8th International Symposium on the Conservation of Monuments in the Mediterranean Basin

Monument Damage Hazards and Rehabilitation Technologies

May 31 - June 2, 2010 - Patras, Greece

EXPERIMENTAL INVESTIGATION ON LOCAL ASPECTS OF THE FRP STRENGTHENING OF MASONRY ARCHES

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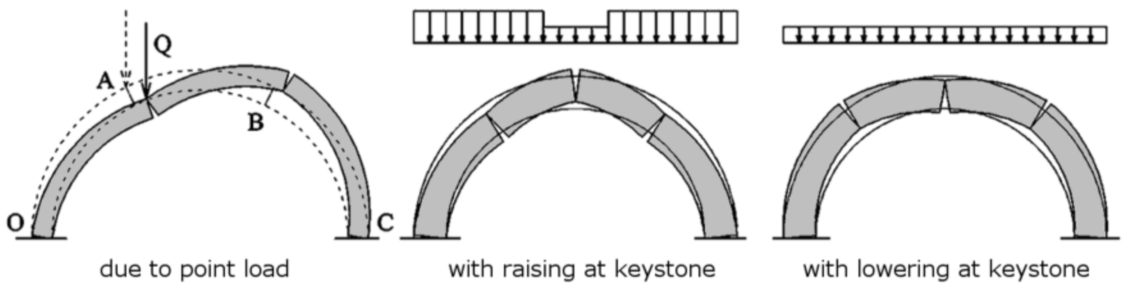
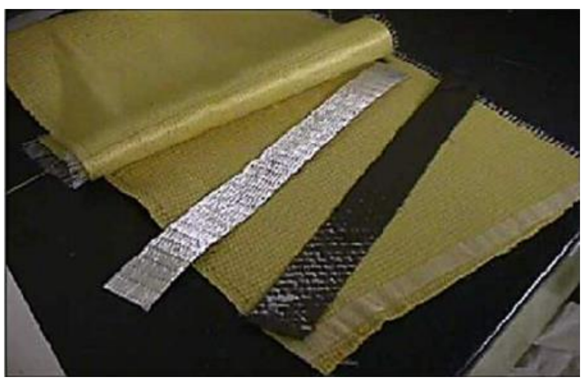
FRP strengthening of masonry arches



Examples of collapse mechanisms of unreinforced arches

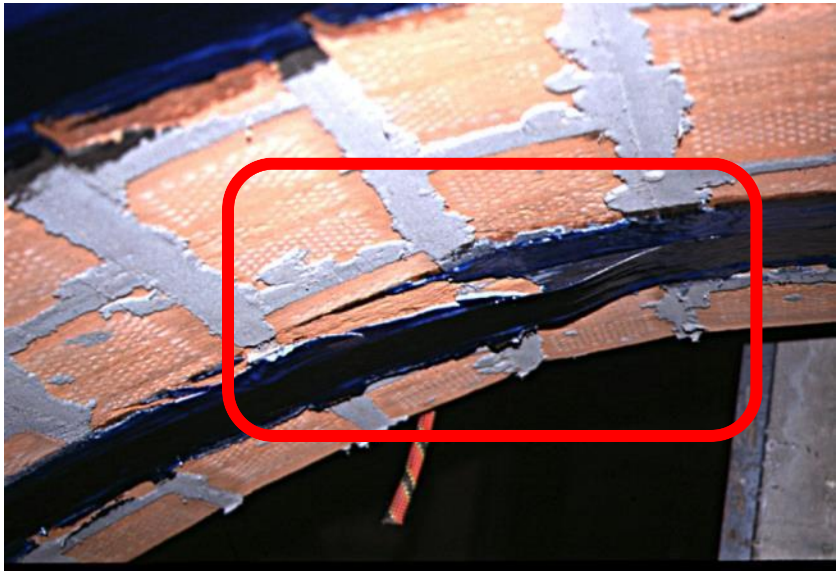


Externally bonded FRP textiles (carbon, glass, aramid, basalt…)

