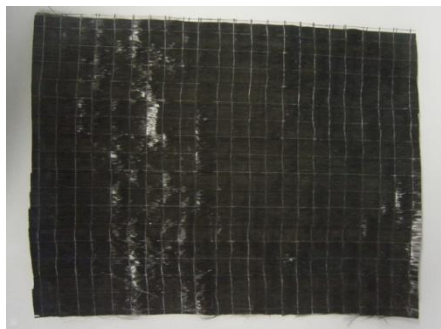
$$t = 0.095 \text{ mm}$$



TRM - 4 στρώσεις

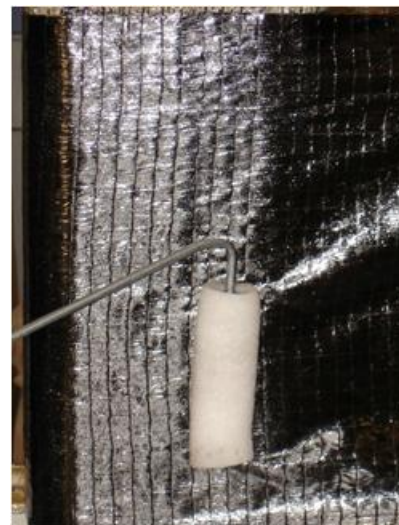
~ ΙΣΟΔΥΝΑΜΑ ΣΥΣΤΗΜΑΤΑ ΠΕΡΙΣΦΙΓΞΗΣ

FRP - 2 στρώσεις

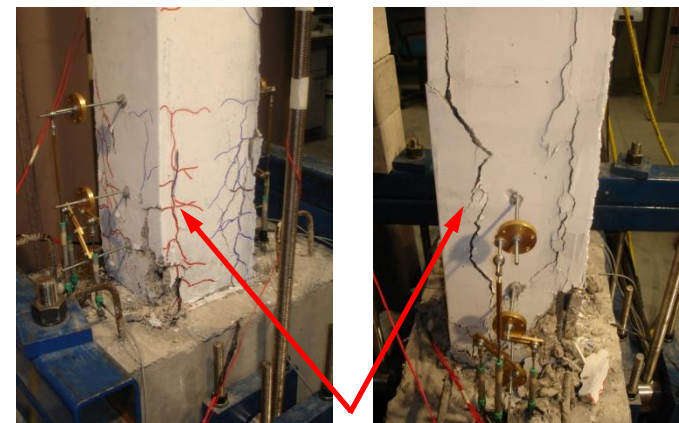
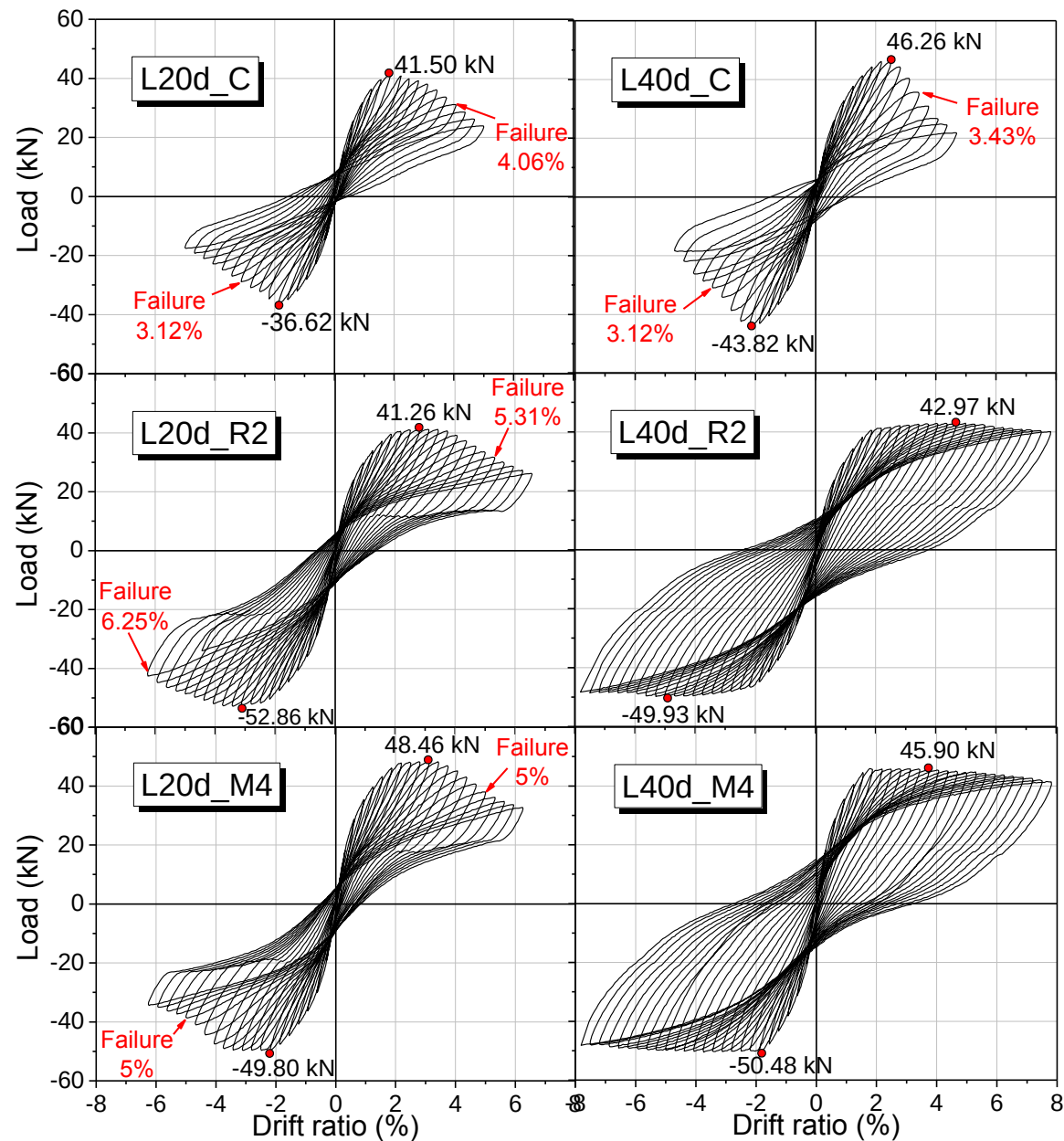


$$\rho = 300 \text{ g/m}^2$$

$$t = 0.17 \text{ mm}$$



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Longitudinal splitting cracks

L20d_

Strength increase:

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

Deformation capacity increase:

65% (FRP jacket) 39% (TRM jacket)

L40d_

Strength increase :

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

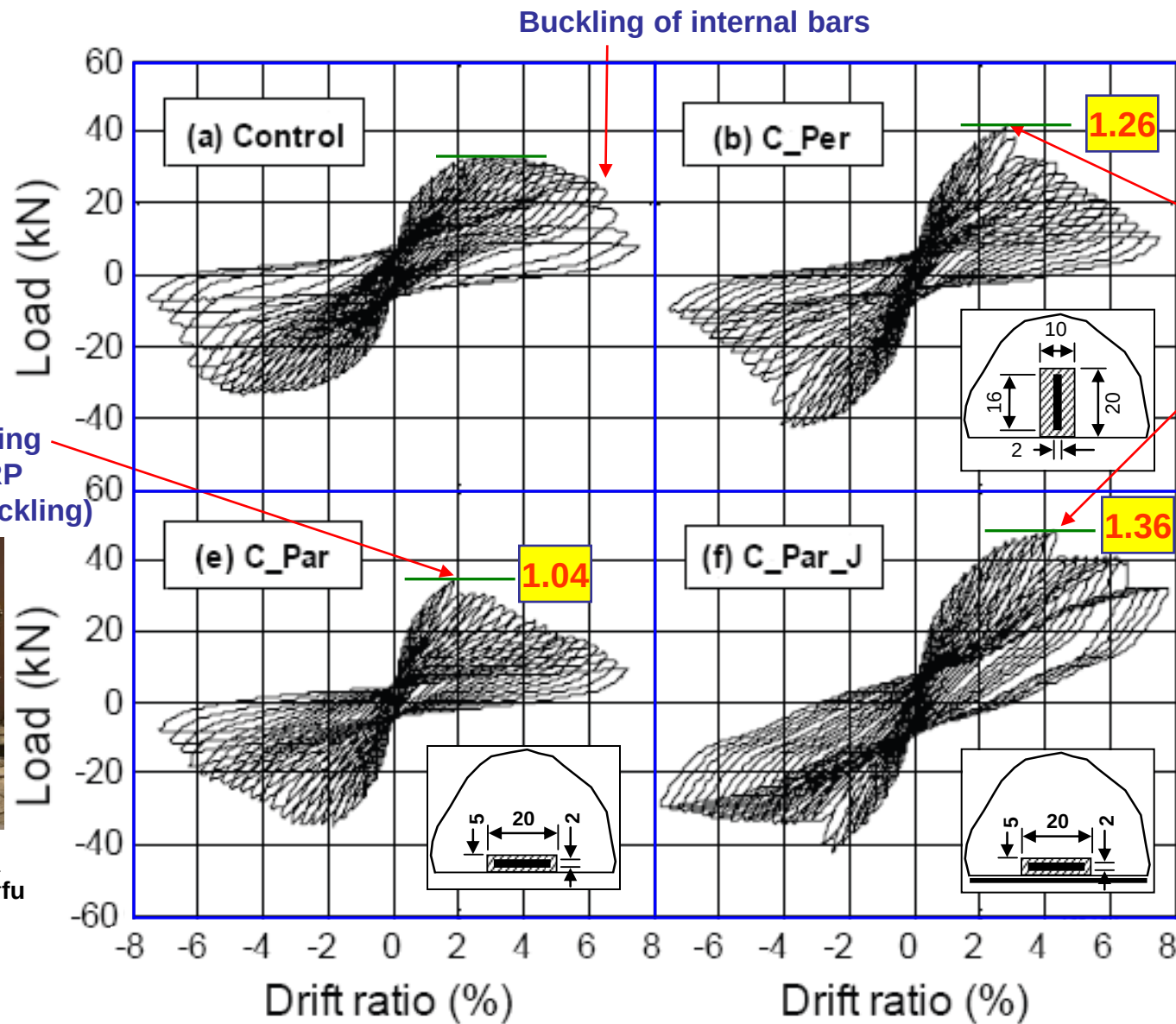
Deformation capacity increase:

>150% (FRP jacket) >150% (TRM jacket)

ΤΟΠΙΚΗ ΠΕΡΙΣΦΙΓΞΗ ΓΥΡΩ ΑΠΟ ΟΠΛΙΣΜΟ ΣΕ ΕΓΚΟΠΕΣ



SELECTED TEST RESULTS



$$\epsilon_{f,eff} = 0.5 \epsilon_{fu}$$

Fracture of CFRP strips



Debonding of CFRP (outward buckling)



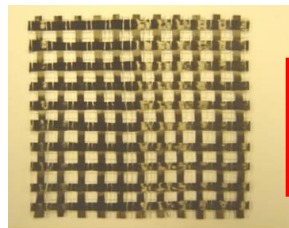
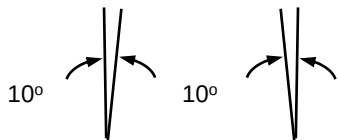
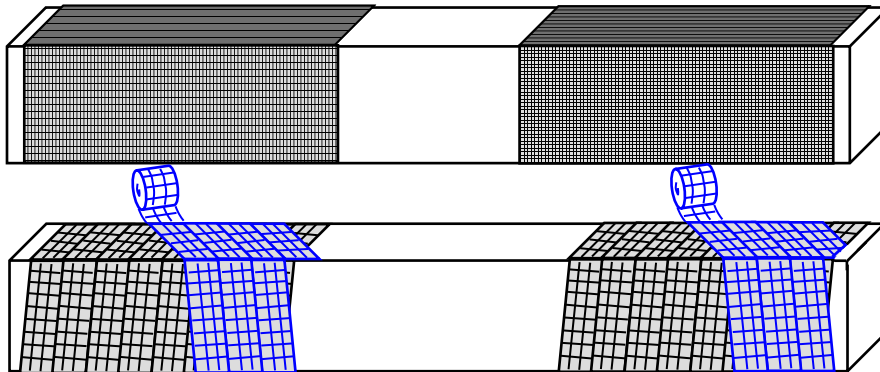
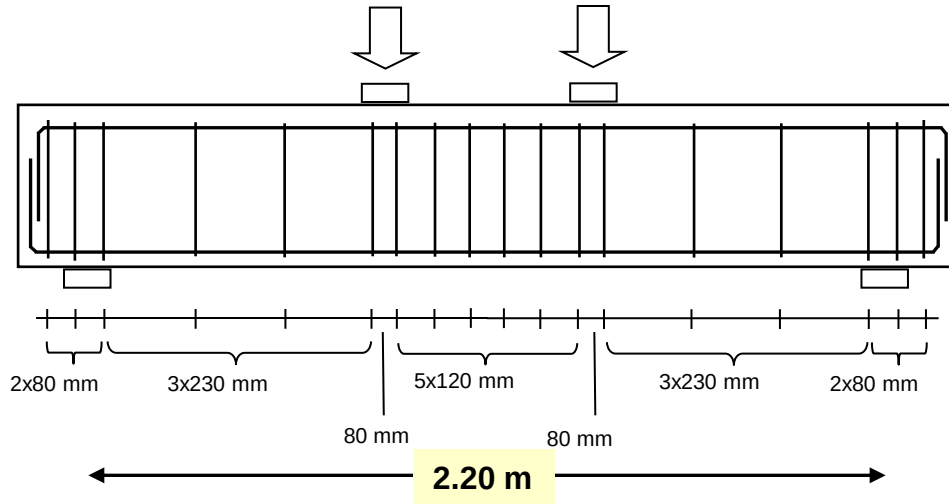
$$\epsilon_{f,eff} = 0.25 \epsilon_{fu}$$

$$\epsilon_{f,eff} = 0.67 \epsilon_{fu}$$

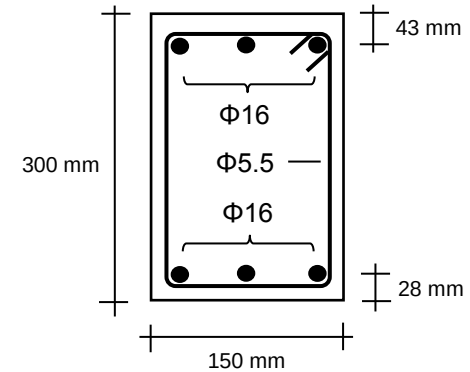
DEGREE OF STRENGTHENING=

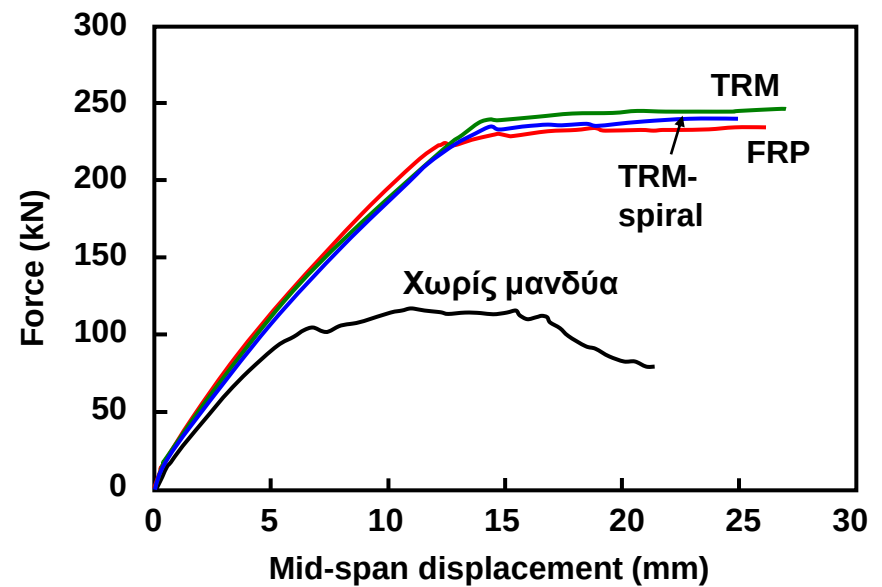
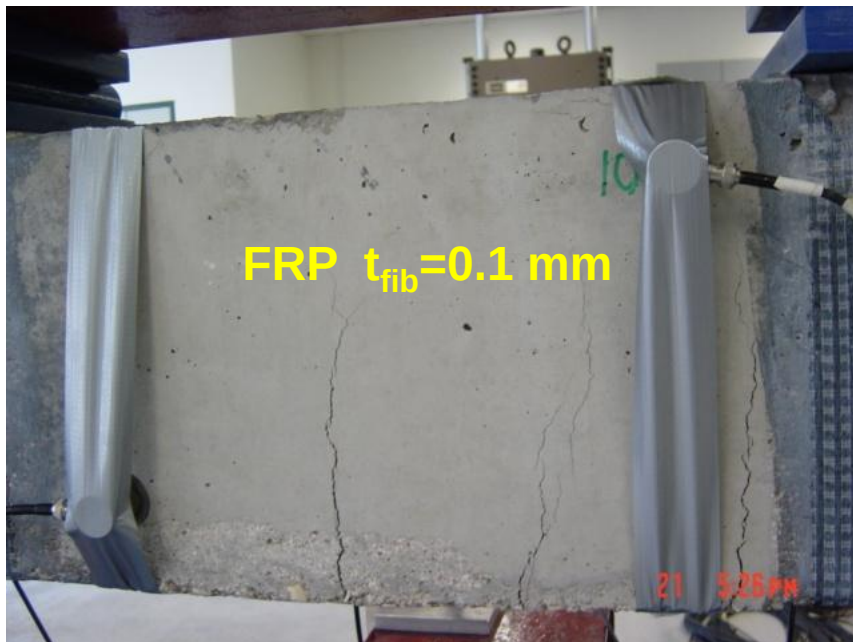
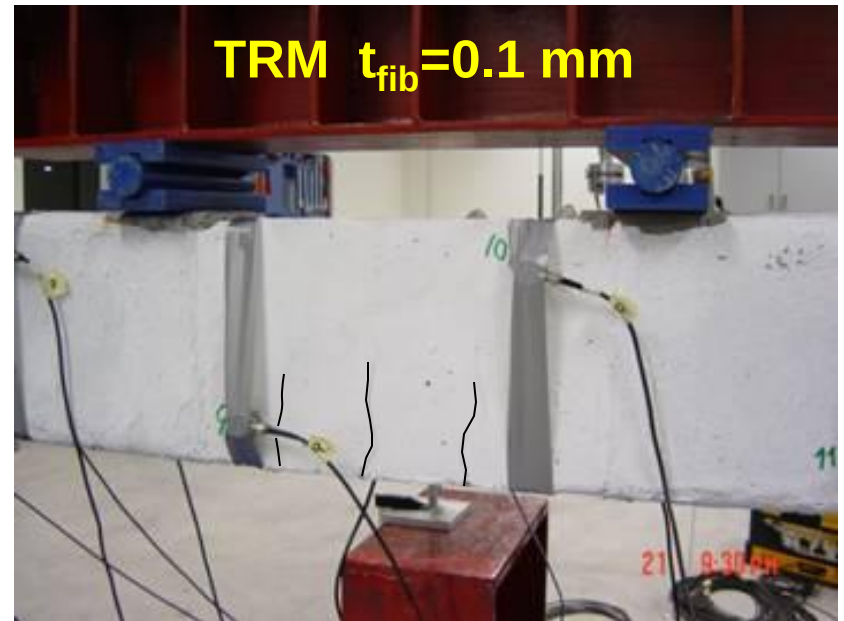
$$P_{max,Specimen} / P_{max,Control}$$

