Dipartimento di Ingegneria
Dottorato in Ingegneria Civile - Ciclo XXXV

ROMA TRE UNIVERSITÀ DEGLI STUDI

EXPERIMENTAL LONG-TERM BEHAVIOUR OF FRCM SYSTEMS

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AIM OF THE RESEARCH

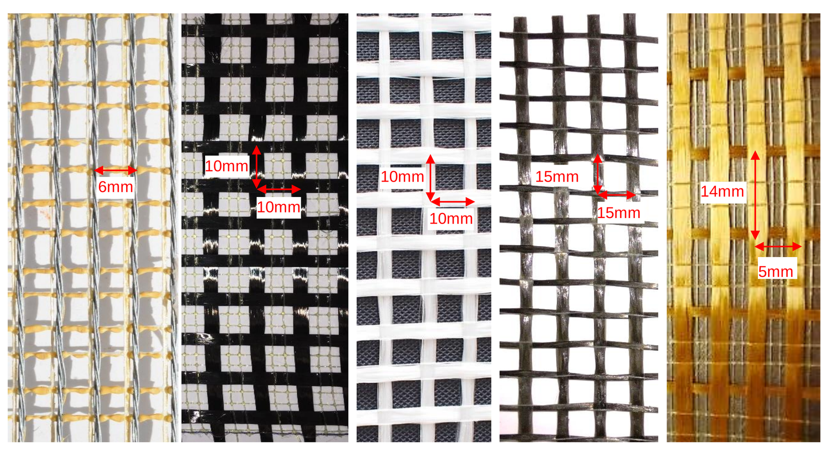
Fabric Reinforced Cementitious Matrix (**FRCM**) composites, made of **high strength textiles** externally bonded with **inorganic matrices**, represent an innovative solution, recently introduced in the market and installed in the field, for the **repair** and the **strengthening** of existing structures. Despite their well-known advantages, amongst others their high strength-to-weight ratio, their effectiveness over time still remains an open issue. Indeed, few information on their **durability** and on their **fatigue** and **seismic behaviour** is available in the scientific literature.

Aiming at filling this gap of knowledge, the present work is focused on the **experimental investigation** of the mechanical behaviour of FRCM systems subject to environmental conditioning (salt water solutions, high relative humidity, alkaline solutions and freeze-thaw cycles), as well as, on their response to cyclic actions.

FRCM COMPOSITES

FABRIC

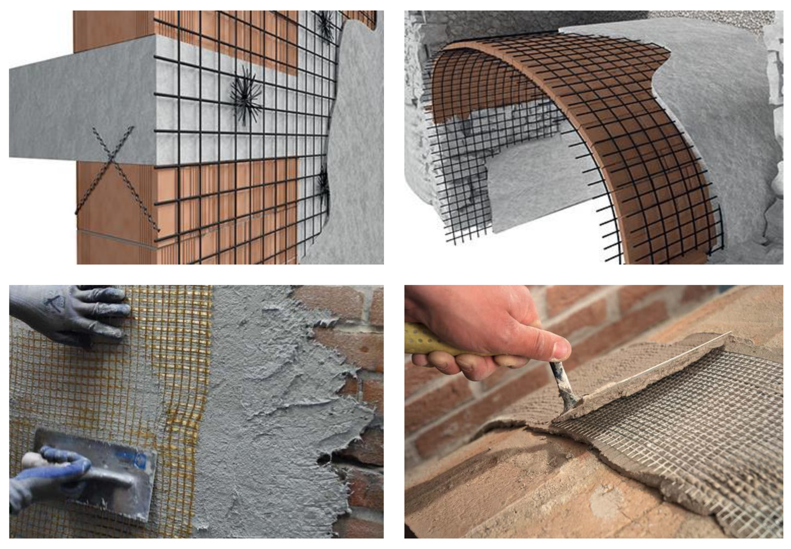
Steel | Carbon | Glass | Basalt | PBO



MORTAR

Lime, cement or geopolymer
(possibly enriched with short fibres and/or polymeric additives)