Intrados application

Extrados application

Local failure mechanisms of reinforced structures

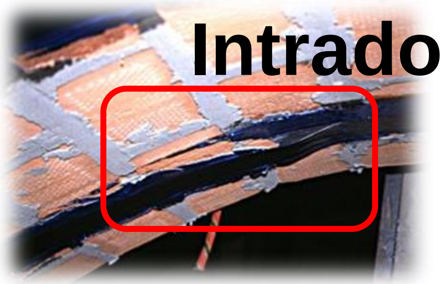


INTRADOS REINFORCEMENT

detachment of the reinforcement from the support, due to normal stresses related to the curved shape of the FRP itself, which is working under tension

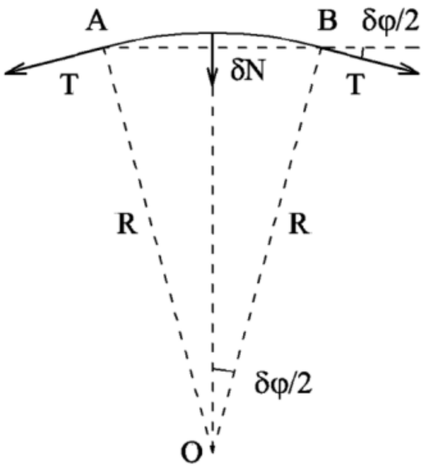
EXTRADOS REINFORCEMENT

sliding on a mortar joint, due to excessive shear force, close to the springer opposite to the loading point in the case of asymmetric configuration



Intrados reinforcement – fibres detachment

The available model (see Valluzzi et al. 2001, Foraboschi 2004, Briccoli Bati & Rovero 2008) relates the critical load to the normal stress acting on the interface, assuming that it has to be lower than the tensile strength empirically measured by pull-off tests.

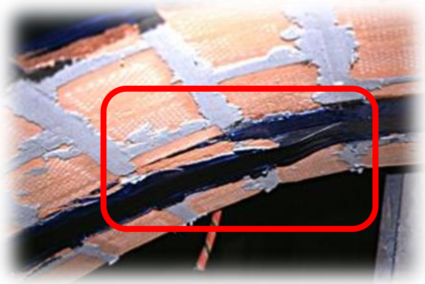


Basic idea: performing of an extensive campaign of mechanical tests on various types of solid clay bricks (extruded and facing ones, from different manufacturers), in order to investigate possible correlations among their main mechanical properties and the pull-off tensile strength

Investigated parameters: seven sets of bricks (4 extruded + 3 facing elements), two types of reinforcement (carbon and glass), presence/absence of primer

Three types of test on each brick: flexural, compressive or splitting, and pull-off tests (after the application of a layer of reinforcement) dCT

Mechanical tests performed

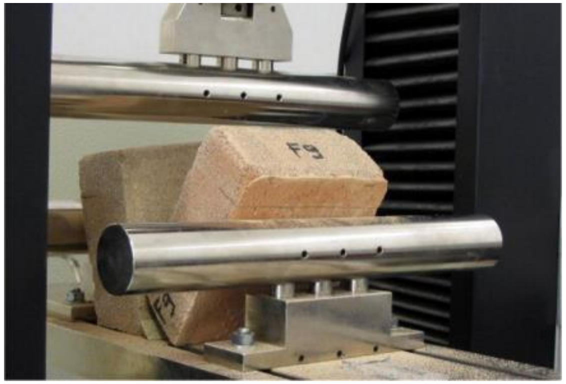


Series	Brick type	Flexural tests	Compressive tests	Splitting tests	Pull-off tests
S1	extruded	⋆	⋆		CFRP w/o primer
		⋆	⋆		CFRP with primer
		⋆	⋆		GFRP with primer
S2	facing	⋆	⋆		CFRP with primer
		⋆	⋆		GFRP with primer
S3	extruded	⋆	⋆		CFRP with primer
		⋆	⋆		GFRP with primer
		⋆		⋆	CFRP with primer
S4	facing	⋆	⋆		CFRP with primer
		⋆		⋆	CFRP with primer
S5	extruded	⋆	⋆		CFRP with primer
		⋆		⋆	CFRP with primer
S6	facing	⋆	⋆		CFRP with primer
		⋆		⋆	CFRP with primer
S7	facing	⋆	⋆		CFRP with primer No fibres, with primer
		⋆		⋆	GFRP with primer No fibres, with primer