ΕΝΙΣΧΥΣΗ ΣΕ ΤΕΜΝΟΥΣΑ

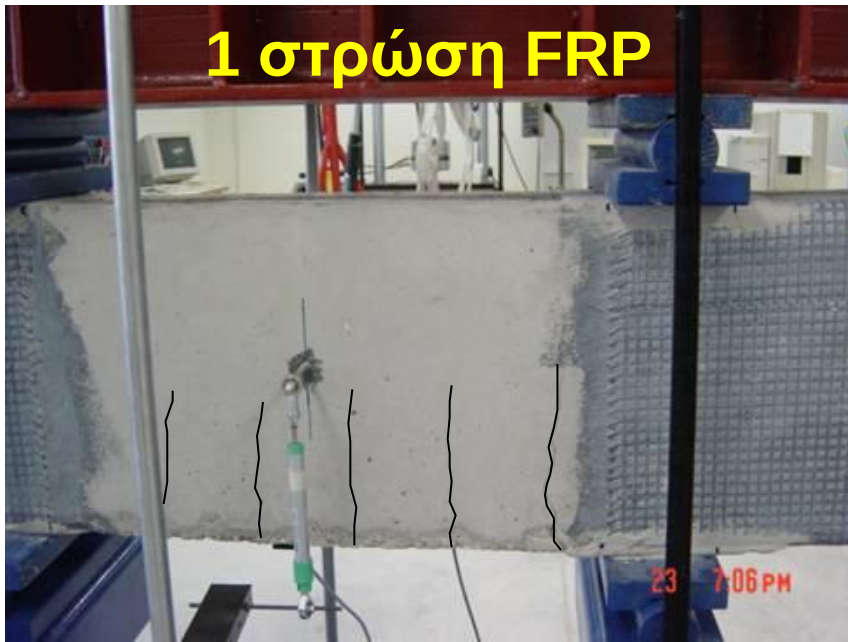


$\rho = 160 \text{ g/m}^2$
 $t_{\text{fib}} = 0.047 \text{ mm}$

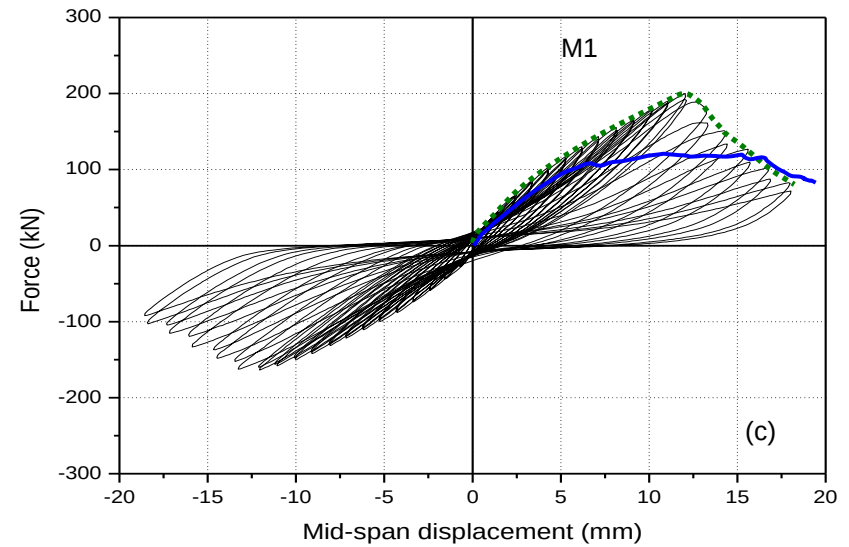
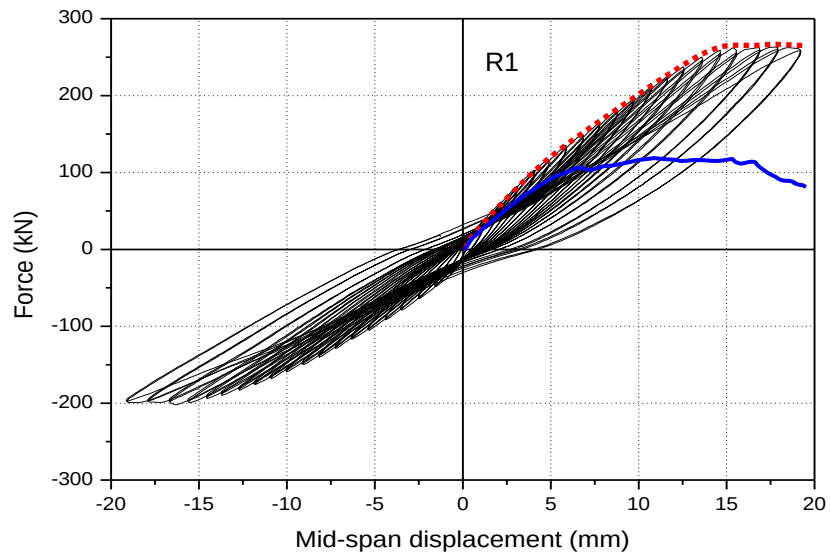




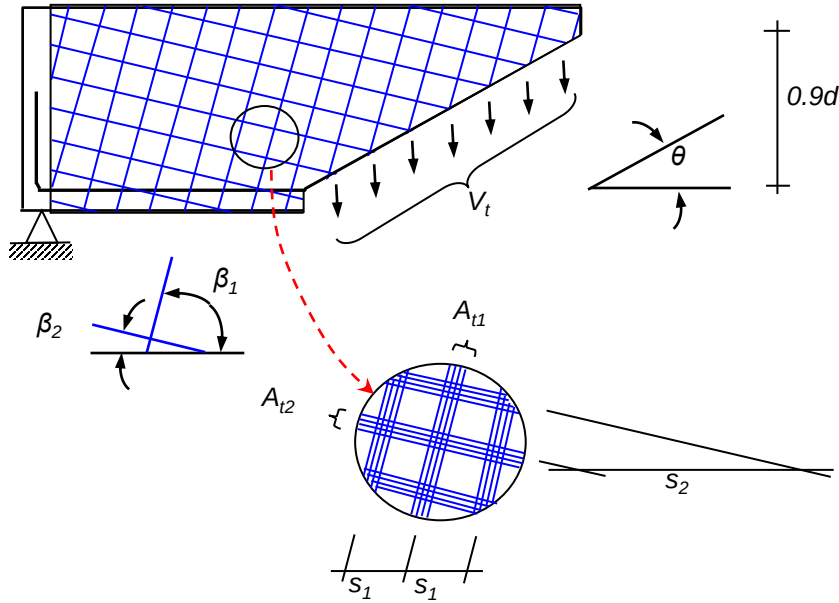
1 στρώση FRP



1 στρώση TRM



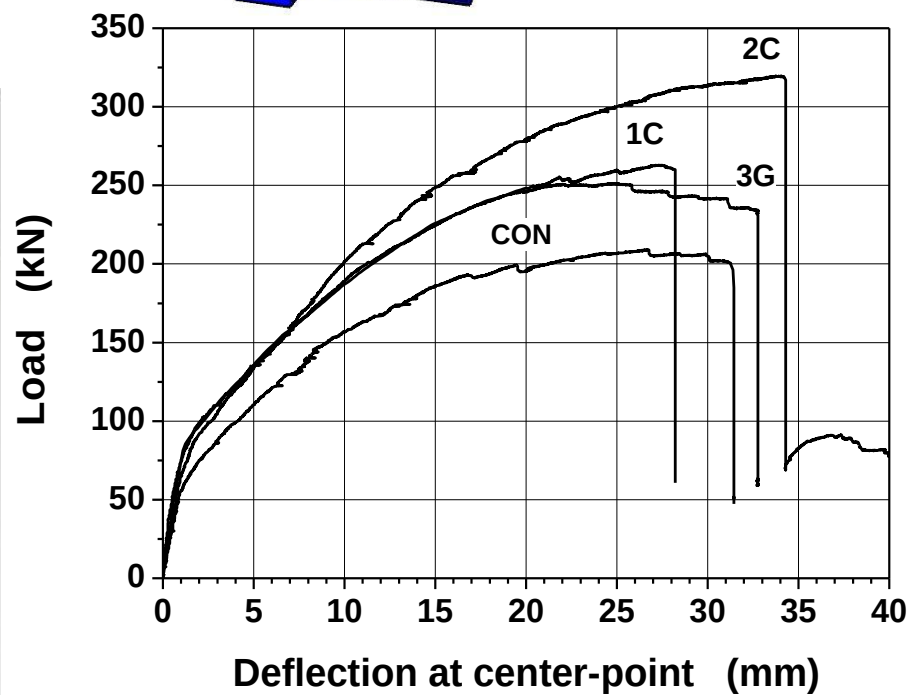
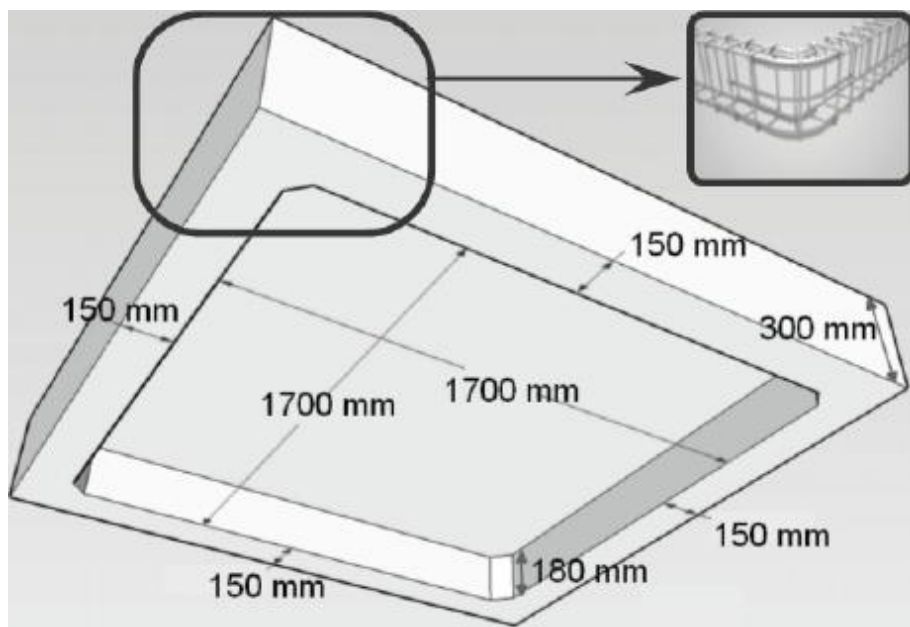
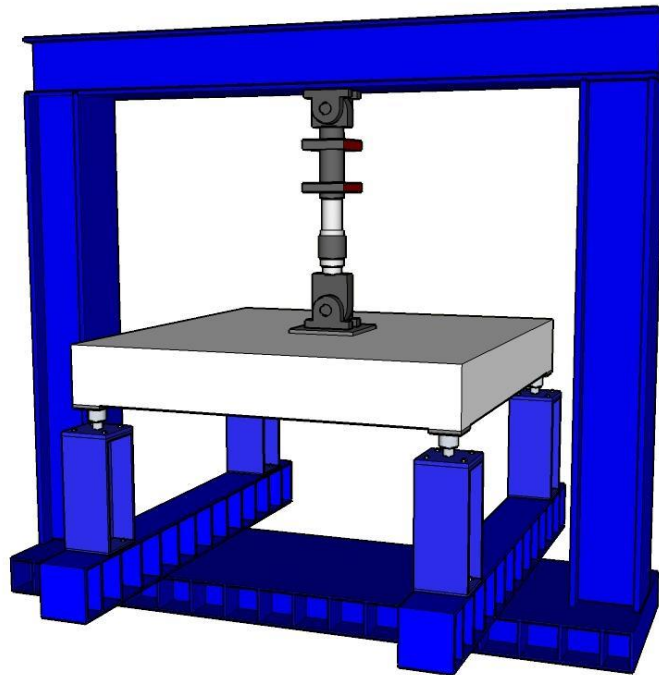
Αναλυτικό προσομοίωμα



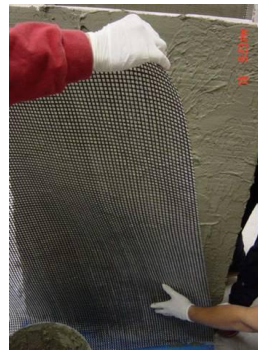
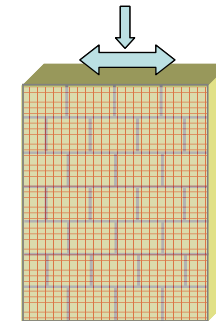
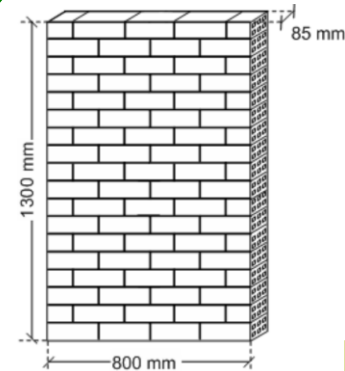
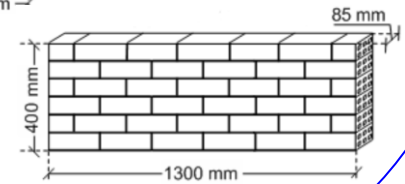
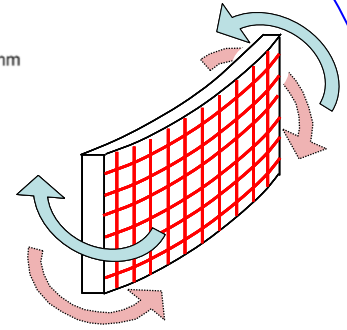
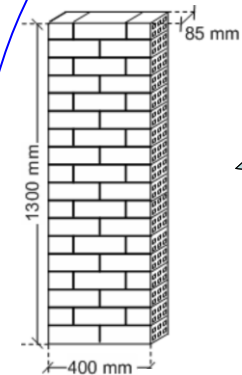
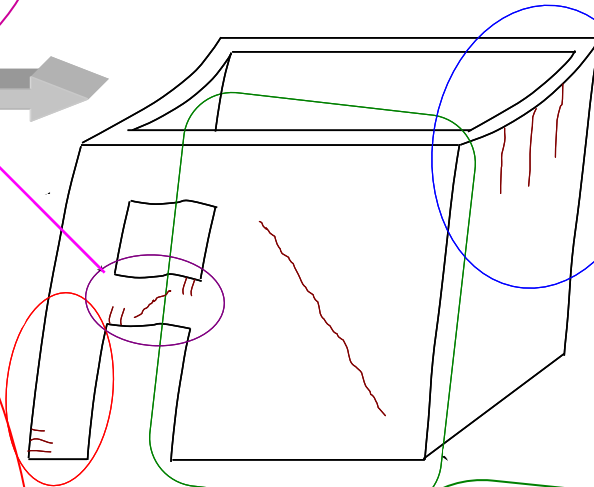
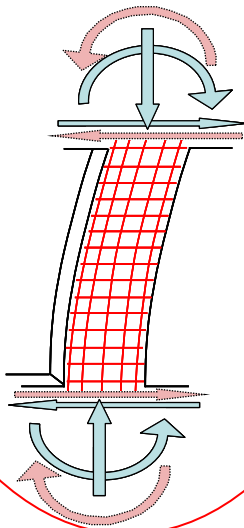
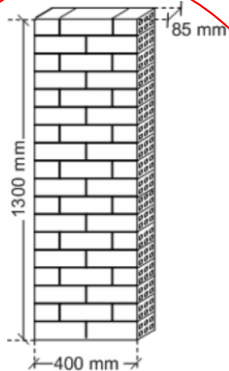
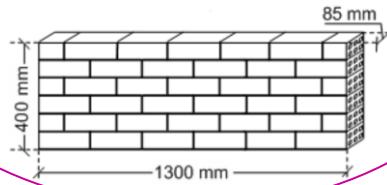
$$V_t = \sum_{i=1}^2 \frac{A_{ti}}{S_i} \sigma_{te,i} 0.9d (\cot \theta + \cot \beta_i) \sin \beta_i$$