Fabric Reinforced Cementitious Matrix



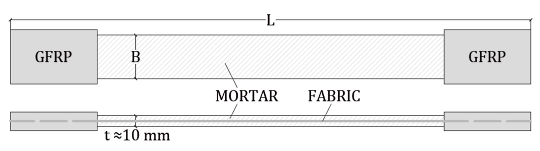
Main advantages:

- high strength-to-weight ratio, providing a significant improvement of the capacity of the structure with minimum mass, and also stiffness, increase;
- reversibility;
- ease of integration with traditional strengthening techniques, thanks to the limited thickness (5-10 mm) and the relatively ease of application, even on wet or irregular surfaces;
- resistance to high temperature and high vapour permeability;
- compatibility with historic masonry (when lime mortar is used).

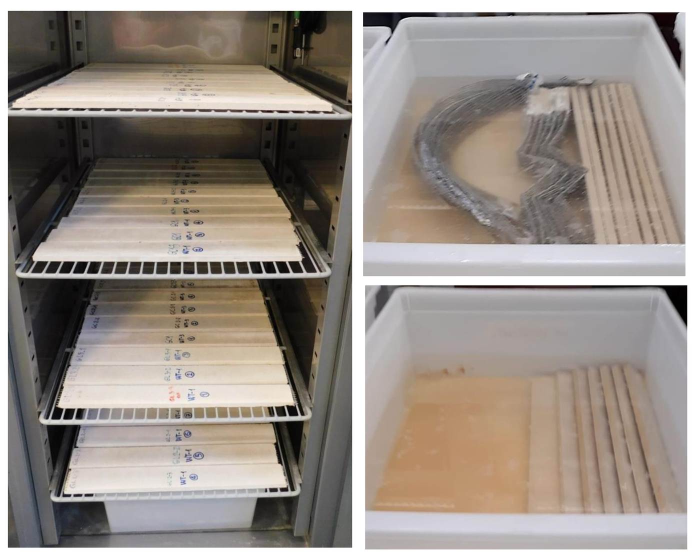
DURABILITY

SPECIMENS

- **Galvanized steel** cords and **lime** mortar (G-L);
- **Galvanized steel** cords and **cementitious** mortar (G-C);
- **Stainless steel** cords and **lime** mortar (I-L);
- **Basalt** fibres and **lime** mortar (B-L).



ENVIRONMENTAL CONDITIONING



- **Freeze/thaw** (FT): 1 week in a humidity chamber [UR>95%, 38±2°C]+20 freeze-thaw cycles [4h at -18±2°C, 12h at UR>95%, 38±2°C];
- **Relative humidity** (WT): 1000 and 3000 hours in a humidity chamber (ASTM D 2247-11) [UR>95%, 38±2°C];
- Immersion in **saltwater** (SW): 1000, 3000 and 5000 hours in Substitute Ocean Water (ASTM D 1141-98) [23±2°C];
- Immersion in **alkaline solution** (AK): 1000 and 3000 hours in a liquid with pH≥9,5 [23±2°C].

RESULTS OF TENSILE TESTS (1): *tensile strength*

***Basalt** fibers and **lime** mortar*

Conditioning		NC	FT	WT1	WT3	AK1	AK3	SW1	SW3
Mean value	σ_f [N/mm²]	1215.2	1102.1	1071.7	1075.0	1127.4	971.0	929.7	616.4
	σ_f [%]	-	9.3	11.8	11.5	7.2	20.1	23.5	49.3

***Stainless steel** cords and **lime** mortar*

Conditioning		NC	FT	WT1	WT3	AK1	AK3	SW1	SW3	SW5
Mean value	σ_f [N/mm²]	1712.4	1708.7	1596.7	1742.0	1691.0	1687.9	1636.6	1700.2	1640.6
	σ_f [%]	-	0.2	6.8	-1.7	1.2	1.4	4.4	0.7	4.2