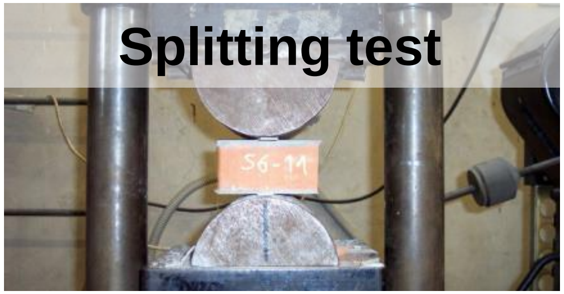
Extruded brick

Facing brick

Three-point flexion

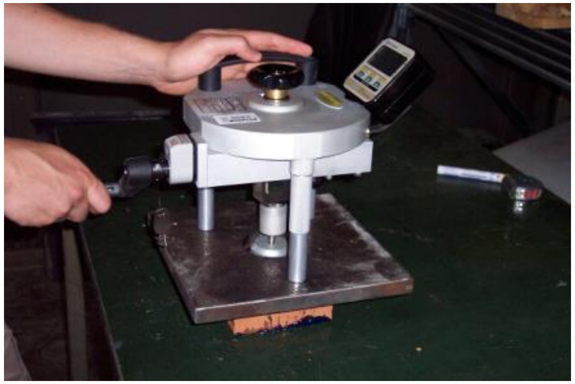


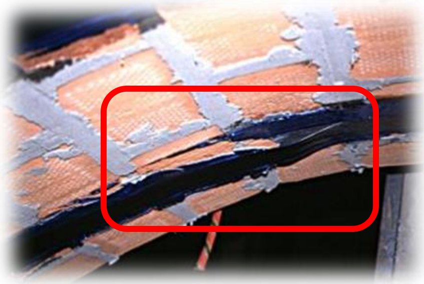
Compression



Splitting test

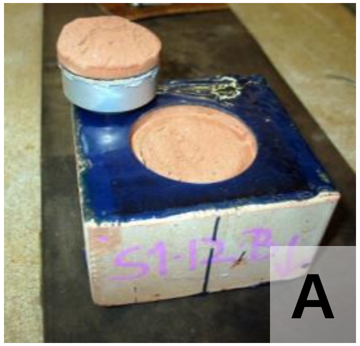
Pull-off test



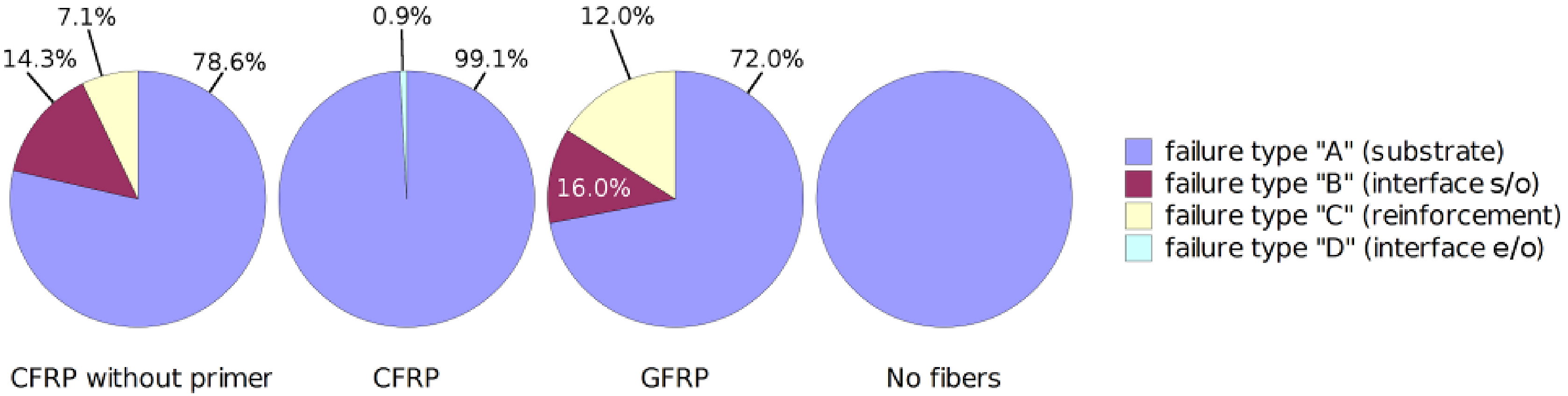