Ενεργός τάση στη διεύθυνση $i = k \sigma_{fe,i}$

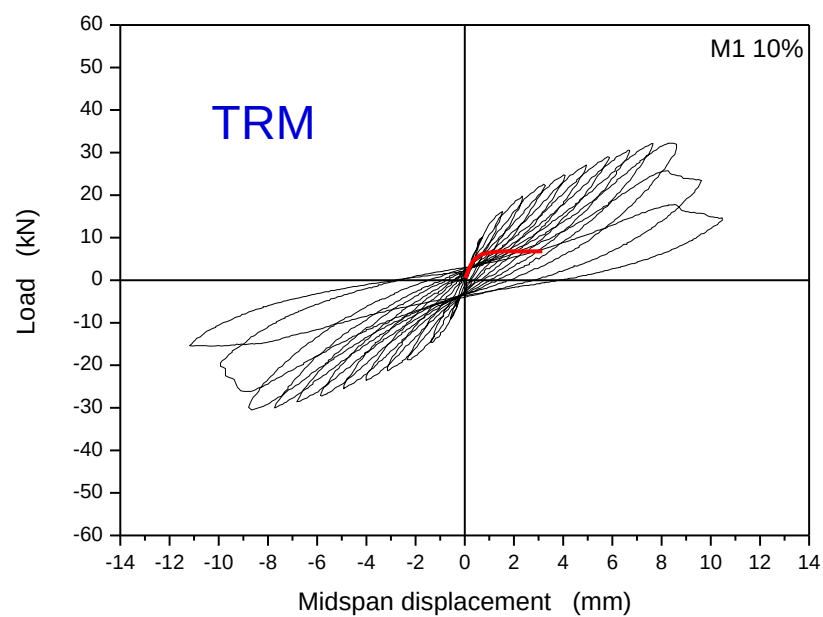
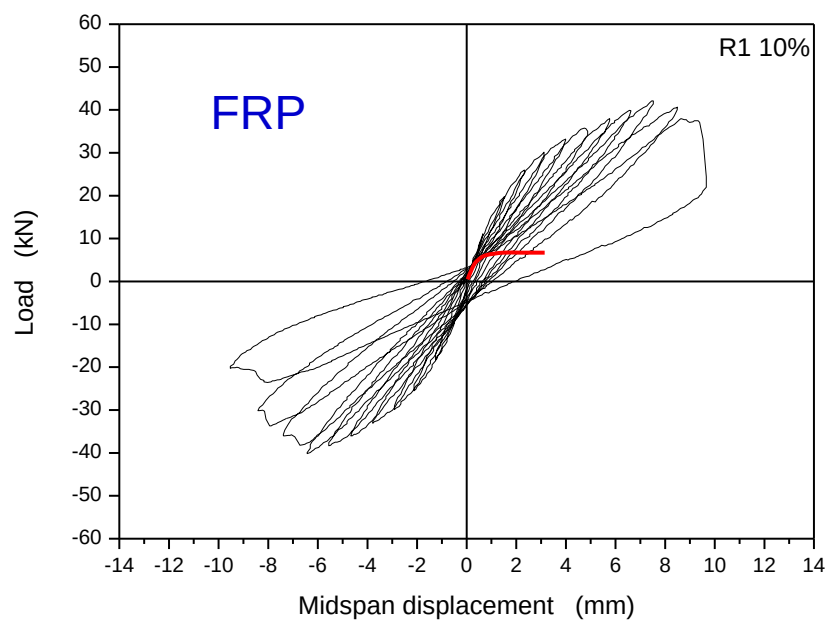
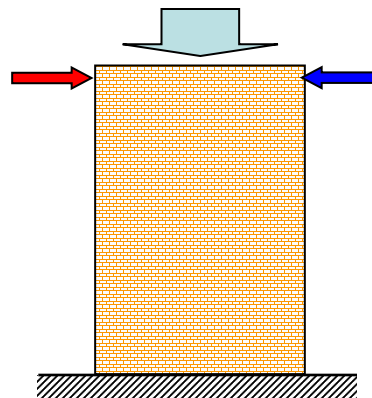
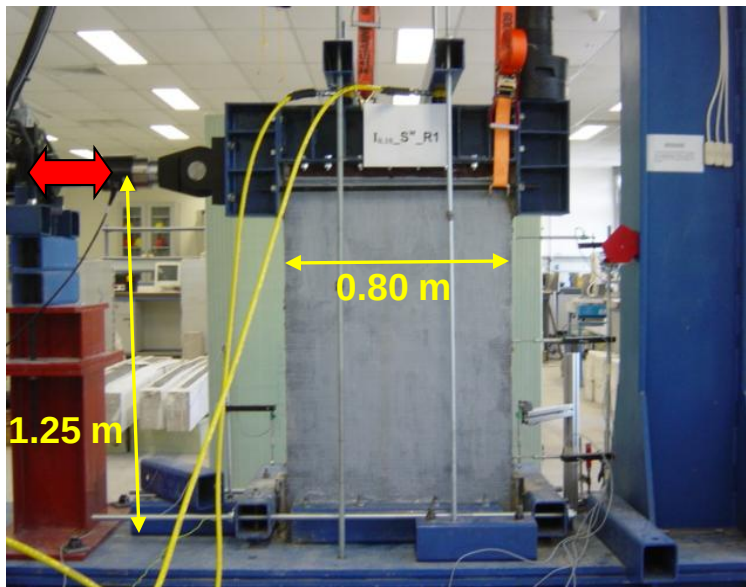
ΠΛΑΚΕΣ 2 ΔΙΕΥΘΥΝΣΕΩΝ

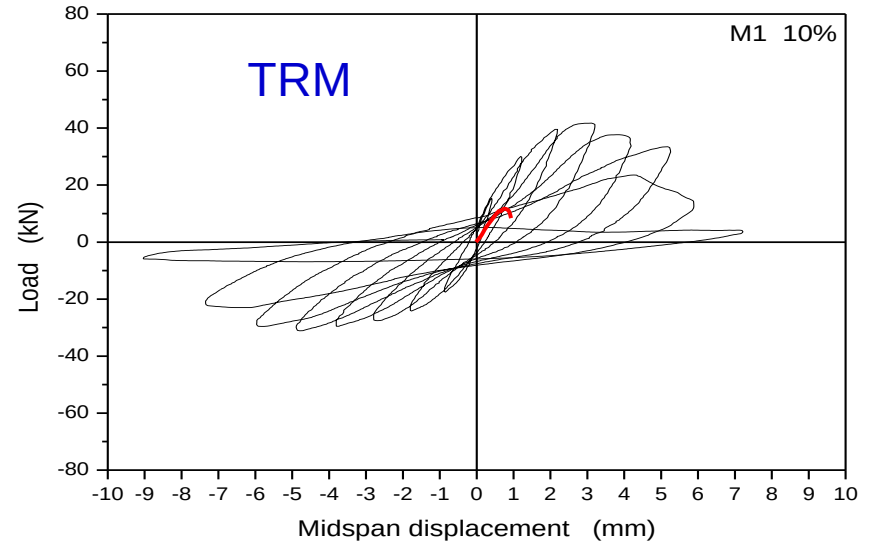
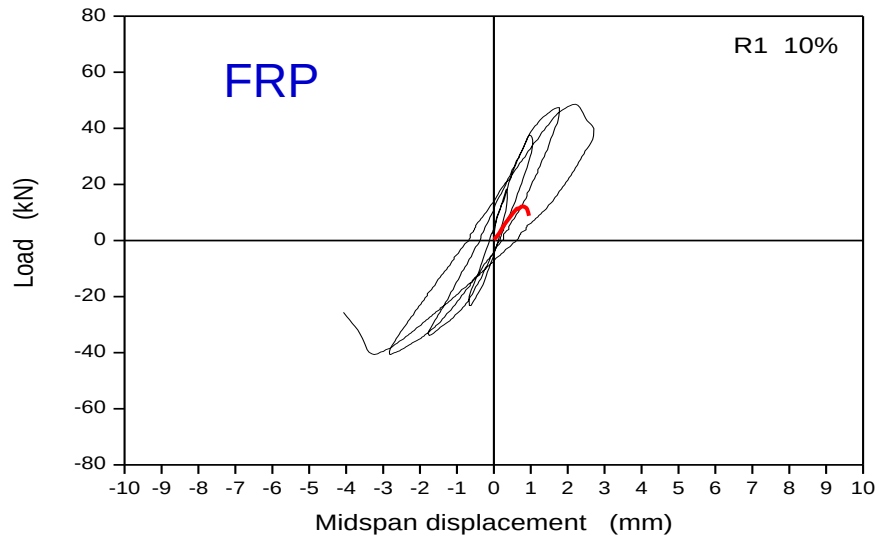
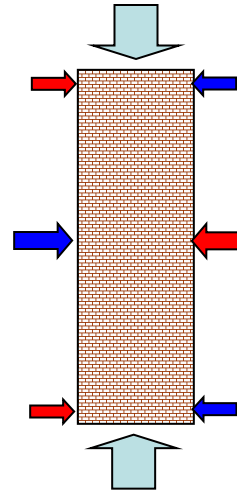
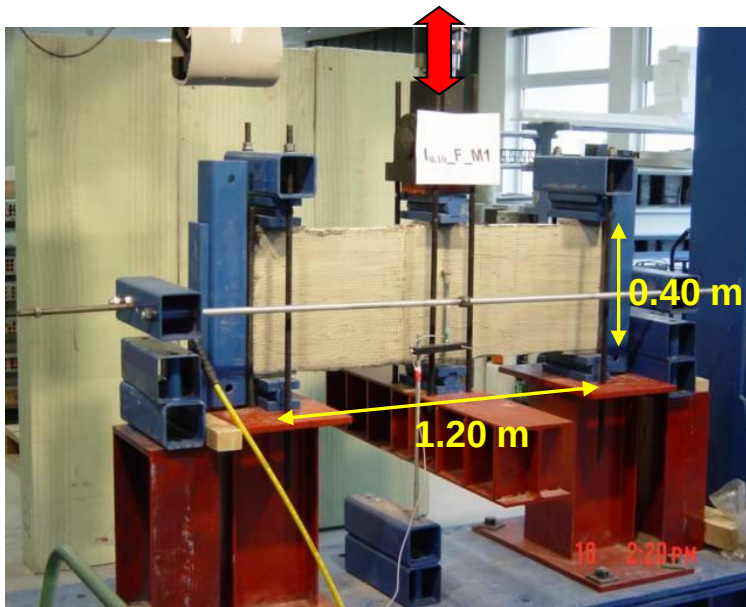


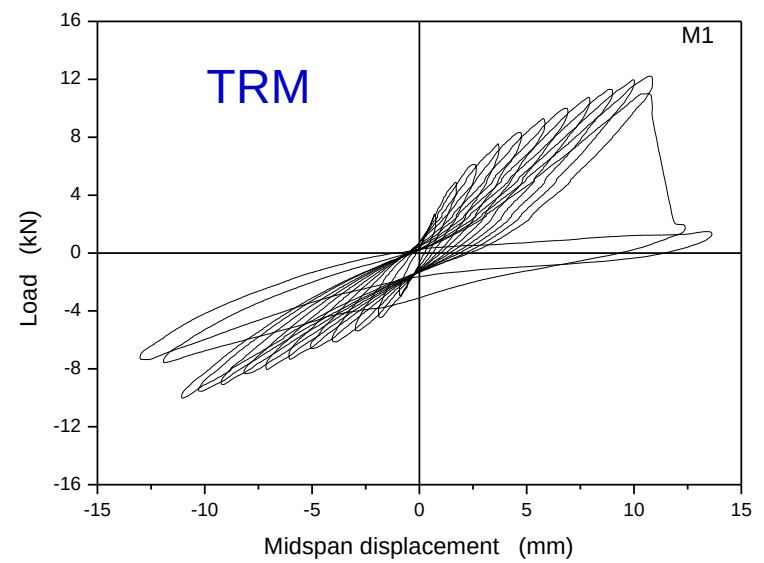
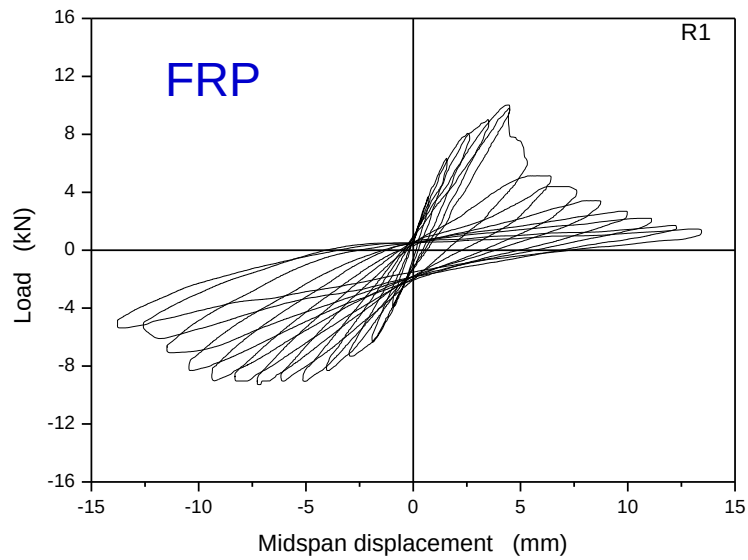
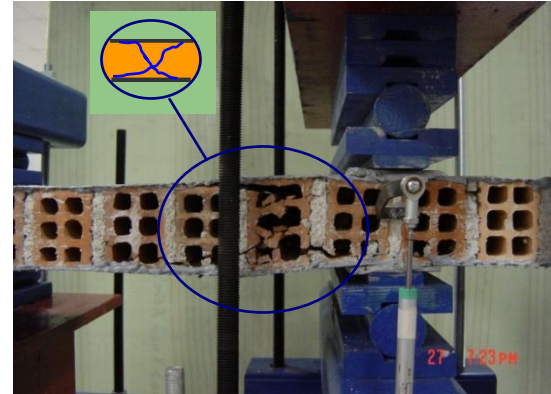
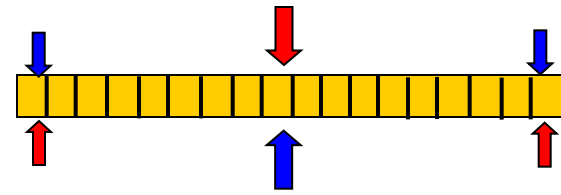
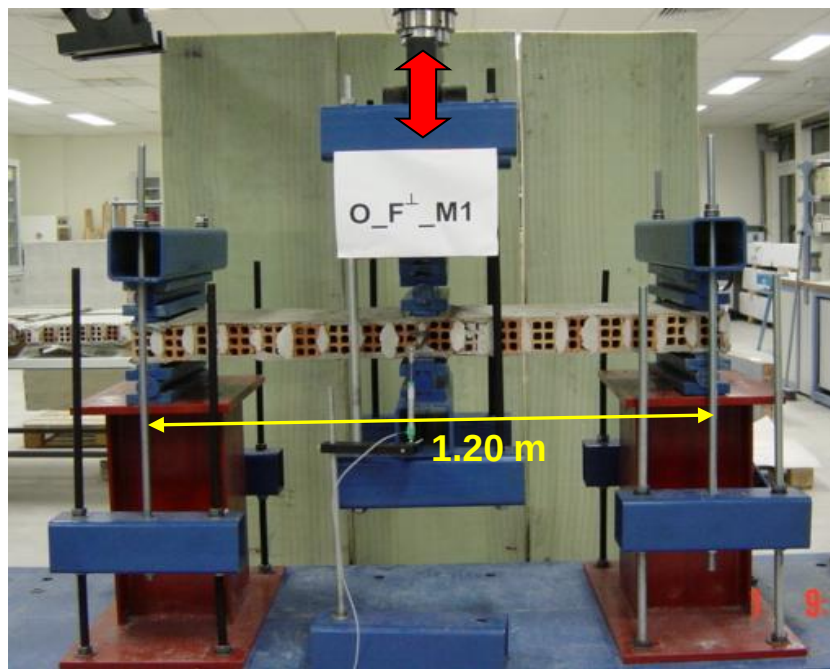
ΦΕΡΟΥΣΑ ΤΟΙΧΟΠΟΙΪΑ