Results of pull-off tests

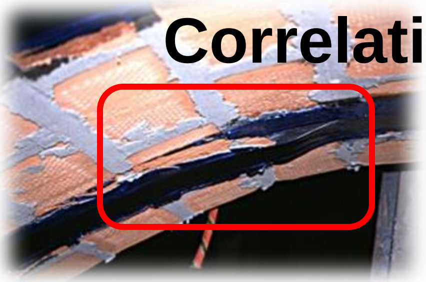
Failures (according to ASTM C1583/2004)



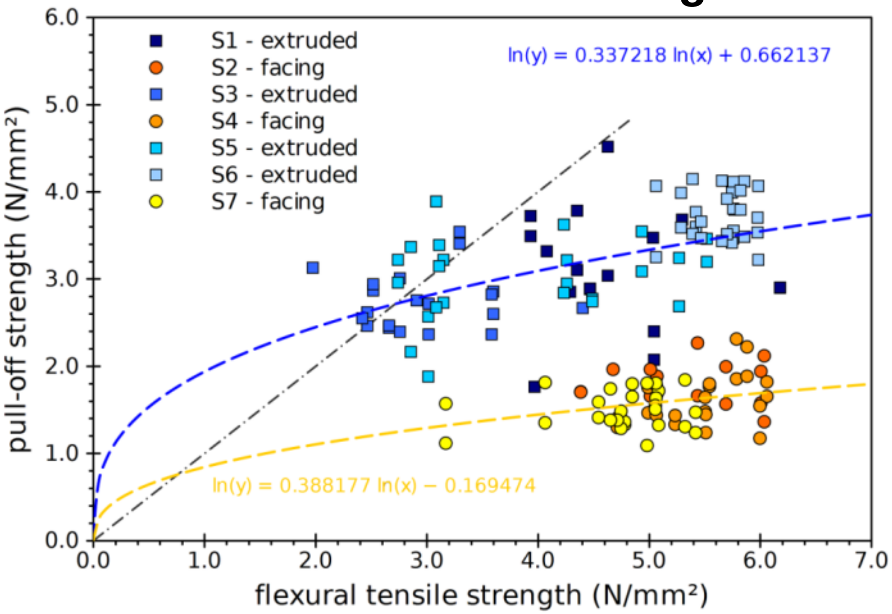
Incidence of the failure types



Correlations between: pull-off and flexural strength
pull-off and splitting strength



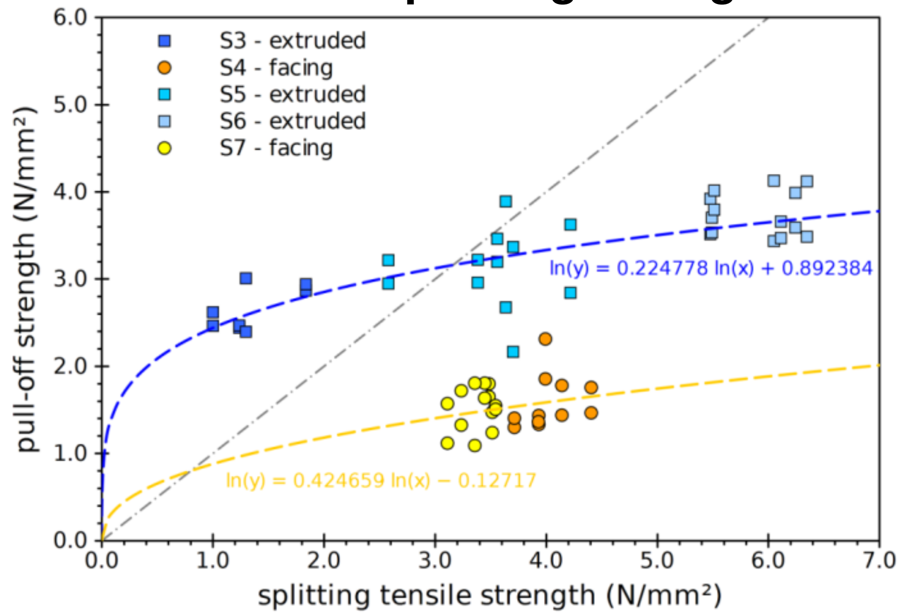
Pull-off vs flexural strength



$$f_{p-o} = 1.939\, f_f^{\,0.337} \quad \text{(extruded bricks)}$$

$$f_{p-o} = 0.844\, f_f^{\,0.388} \quad \text{(facing bricks)}$$

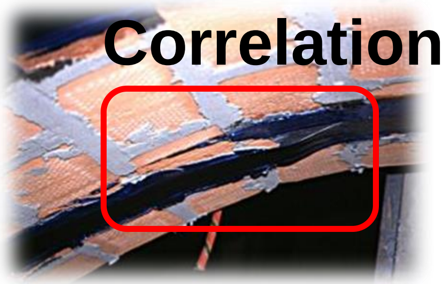
Pull-off vs splittling strength



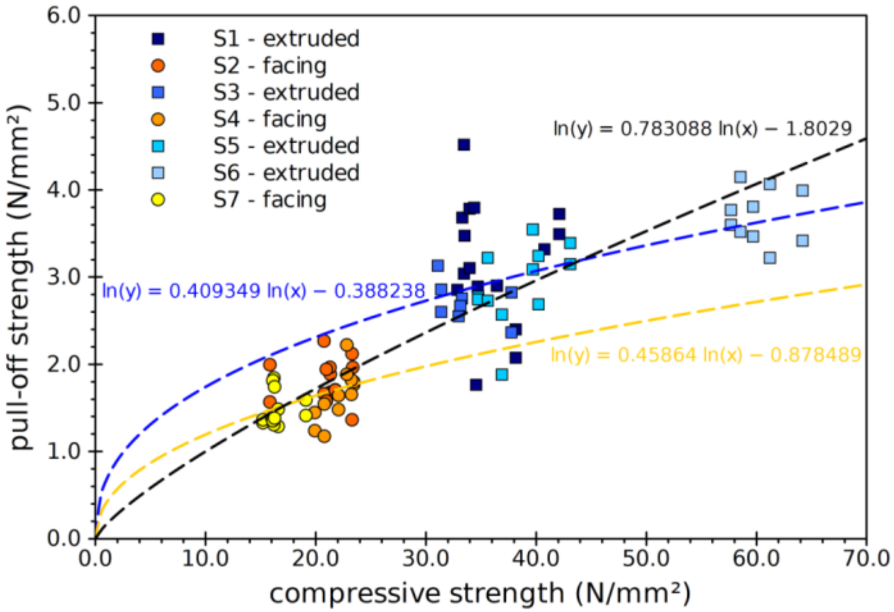
$$f_{p-o} = 2.441\, f_s^{\,0.225} \quad \text{(extruded bricks)}$$