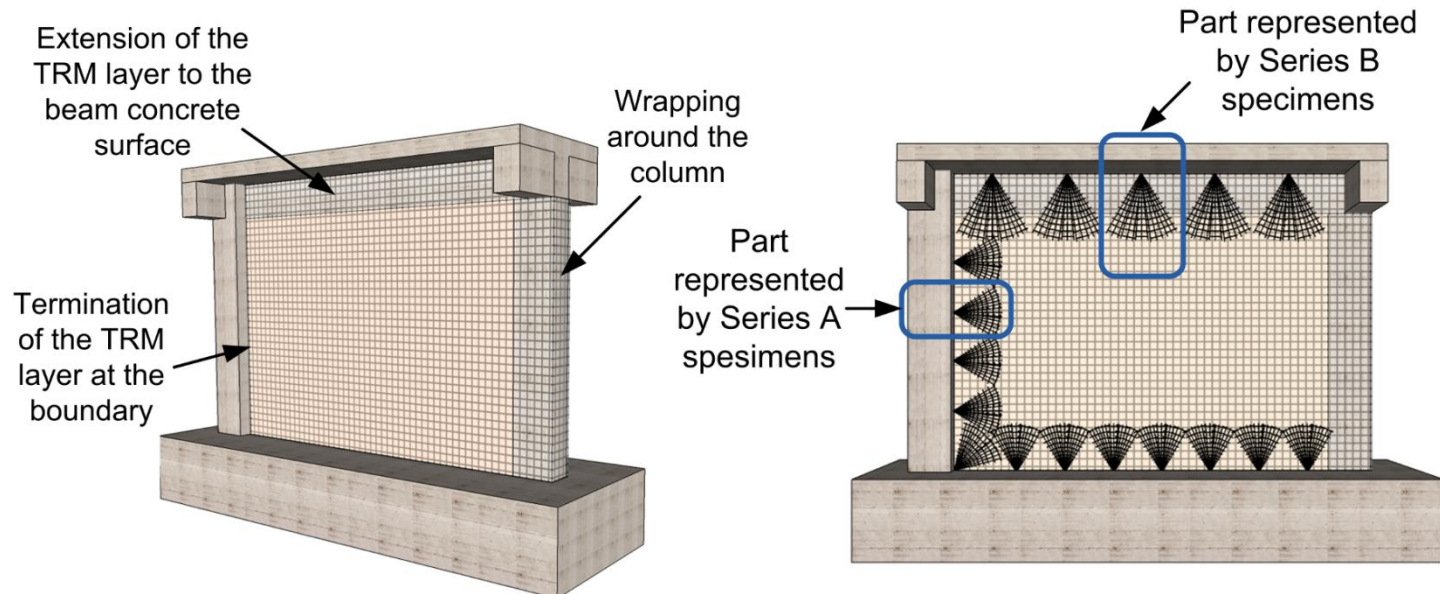
ΑΘ. Τριανταφύλλου



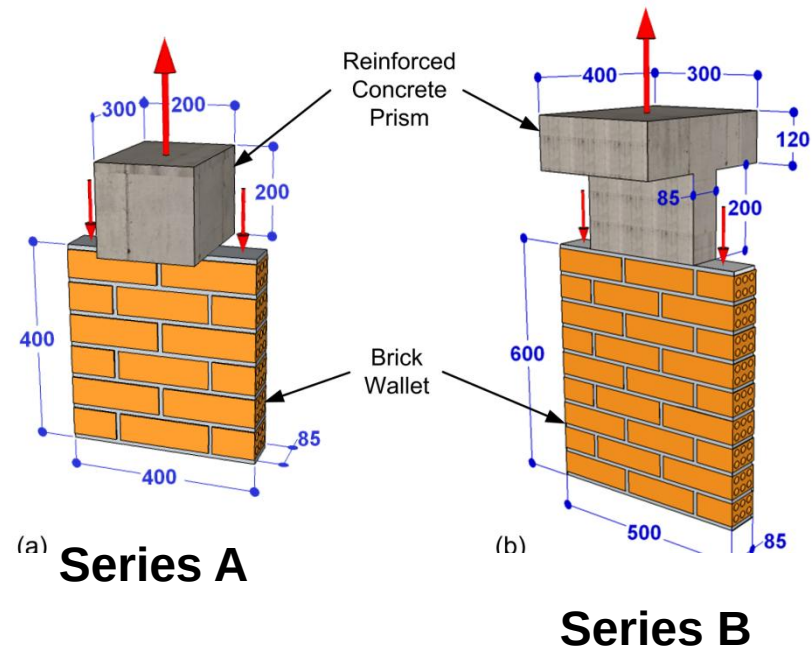


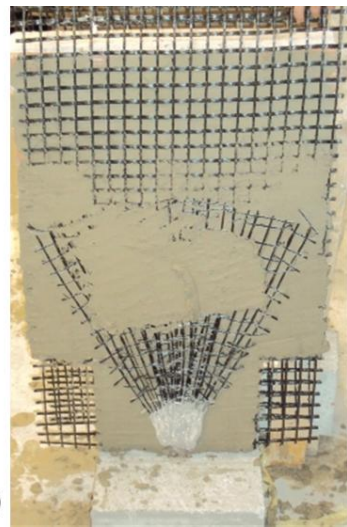


ΕΝΙΣΧΥΣΗ ΤΟΙΧΟΠΛΗΡΩΜΕΝΩΝ ΠΛΑΙΣΙΩΝ



Experiments for the investigation of the effectiveness of the technique



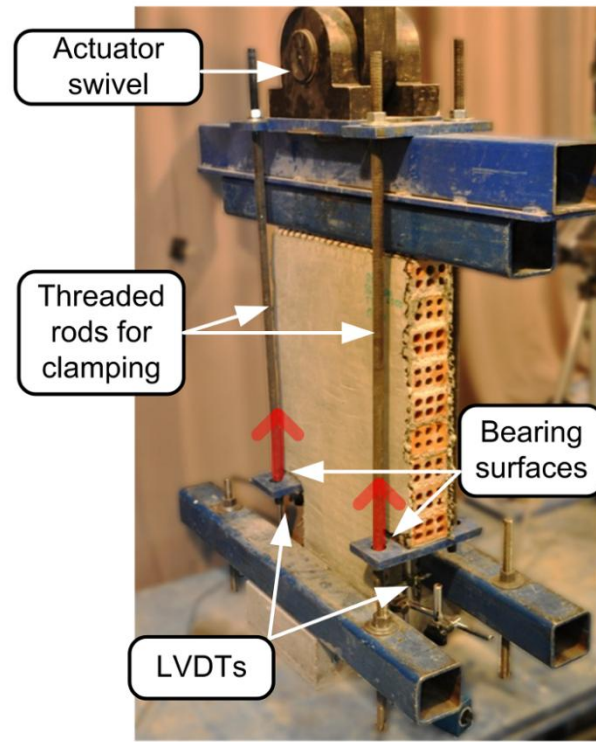
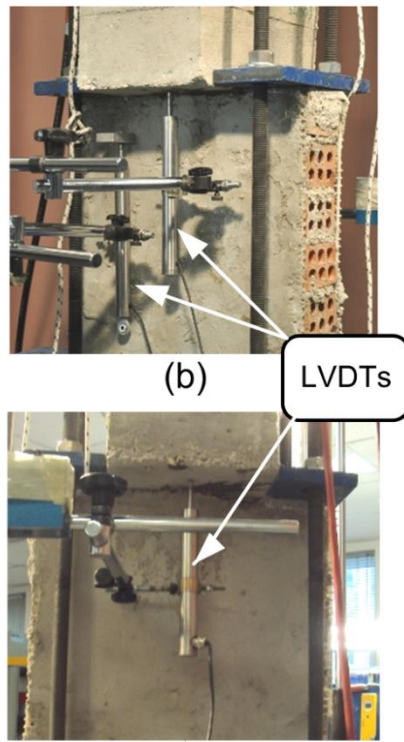
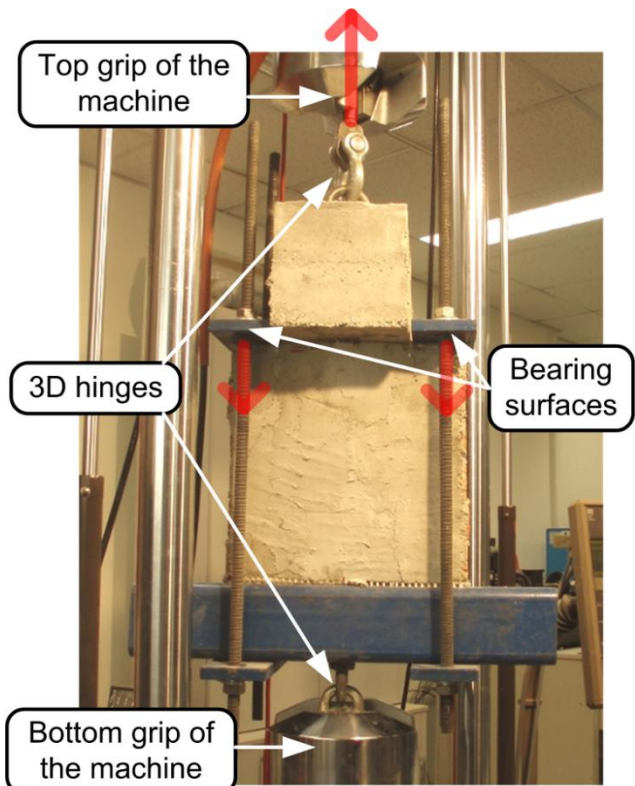


(a)

(b)

(c)

(d)



ΑΘ. Τριανταφύλλου

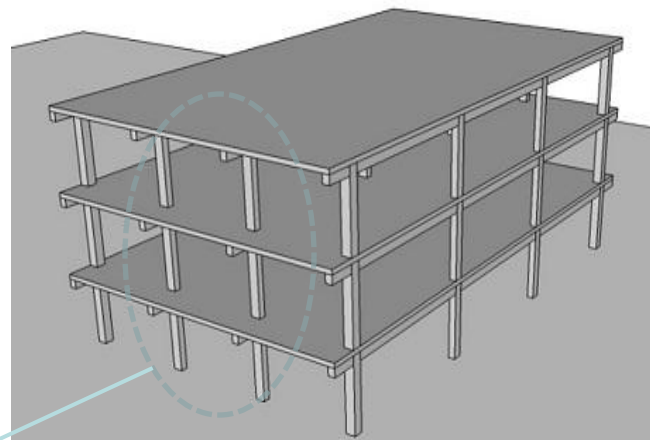
Series A

(c)

Series B (d)

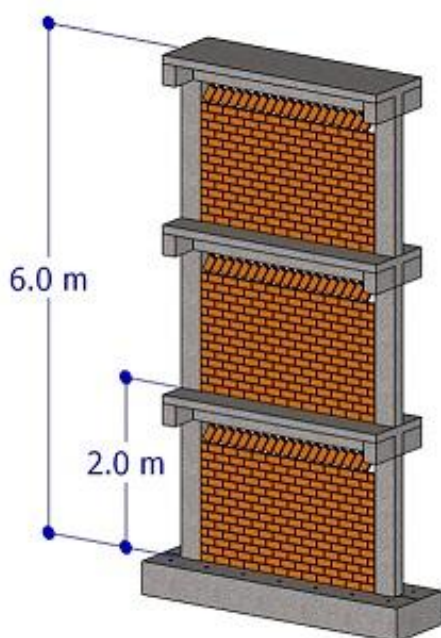
Δοκιμές σε επίπεδο ΚΑΤΑΣΚΕΥΗΣ

Τριώροφο κτίριο σχεδιασμένο σύμφωνα με
τον Αντισεισμικό Κανονισμό του 1959 :
Τρωτά υποστυλώματα – ανυπαρξία
“αντισεισμικών” λεπτομερειών όπλισης

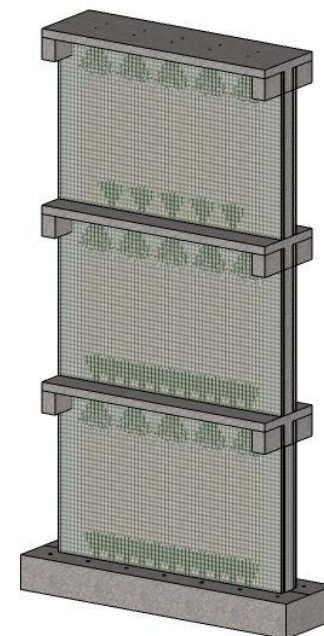


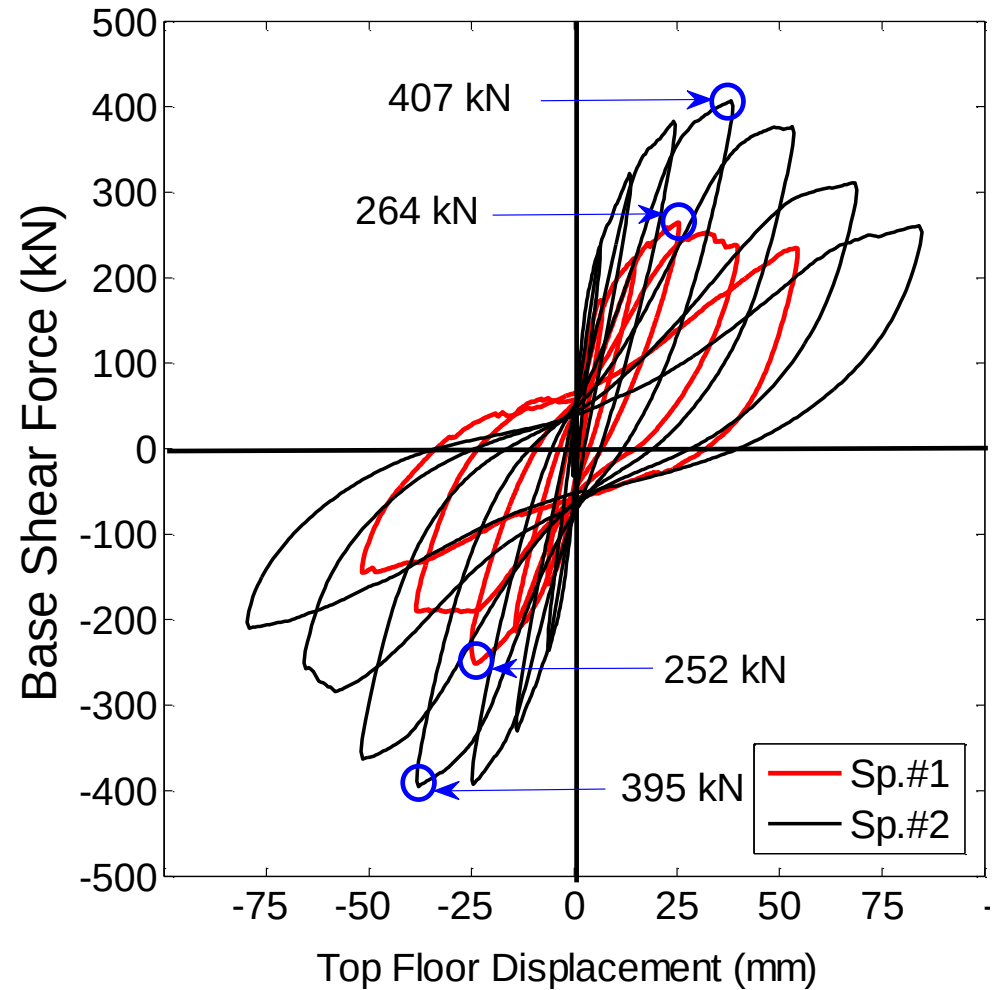
Εξετάσθηκε
πειραματικά
τμήμα του
κτιρίου που
θεωρείται
τοιχοπληρωμένο
(Κλίματα 2/3)

1 πλαίσιο
μη ενισχυμένο



1 πλαίσιο
ενισχυμένο





- Εν γένει βελτιωμένη συμπεριφορά, περιορισμός βλαβών
- Αύξηση τέμνουσας βάσης κατά ~ 50%.
- Αύξηση ικανότητας παραμόρφωσης

ΣΥΝΔΥΑΣΜΕΝΗ ΑΝΤΙΣΕΙΣΜΙΚΗ & ΕΝΕΡΓΕΙΑΚΗ ΑΝΑΒΑΘΜΙΣΗ



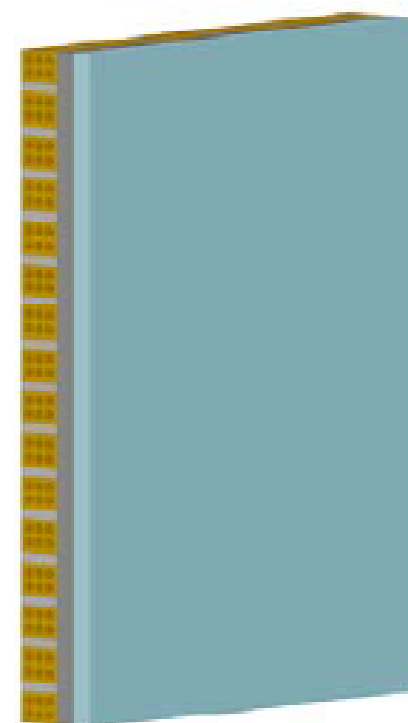
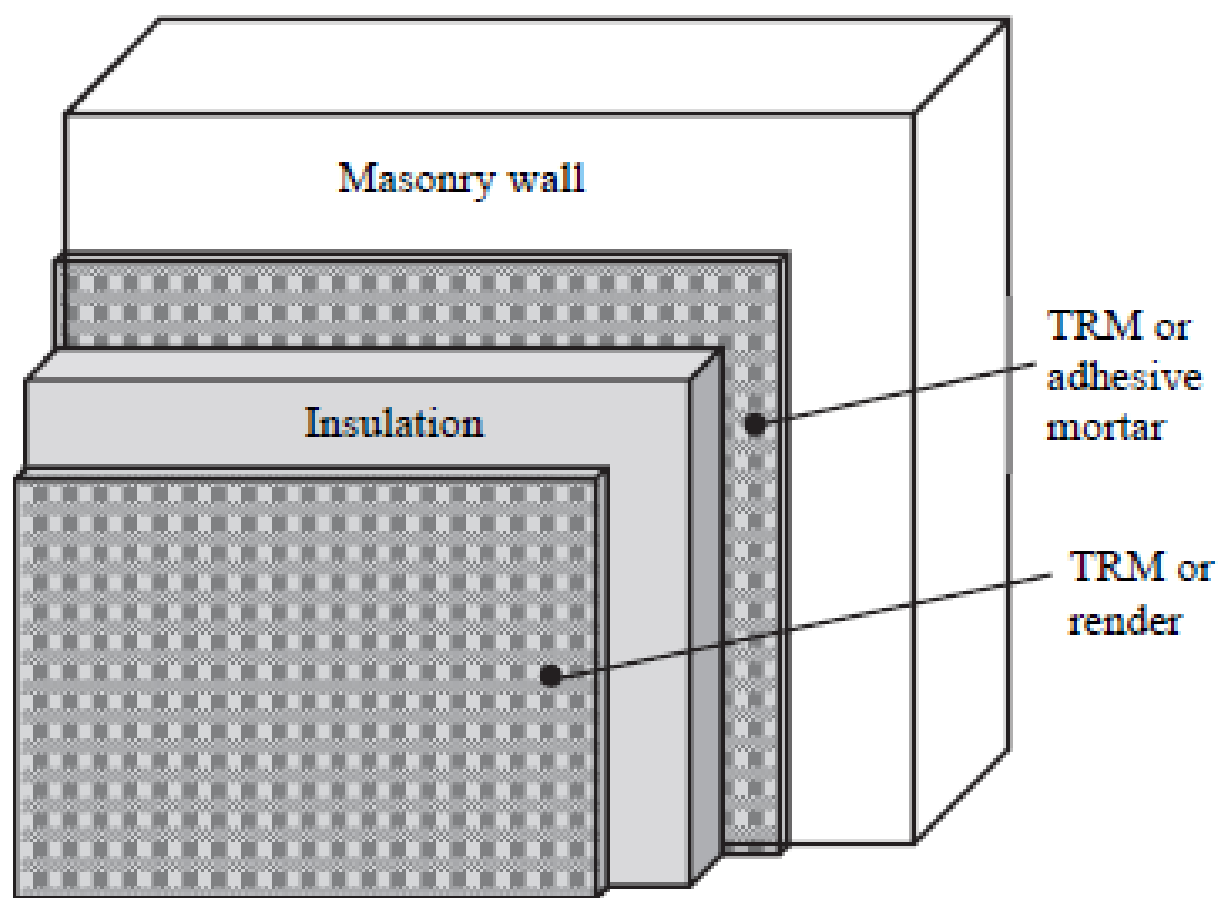
TRM (δομική αναβάθμιση)

+



Θερμομονωτικές πλάκες
(ενεργειακή αναβάθμιση)



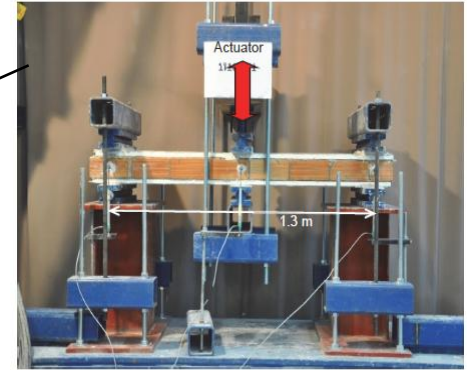
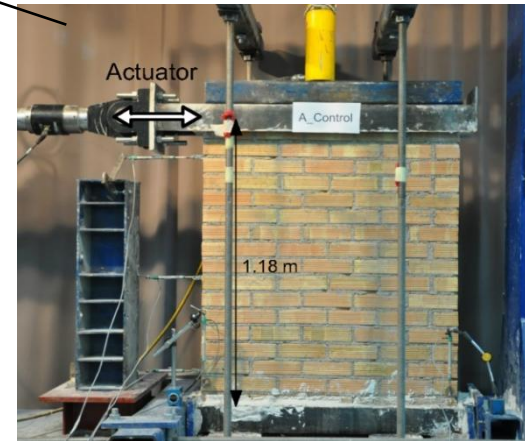
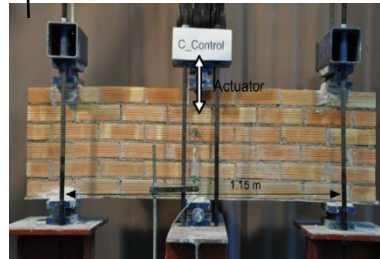
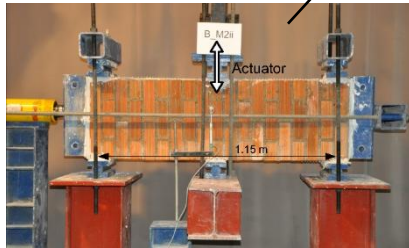


Beam-type element,
in-plane flexure/shear

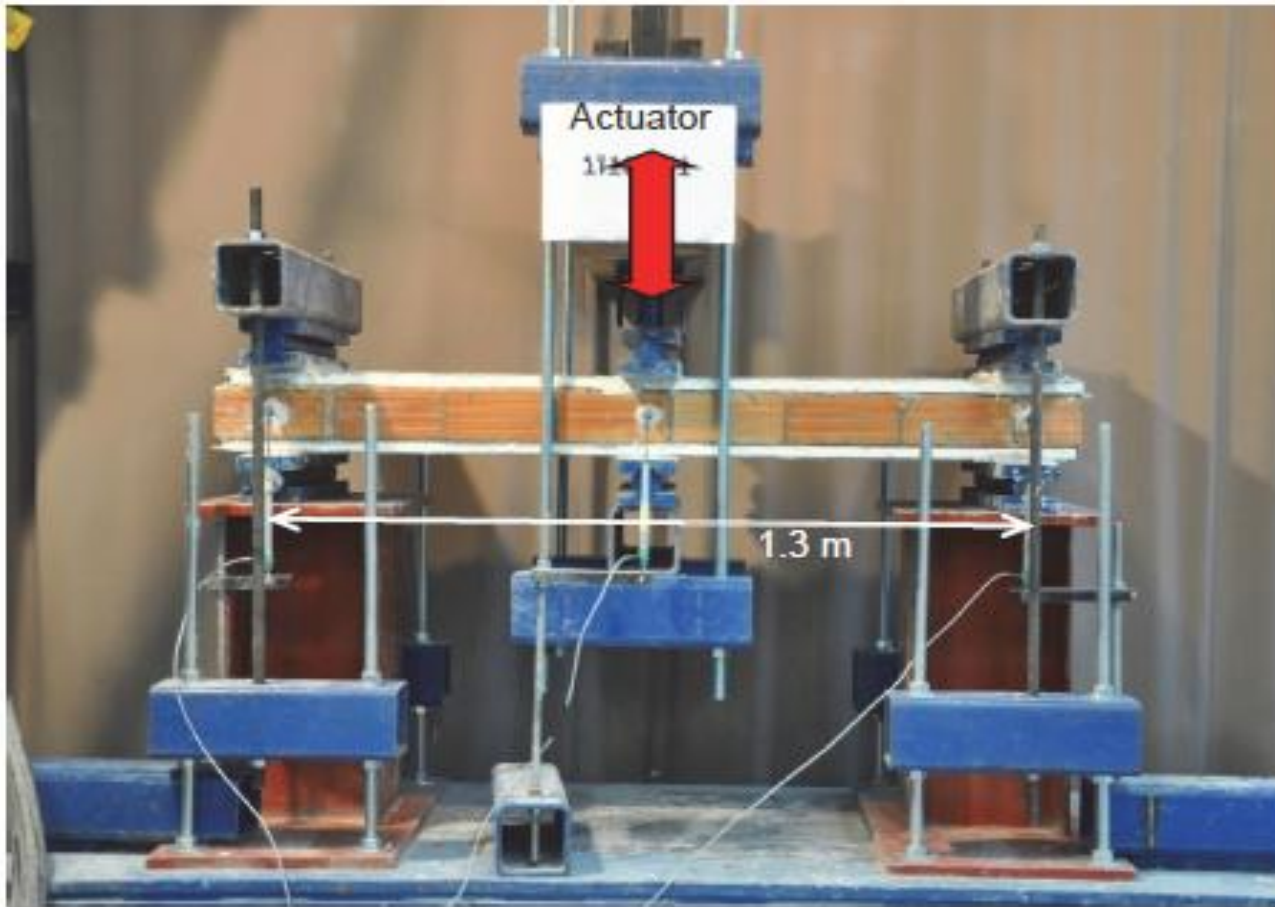
In-plane
flexure

Out-of-
plane
flexure

Shear wall, in-plane shear



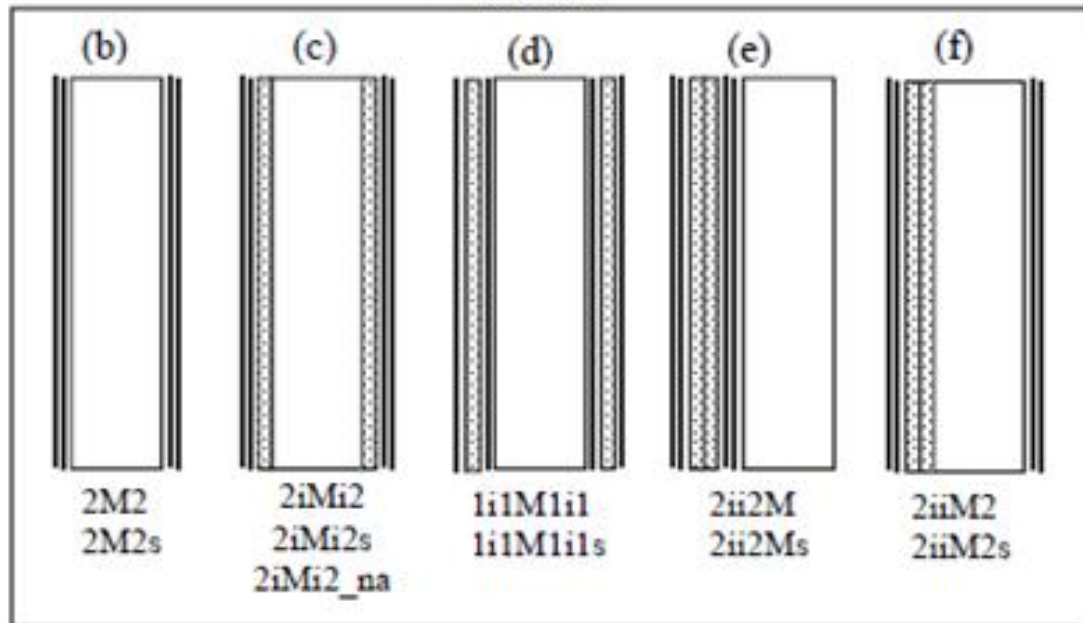
ΕΚΤΟΣ ΕΠΙΠΕΔΟΥ ΦΟΡΤΙΣΗ



Ανακυκλιζόμενη φόρτιση (βήμα αύξησης μετατόπισης 2 mm (ή 1 mm))



Series A



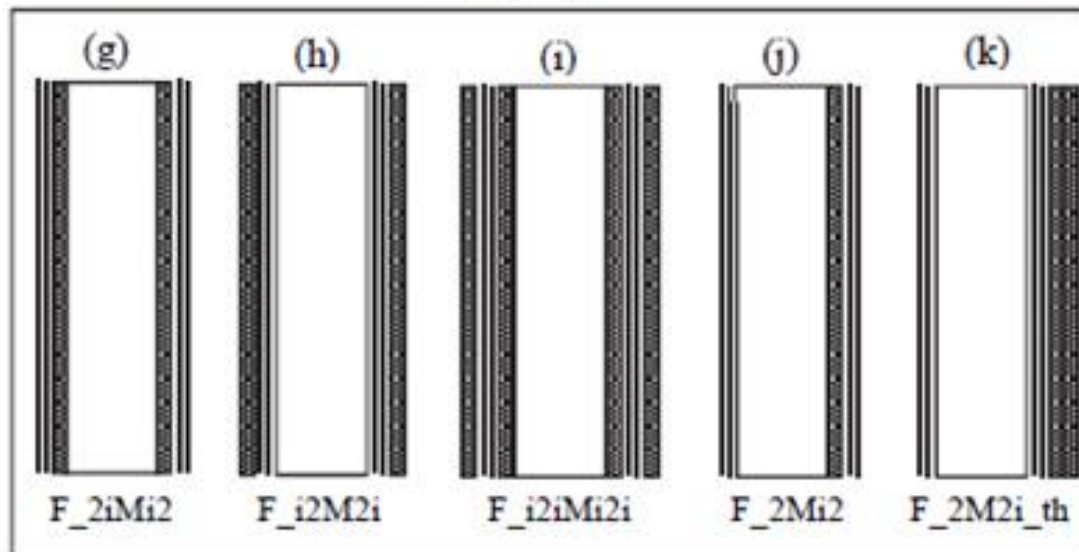
Διογκωμένη πολυστερίνη,
 $\rho=29 \text{ kg/m}^3$ $\lambda=0.029 \text{ W/mK}$

17 ΤΟΙΧΙΣΚΟΙ

20 mm πάχος

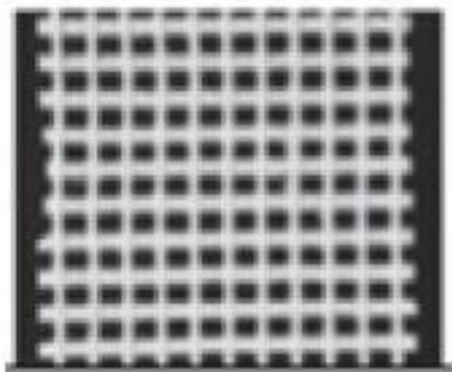
θερμομονωτικών πλακών
 (70 mm σε μία
 περίπτωση)

Series B

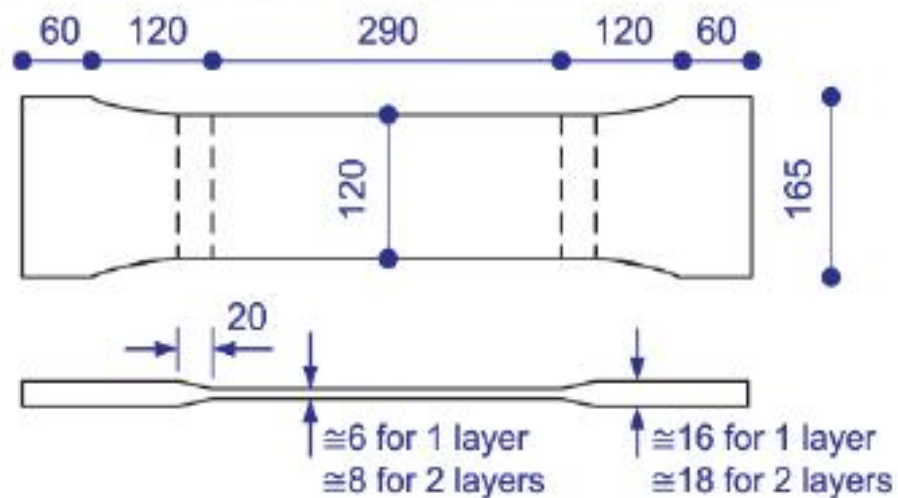


Κυψελωτό τσιμεντοκονίαμα,
 $\rho=115 \text{ kg/m}^3$ $\lambda=0.045 \text{ W/mK}$

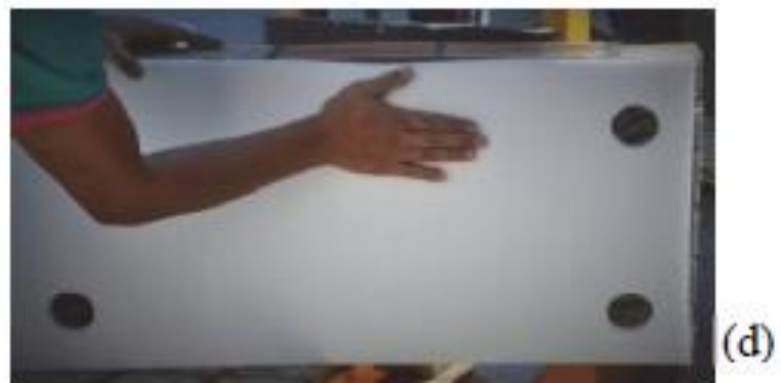
Ινοπλέγματα
επικαλυμμένου γυαλιού
300 g/m², ονομ. πάχος
0.06 mm



(a)

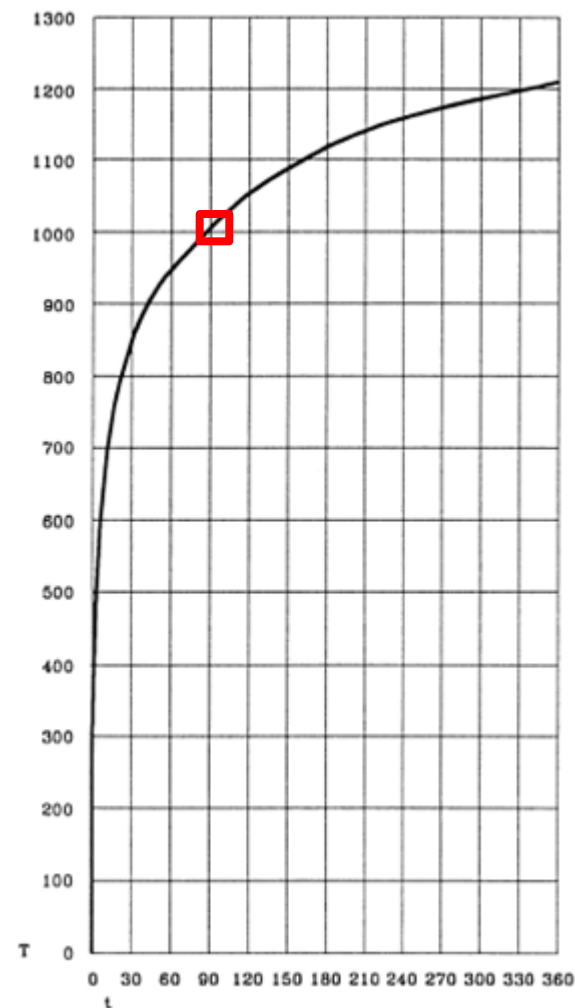


(b)





ΚΛΙΒΑΝΟΣ ΔΟΚΙΜΩΝ ΦΩΤΙΑΣ



$$T = 345 \log_{10}(8t + 1) + 20$$

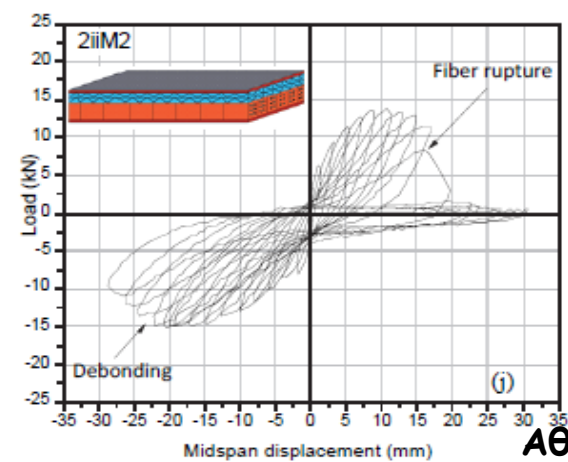
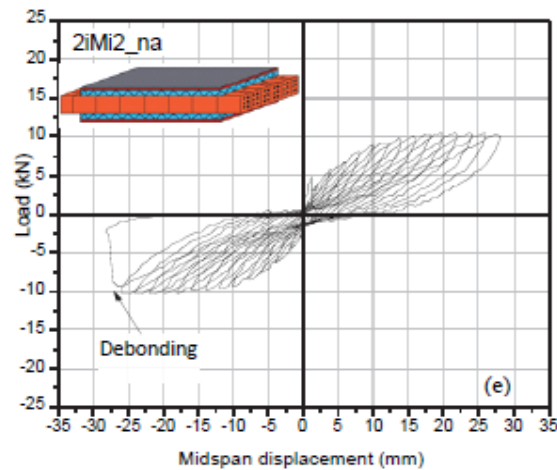
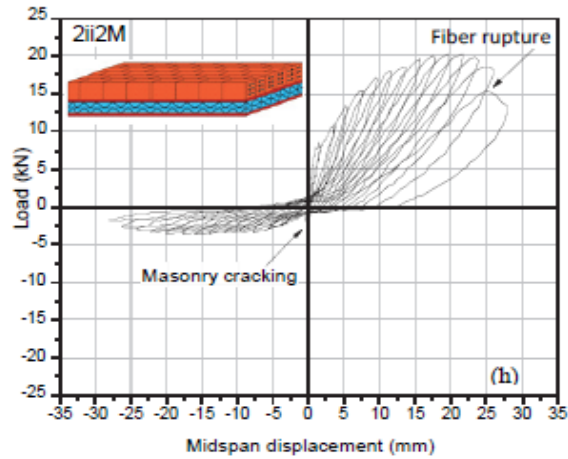
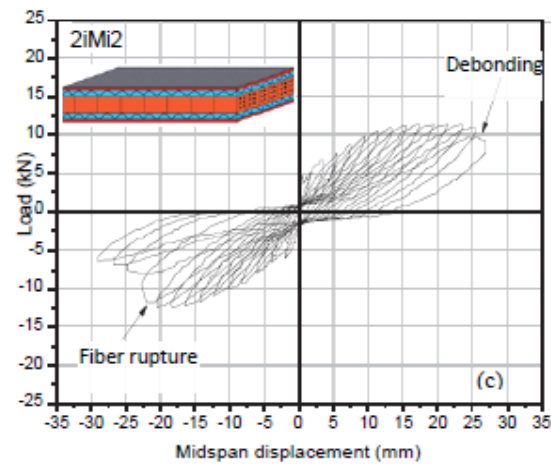
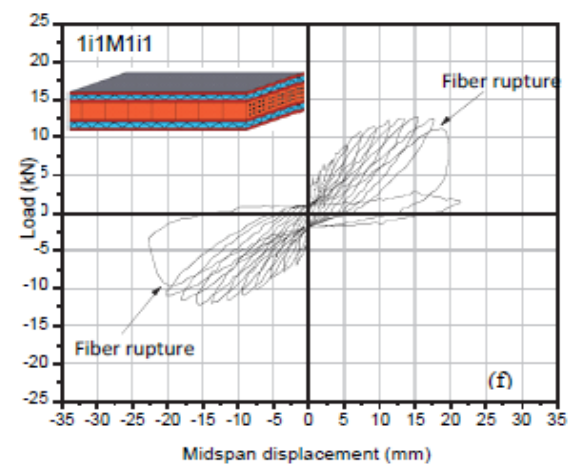
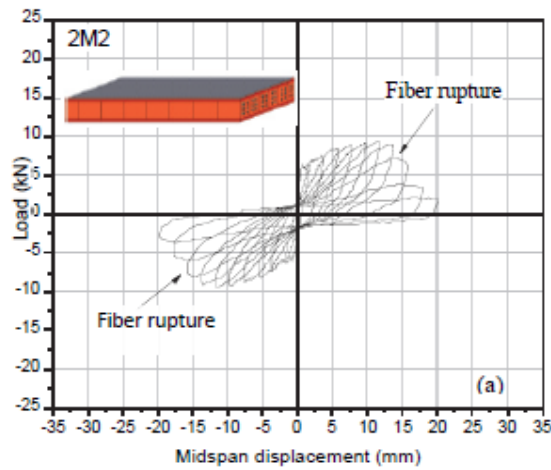