$$f_{p-o} = 0.881\, f_s^{\,0.425} \quad \text{(facing bricks)}$$

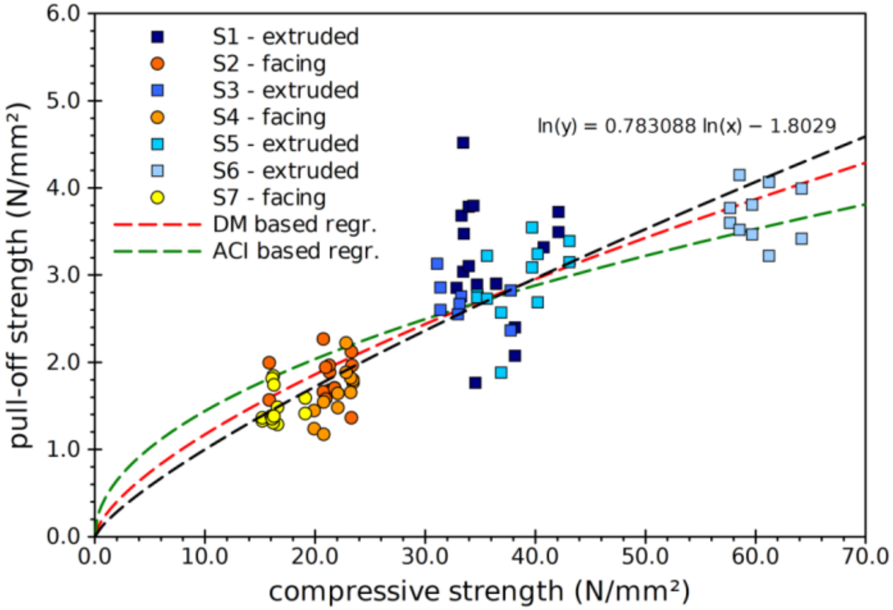
Correlations between pull-off and compressive strength