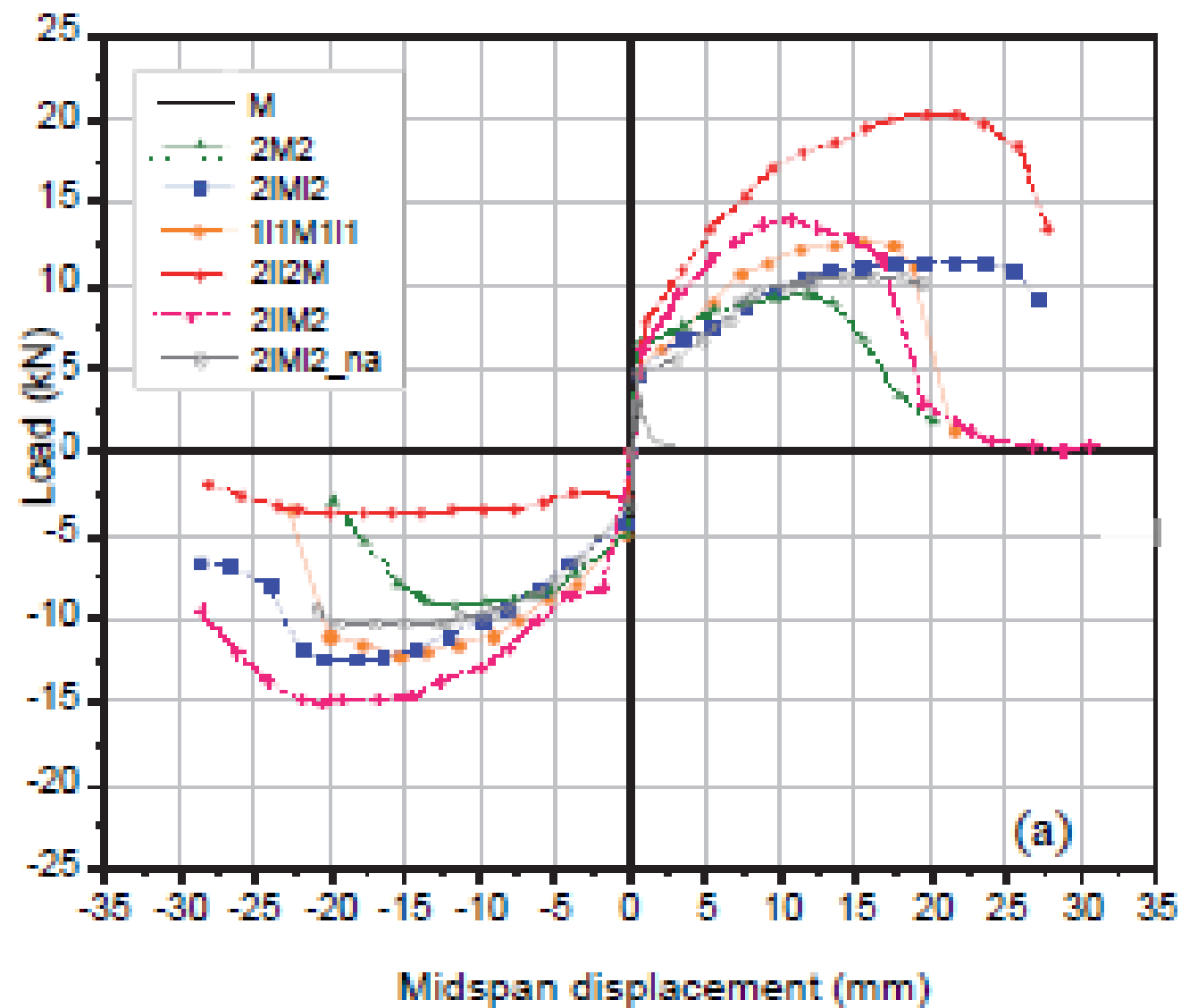
Σοβαρή βλάβη στο TRM



(b)

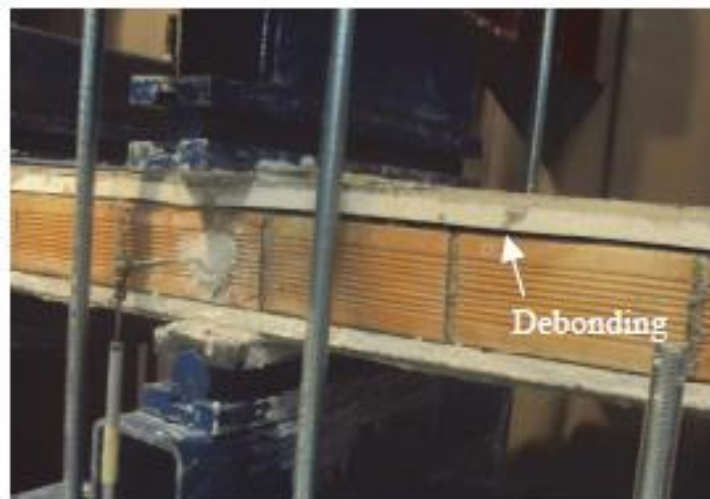
Χρήση πυράντοχου θερμομονωτικού υλικού







(a)



(b)



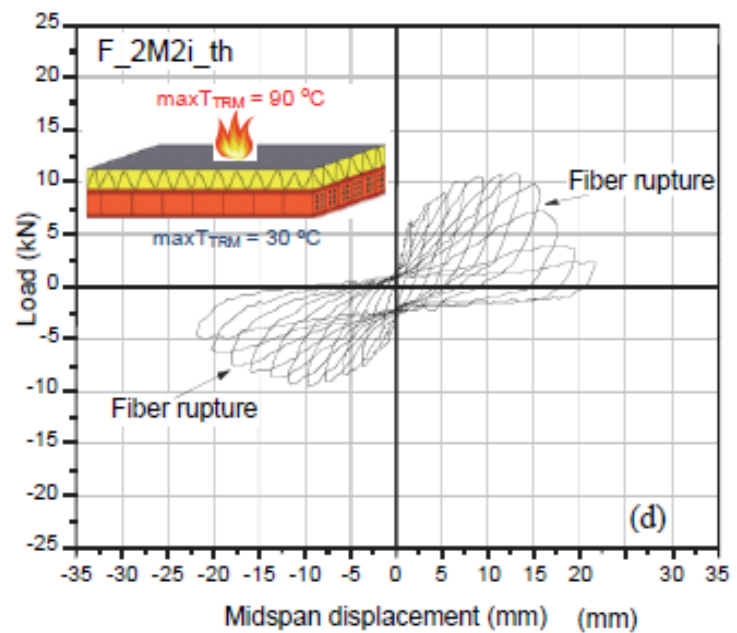
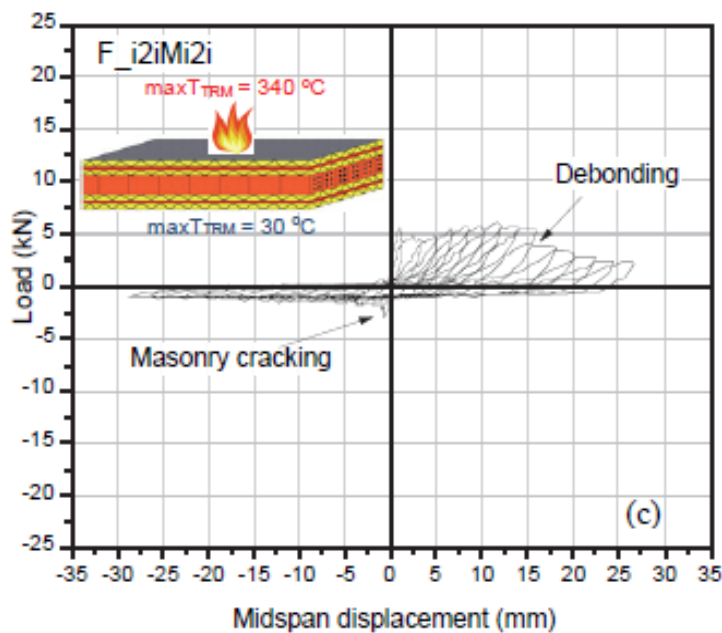
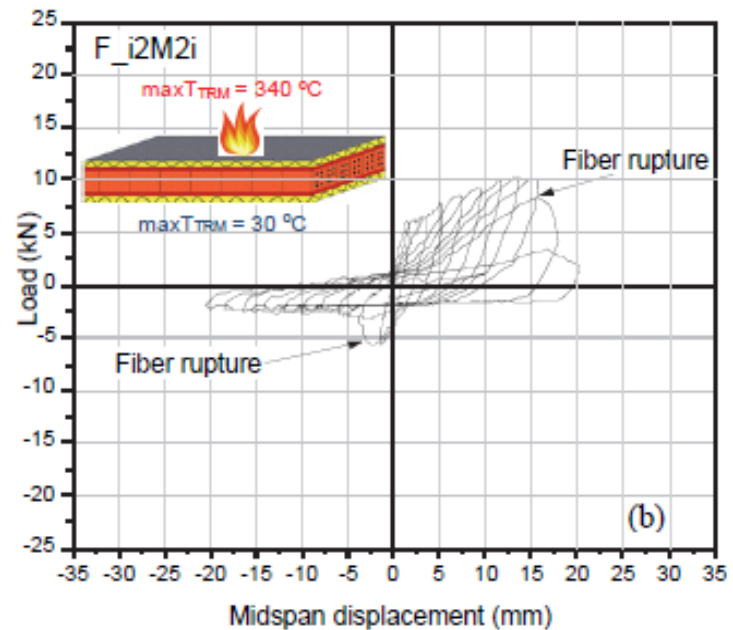
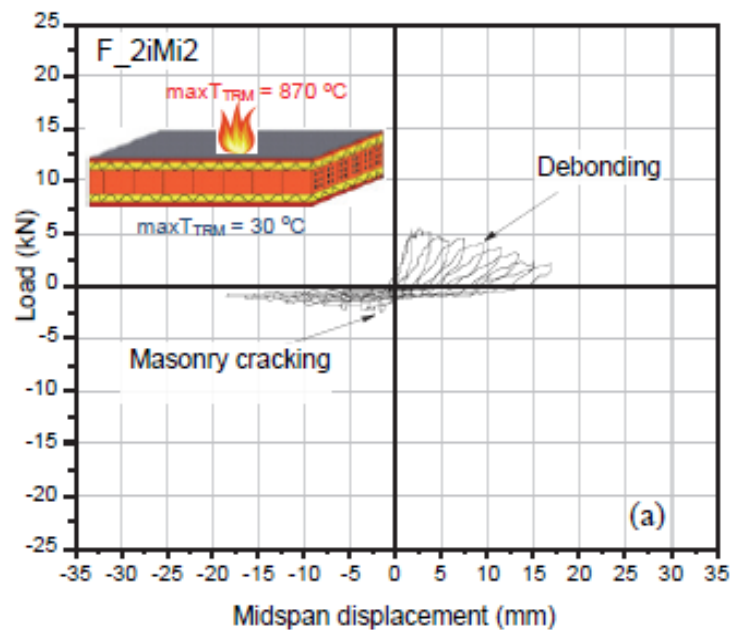
(c)

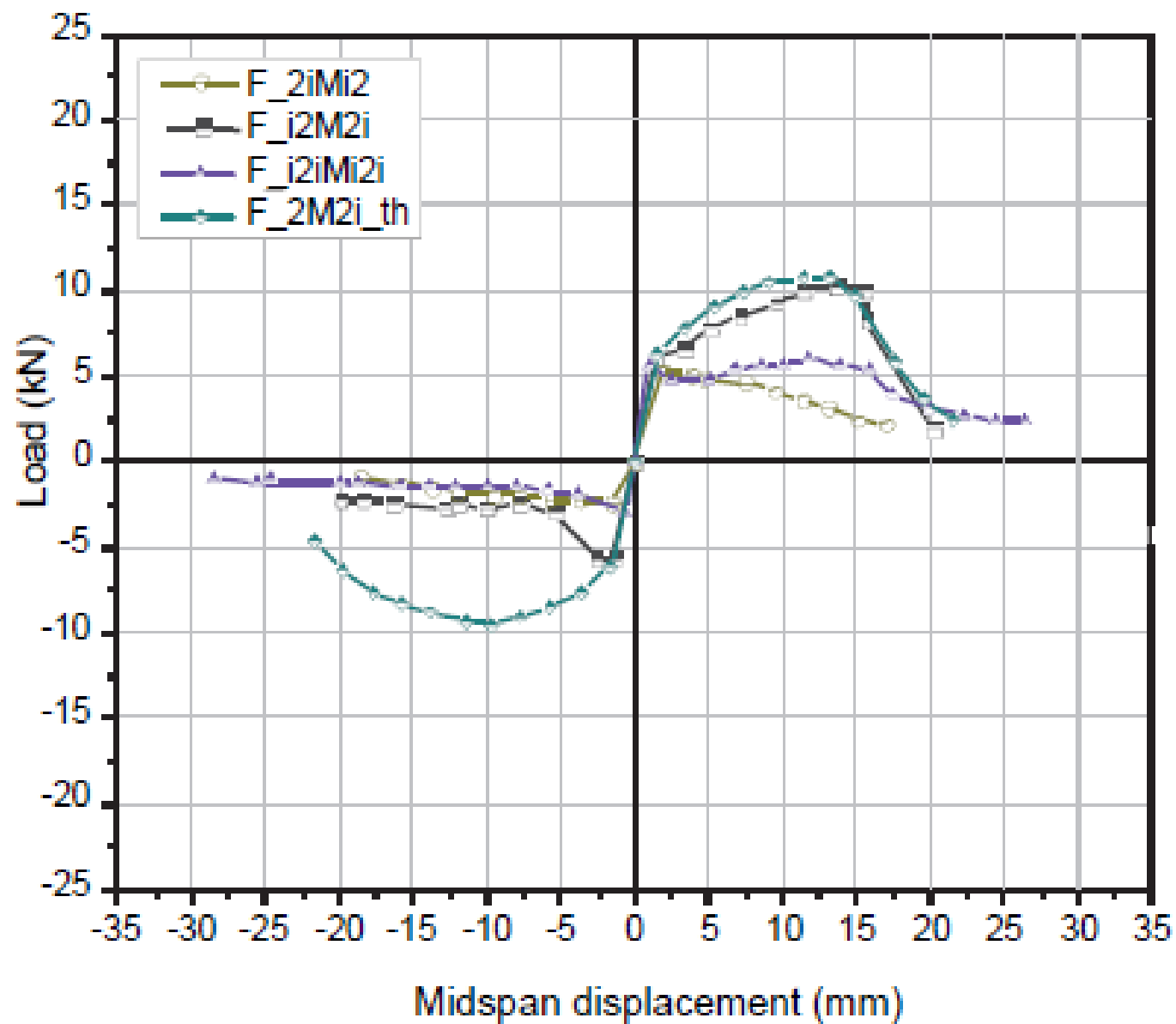


(d)

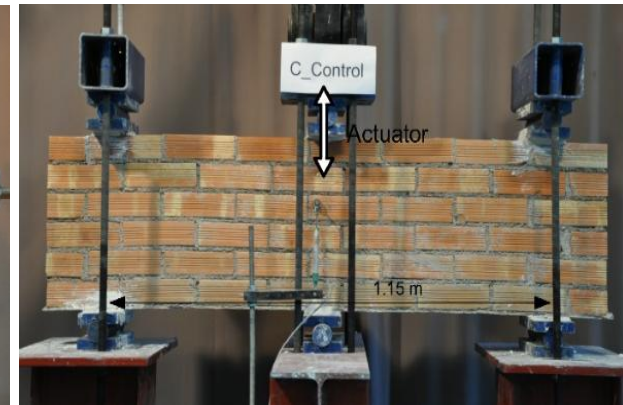
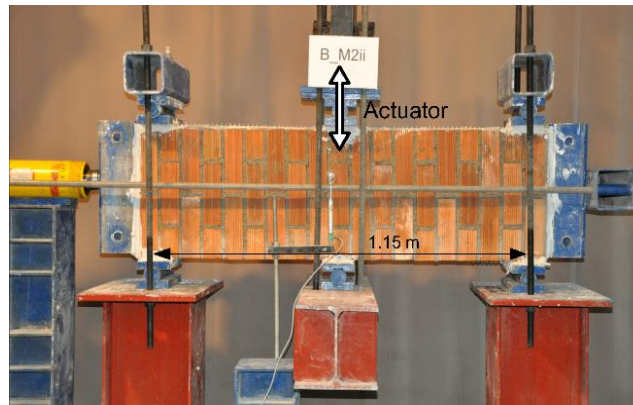
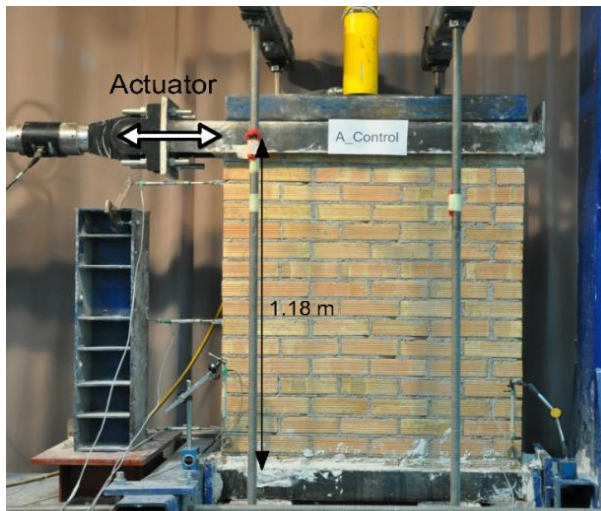


(e)





ΕΝΤΟΣ ΕΠΙΠΕΔΟΥ ΦΟΡΤΙΣΗ: 3 σειρές δοκιμών, 5 τοιχίσκοι ανά σειρά

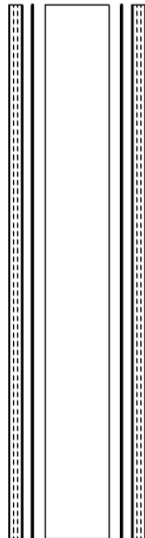


(a)



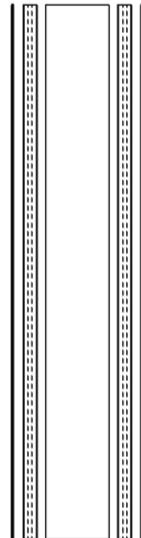
Control

(b)



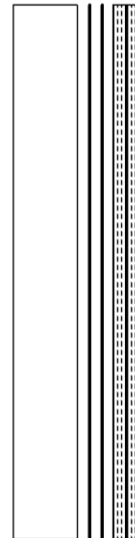
i1M1i

(c)



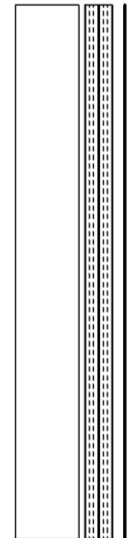
1iM1l

(d)



M2ii

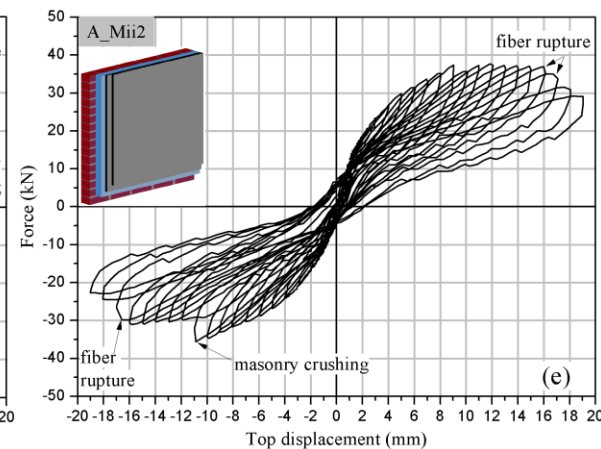
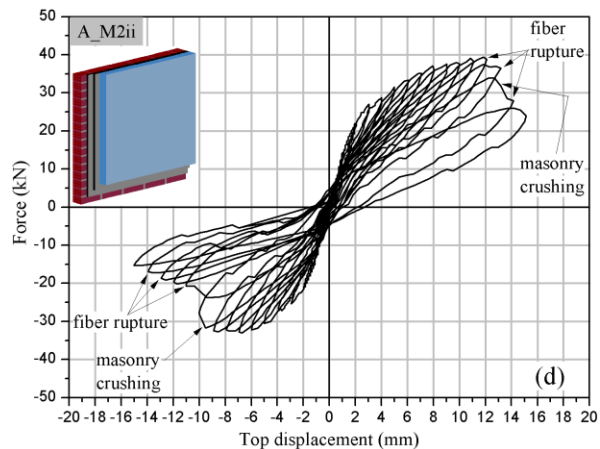
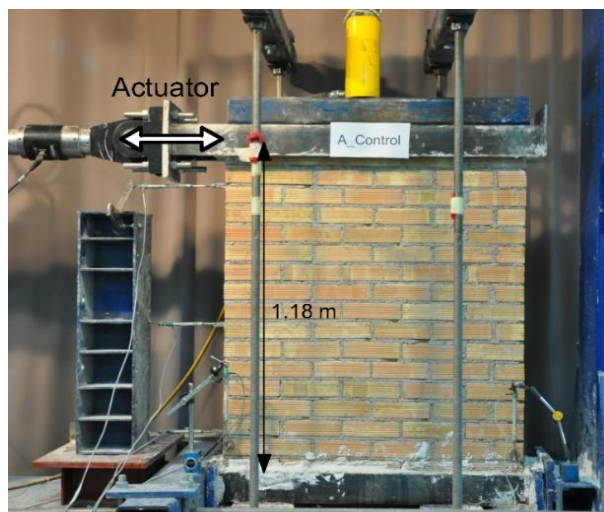
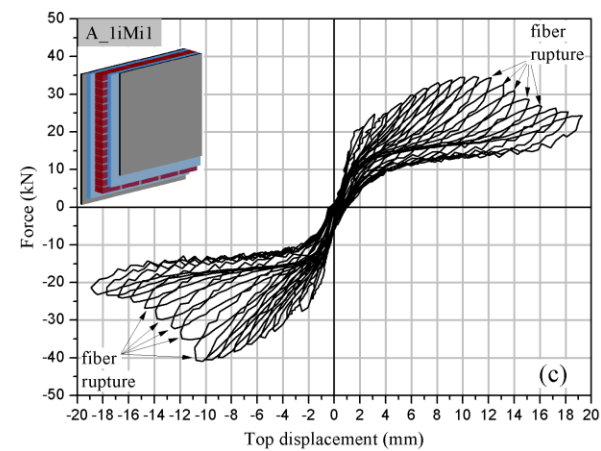
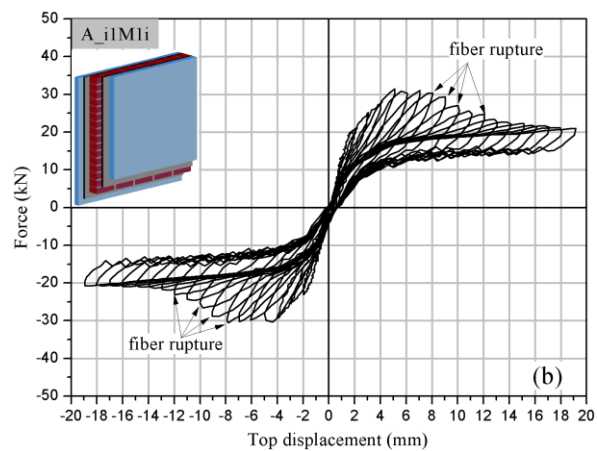
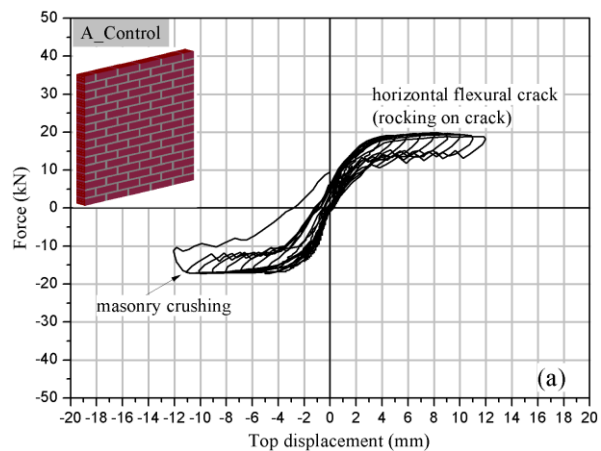
(e)

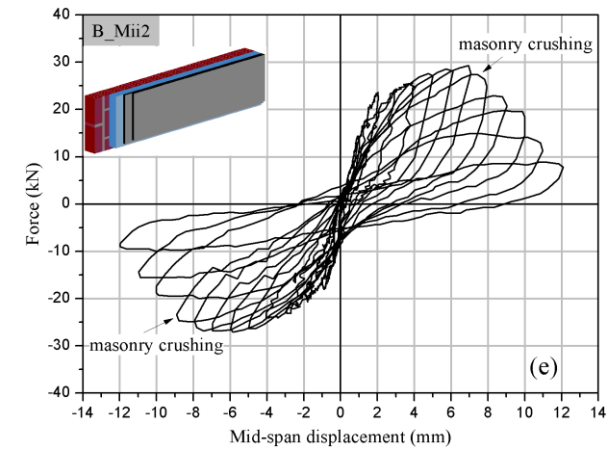
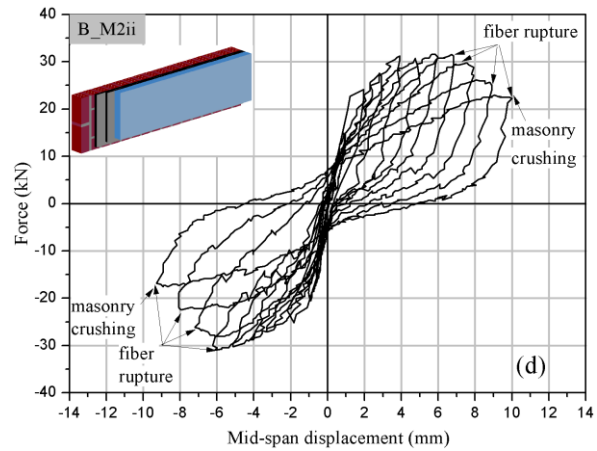
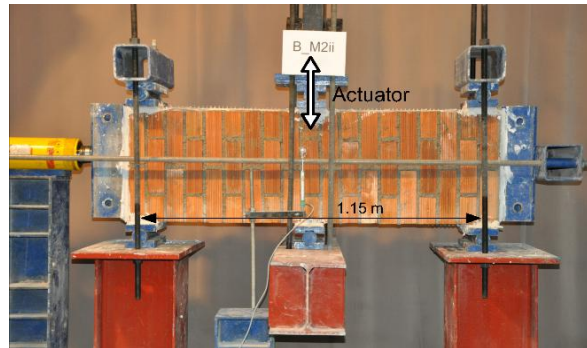
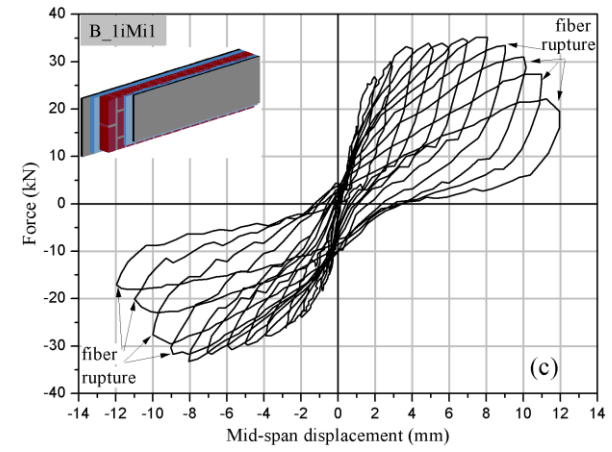
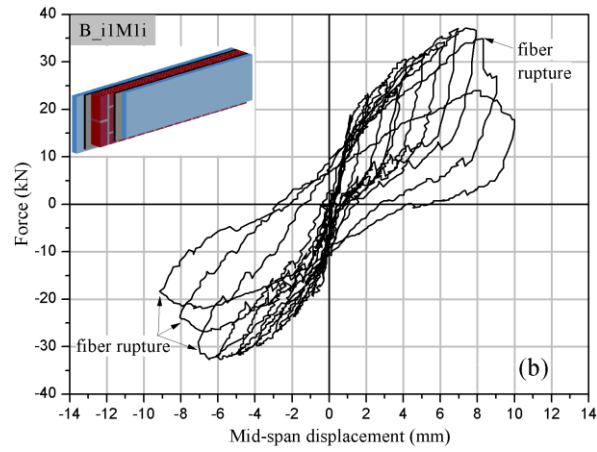
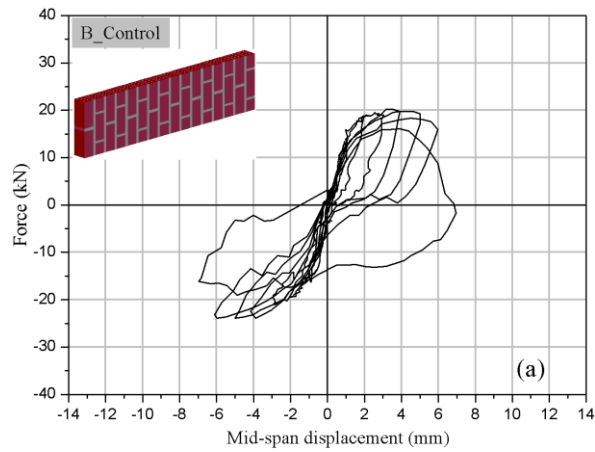


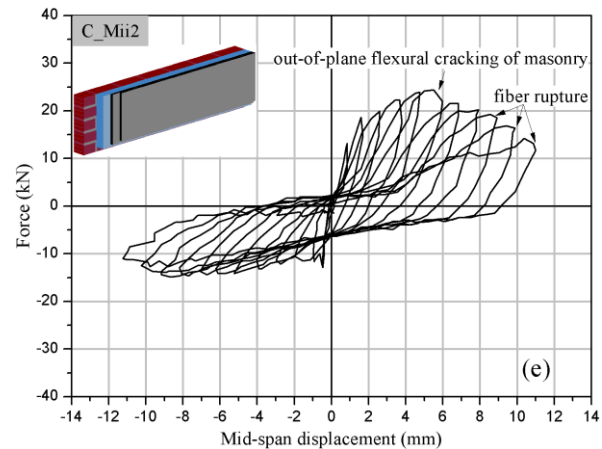
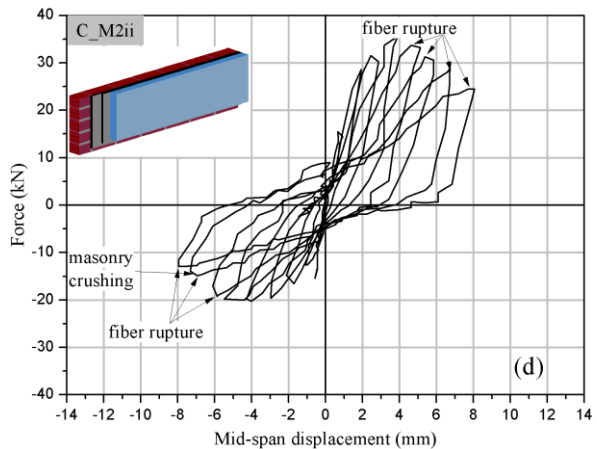
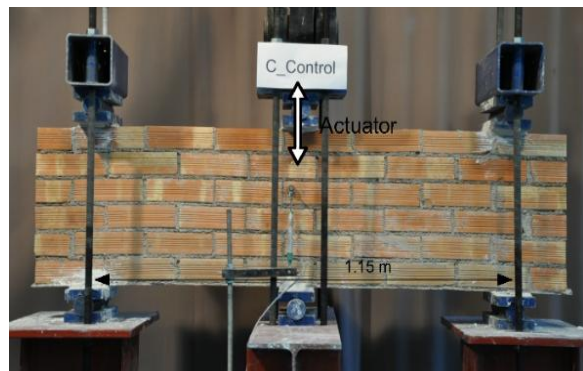
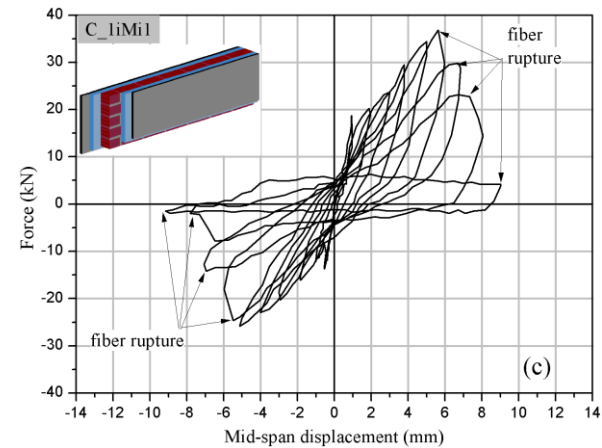
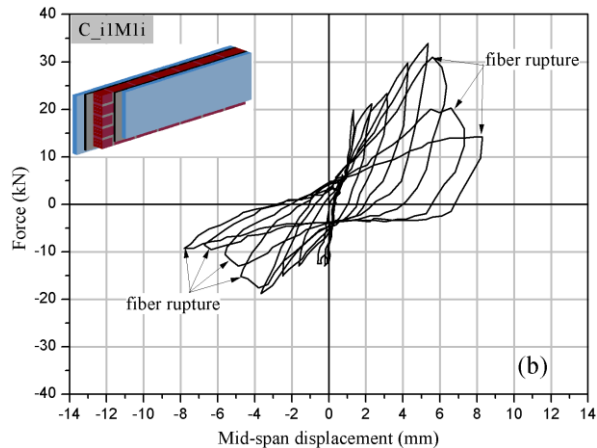
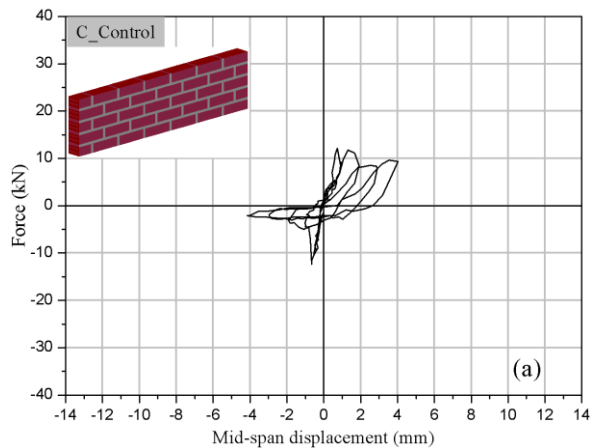
Mii2

Διογκωμένη πολυστερίνη,
 $\rho=29 \text{ kg/m}^3$ $\lambda=0.029 \text{ W/mK}$

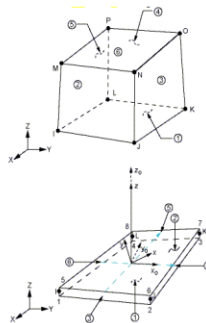
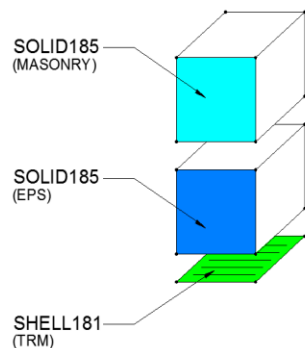
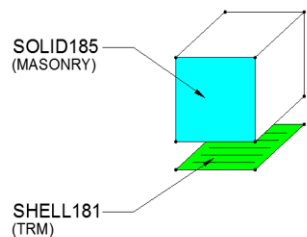
Θερμομονωτικές
πλάκες πάχους 20
mm