Power-based regressions



Regressions based on code provisions (ACI, Italian DM96) for concrete

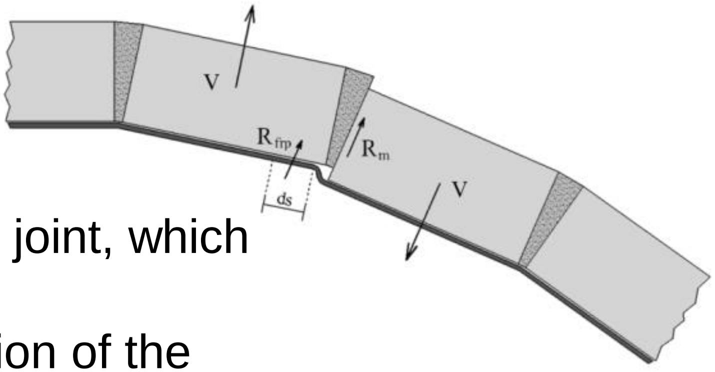


$$f_{p-o} = 0.165\, f_c^{\,0.783}$$

$$f_{p-o} = 0.456\sqrt{f_c} \qquad \text{(based on ACI provision)}$$

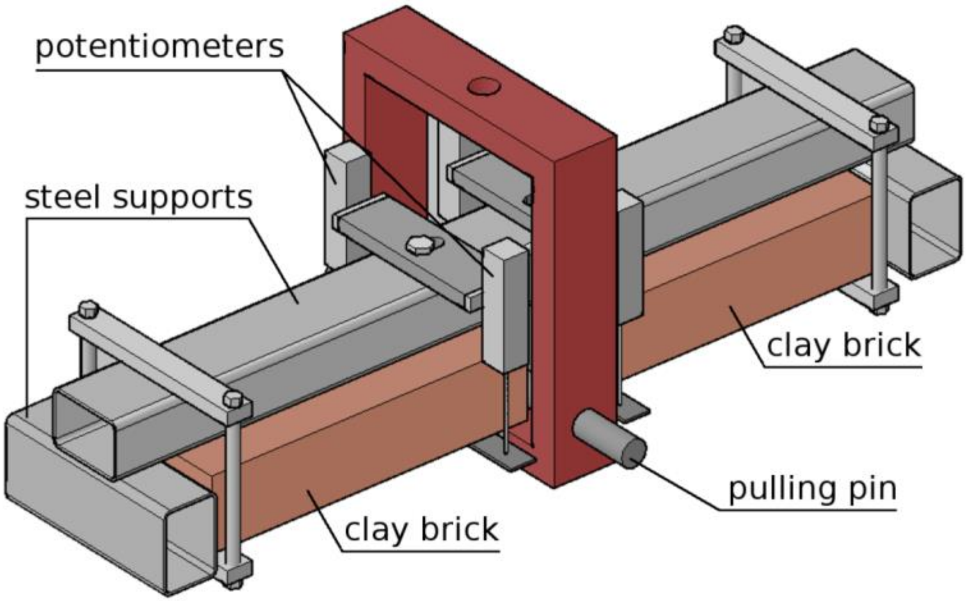
$$f_{p-o} = 0.253\sqrt[3]{f_c^{\,2}} \qquad \text{(based on DM provision)}$$

Shear failure – extrados reinforcement



Available model: Coulomb-like strength of the mortar joint, which consider only the masonry contribution.
Starting point: trying to measure a possible contribution of the reinforcement to the resistance mechanism of the joint.

Investigation method: performing of fourteen V-shape Peel Tests on solid clay bricks with EB CFRP.
Test set-up was derived from similar set-ups developed for reinforced concrete (Wu et al. 2004, Dai & Ueda 2007)
Tests were aimed at isolating the reinforcement contribution



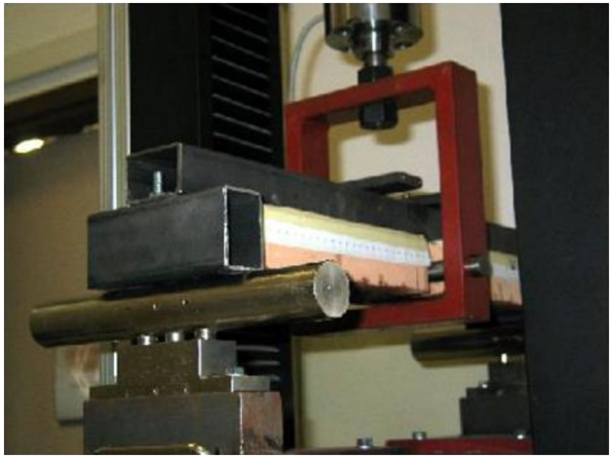
V-shape Peel Tests (1)

Experimental program

Specimen	brick type	loading path
Vp01	S4 - facing	monotonic (A)
Vp02	S3 - extruded	cyclic (A)
Vp03	S3 - extruded	cyclic (A)
Vp04	S4 - facing	cyclic (A)
Vp05	S4 - facing	monotonic (A)
Vp06	S4 - facing	cyclic (A)
Vp07	S3 - extruded	cyclic (B)
Vp08	S3 - extruded	cyclic (B)
Vp09	S3 - extruded	monotonic (B)
Vp10	S3 - extruded	cyclic (B)
Vp11	S4 - facing	cyclic (B)
Vp12	S5 - extruded	monotonic (B)
Vp13	S2 - facing	monotonic (C)
Vp14	S2 - facing	cyclic (C)

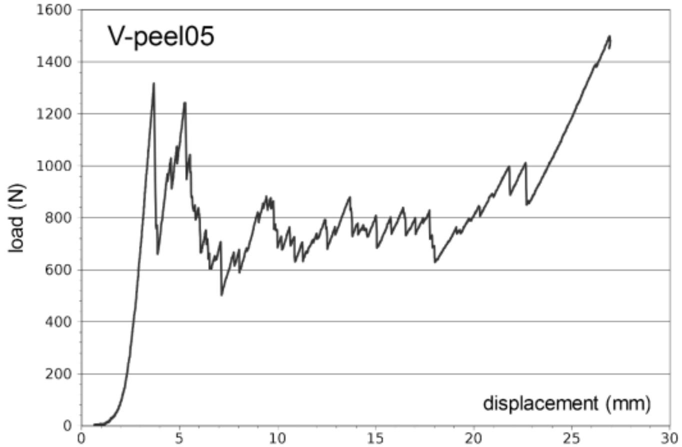
Specimens preparation

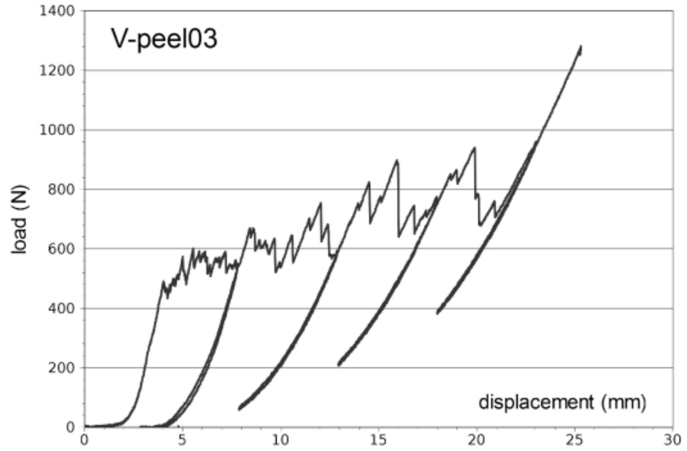
Test execution



V-shape Peel Tests (2)

Typical load-displ. curves for monotonic (left) and cyclic test





Failure of extruded bricks

Failure of facing bricks

V-shape Peel Tests: first results

SPECIMEN	brick type	P_u N	P_u/b_f N/mm	failure cycle	failure localization
Vp01	S4 - facing	1555	31.1	-	substrate
Vp02	S3 - extruded	1302	26.0	third	interface
Vp03	S3 - extruded	963	19.3	fourth	interf. and substrate
Vp04	S4 - facing	1280	25.6	second	substrate
Vp05	S4 - facing	1317	26.3	-	substrate
Vp06	S4 - facing	1795	35.9	first	interf. and substrate
Vp07	S3 - extruded	935	18.7	fourth	interface
Vp08	S3 - extruded	853	17.1	first	interface
Vp09	S3 - extruded	717	14.3	-	interface
Vp10	S3 - extruded	830	16.6	fourth	interface
Vp11	S4 - facing	1243	24.9	first	interf. and substrate
Vp12	S5 - extruded	937	18.7	-	interface
Vp13	S2 - facing	912	18.2	-	substrate
Vp14	S2 - facing	912	18.2	first	substrate

Conclusions

Pull-off testing:

- the type of fibres seemed not to affect, as expected, the pull-off strength of the bricks, while some differences occurred on the failure mode;
- pull-off tensile strength could be correlated to the flexural, splitting and compressive strength of the bricks by means of power-based regressions;
- except the relation with the compressive strength, which seems to be correctly depicted by a single function, in the other cases extruded and facing bricks showed different correlations, although the trends were similar.

V-shape Peel Tests:

- peel loads, during the detachment, oscillated within a limited range, though the scattering was in some cases very large;
- maximum loads of around 18 N/mm, except for the S4 (about 28.8 N/mm), were recorded.
- in the case of monotonic tests, first peak loads were generally higher than the others;
- facing bricks, whose surface is more scabrous and irregular, generally showed higher peak loads and their failure involved a thin layer of clay, differently from the extruded bricks, whose failures mainly occurred within the clay-epoxy interface.

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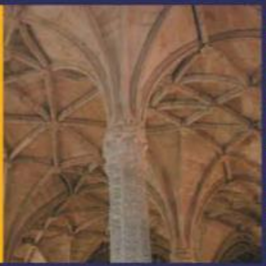

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