ΥΠΟΛΟΓΙΣΤΙΚΗ ΠΡΟΣΟΜΟΙΩΣΗ ΜΕ Π.Σ. (ANSYS)



Τοιχοποιία & θερμομόνωση

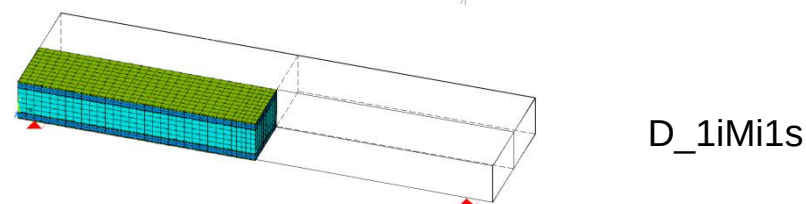
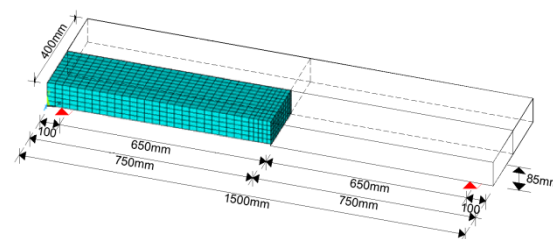
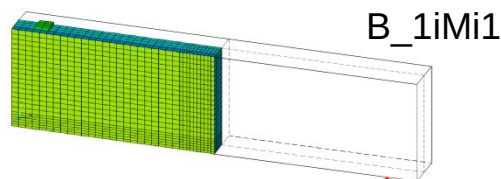
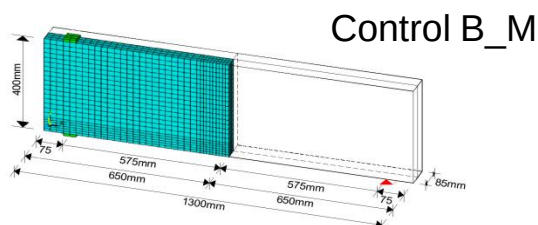
Ισότροπα ομογενή υλικά

TRM

Ορθότροπη «μεμβράνη» (εφελκυσμός μόνο)

Εντός Επιπέδου Φόρτιση

Εκτός Επιπέδου Φόρτιση



¼ ή ½ του δοκιμίου, συνοριακές συνθήκες βάσει συμμετρίας



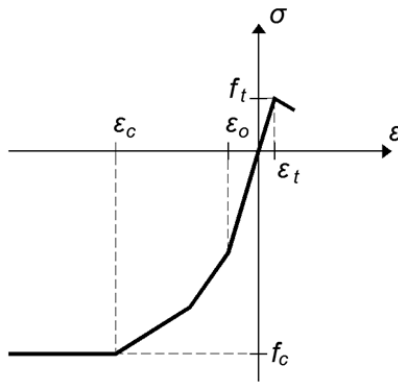
Πλήρης συνάφεια στις διεπιφάνειες



Μονοτονική φόρτιση

Ιδιότητες Υλικών

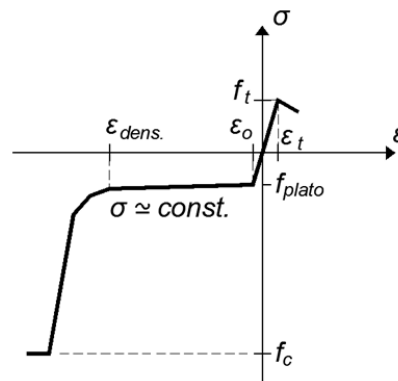
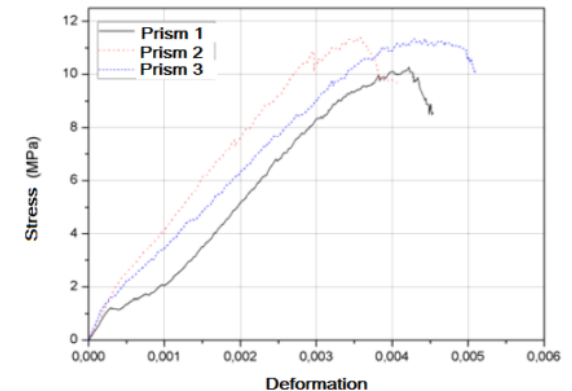
Τοιχοποιία



Θλίψη (f_c)
Δοκιμές σε τοιχίσκους

Εφελκυσμός (f_t)
 $f_t = 0.1 f_c$

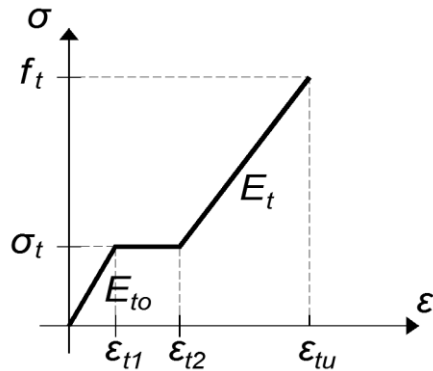
Specimen	Compressive strength f_c (MPa)	Strain at failure ϵ_c (‰)
Series D-“s” Out-of-plane	11.58	4.34
Series B In-plane	11.00	4.00



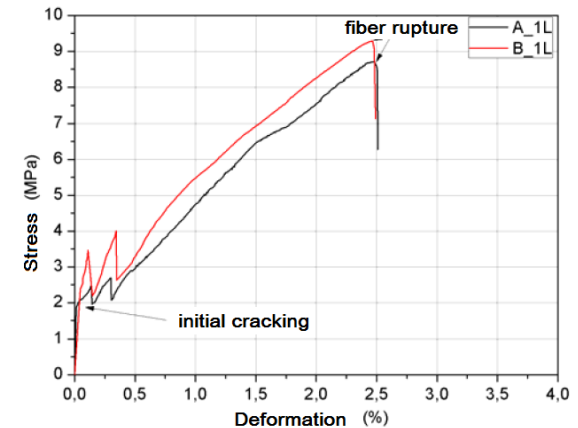
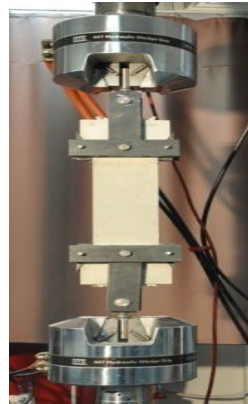
Διογκωμένη πολυστερίνη

Type	Density d (kg/m ³)	Normal stress at $\epsilon=10\%$ σ_{10} (MPa)	Ultimate tension strength σ_t (MPa)	Ultimate shear strength τ_y (MPa)
EPS 200	29	0.2	0.3	0.125

TRM



Εφελκυσμός Δοκιμές σε «κουπόνια»



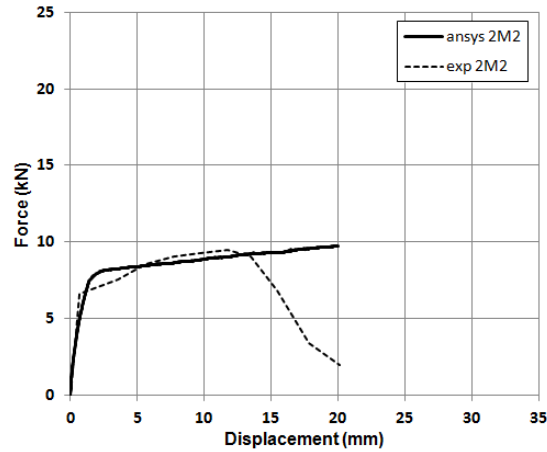
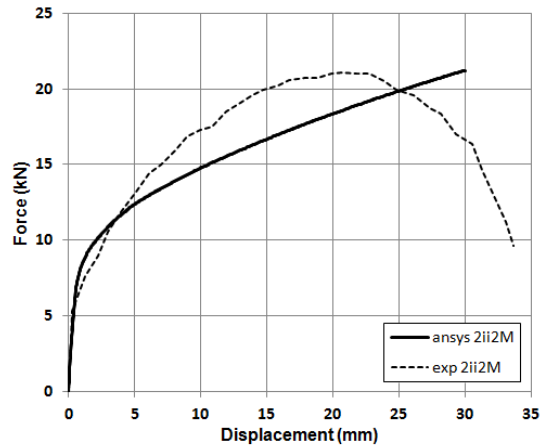
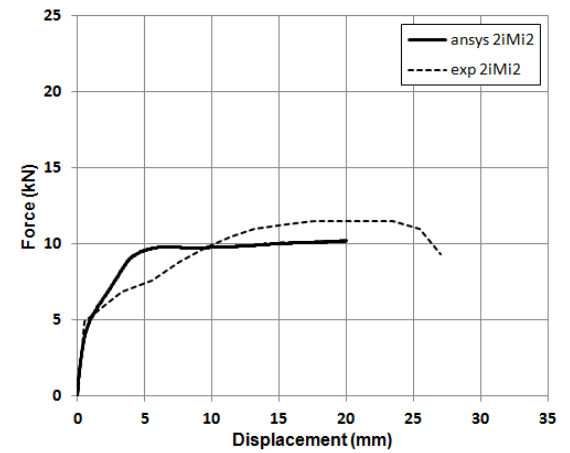
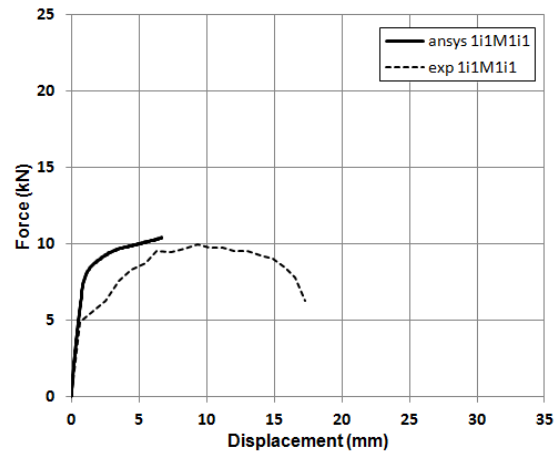
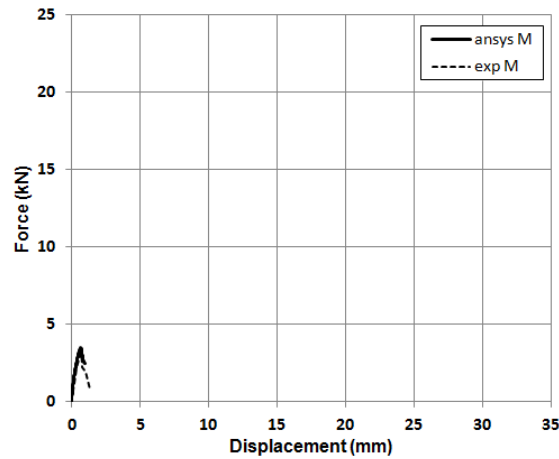
TRM	Thickness t (mm)	Initial stiffness E_{t0} (MPa)	Cracking stress σ_t (MPa)	Stress at failure f_t (MPa)	Cracking strain ϵ_{t1} (%)	Intermediate strain ϵ_{t2} (%)	Strain at failure ϵ_{tu} (%)
1 layer	5	7897	3.38	9.0	0.0428	0.75	3.0
2 layers	8	6353	3.85	9.0	0.0606	1.18	3.0

Δοκίμια περίπτωσης «Εκτός Επιπέδου»

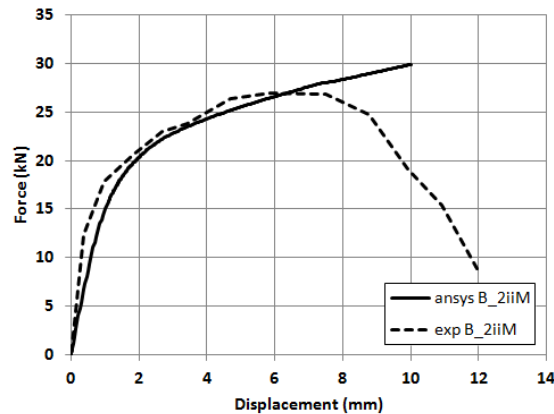
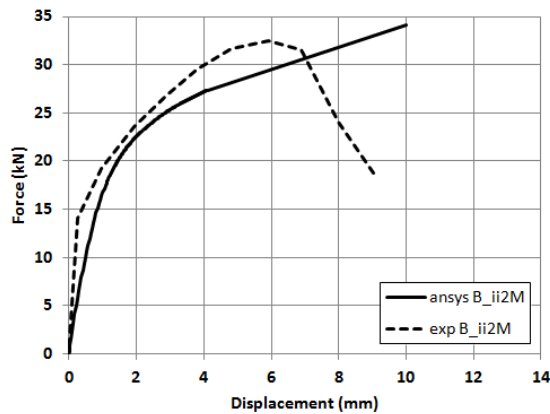
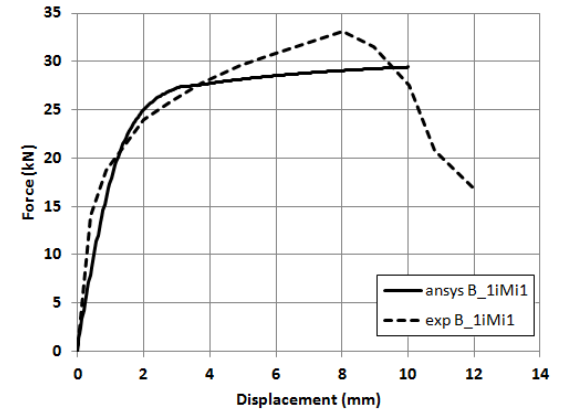
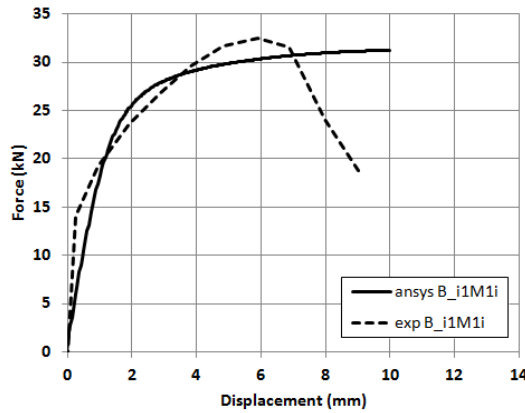
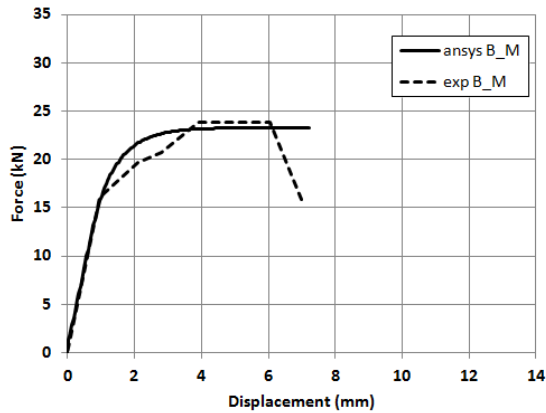
TRM	Thickness t (mm)	Initial stiffness E_{t0} (MPa)	Cracking stress σ_t (MPa)	Stress at failure f_t (MPa)	Cracking strain ϵ_{t1} (%)	Intermediate strain ϵ_{t2} (%)	Strain at failure ϵ_{tu} (%)
1 layer	5	9377	2.80	9.03	0.0298	0.61	2.45
2 layers	8	12036	2.02	8.92	0.0167	0.29	2.92

Δοκίμια περίπτωσης «Εντός Επιπέδου»

Εκτός Επιπέδου Φόρτιση



Εντός Επιπέδου Φόρτιση



ΣΥΜΠΕΡΑΣΜΑΤΑ

- ΕΞΑΙΡΕΤΙΚΗ ΣΥΜΠΕΡΙΦΟΡΑ ΤΩΝ ΙΝΟΠΛΕΓΜΑΤΩΝ ΣΕ ΑΝΟΡΓΑΝΗ ΜΗΤΡΑ - ΙΑΜ (Textile-Reinforced Mortars - TRM)
- Ο/Σ: ΠΕΡΙΠΤΟΥ ΤΟ ΙΔΙΟ ΑΠΟΤΕΛΕΣΜΑΤΙΚΑ ΜΕ ΤΑ ΗΔΗ ΑΠΟΔΕΔΕΙΓΜΕΝΩΣ ΕΞΑΙΡΕΤΙΚΑ ΑΠΟΤΕΛΕΣΜΑΤΙΚΑ ΙΝΟΠΛΙΣΜΕΝΑ ΠΟΛΥΜΕΡΗ (ΙΟΠ)
- ΤΟΙΧΟΠΟΙΪΑ: ΑΚΟΜΑ ΚΑΛΥΤΕΡΑ ΑΠΟ ΤΑ ΙΟΠ
- ΤΟΙΧΟΠΛΗΡΩΜΕΝΑ ΠΛΑΙΣΙΑ: ΕΝΔΙΑΦΕΡΟΥΣΑ ΛΥΣΗ ΑΠΟΔΕΔΕΙΓΜΕΝΗΣ ΑΠΟΤΕΛΕΣΜΑΤΙΚΟΤΗΤΑΣ
- ΤΟ ΠΡΟΤΕΙΝΟΜΕΝΟ ΣΥΣΤΗΜ ΣΥΝΔΥΑΣΜΕΝΗΣ ΑΝΤΙΣΕΙΣΜΙΚΗΣ ΚΑΙ ΕΝΕΡΓΕΙΑΚΗΣ ΑΝΑΒΑΘΜΙΣΗΣ ΜΠΟΡΕΙ ΝΑ ΕΦΑΡΜΟΣΤΕΙ ΜΕ ΕΠΙΤΥΧΙΑ ΣΕ ΣΤΟΙΧΕΙΑ ΤΟΙΧΟΠΟΙΙΑΣ (ΦΕΡΟΥΣΑ, ΤΟΙΧΟΠΛΗΡΩΣΕΙΣ) ΩΣΤΕ ΝΑ ΒΕΛΤΙΩΣΕΙ ΣΗΜΑΝΤΙΚΑ ΤΟΣΟ ΤΗ ΔΟΜΙΚΗ ΟΣΟ ΚΑΙ ΤΗΝ ΕΝΕΡΓΕΙΑΚΗ ΑΠΟΔΟΣΗ ΚΤΙΡΙΩΝ