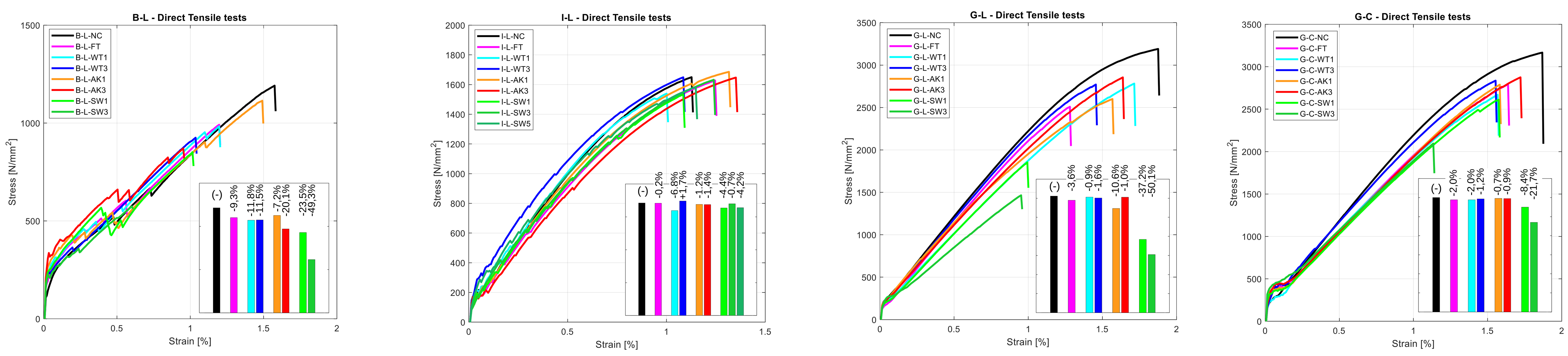
***Galvanized steel** cords and **lime** mortar*

Conditioning		NC	FT	WT1	WT3	AK1	AK3	SW1	SW3
Mean value	σ_f [N/mm²]	3056.1	2947.0	3029.8	3006.5	2732.4	3026.8	1920.7	1524.0
	σ_f [%]	-	3.6	0.9	1.6	10.6	1.0	37.2	50.1

***Galvanized steel** cords and **cementitious** mortar*

Conditioning		NC	FT	WT1	WT3	AK1	AK3	SW1	SW3
Mean value	σ_f [N/mm²]	3001.0	2942.0	2941.4	2965.5	2979.8	2974.2	2750.1	2350.0
	σ_f [%]	-	2.0	2.0	1.2	0.7	0.9	8.4	21.7

RESULTS OF TENSILE TESTS (2): *stress vs. strain response curves*

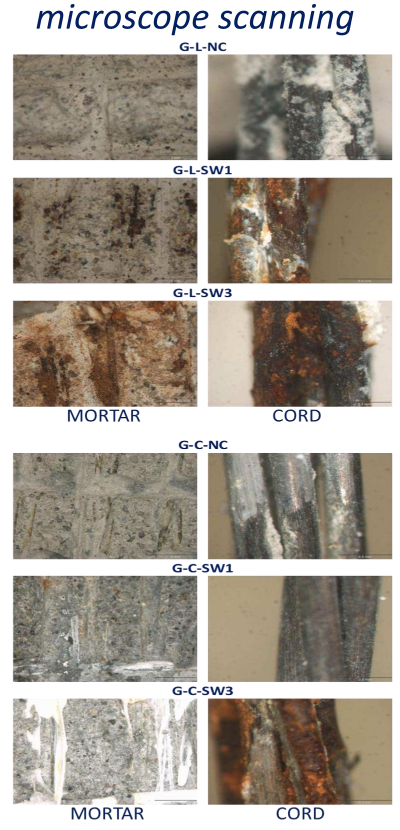


Critical conditioning: **alkaline** and **saline**.
Alkaline environment → fibres corrosion acceleration
Saline environment → salts attacks and increase of the material pH.

Critical conditioning: **none**.
Stainless steel is particularly resistant to aggressive environments.

Critical conditioning: **saline**.
Rusting reduces the steel wires cross section. This phenomenon may cause a significant damage of cords, given the small diameter of the steel wires making up them, which can affect the long-term effectiveness of FRCM system.

RESULTS OF TENSILE TESTS (3): *microscope scanning*



CYCLIC ACTIONS

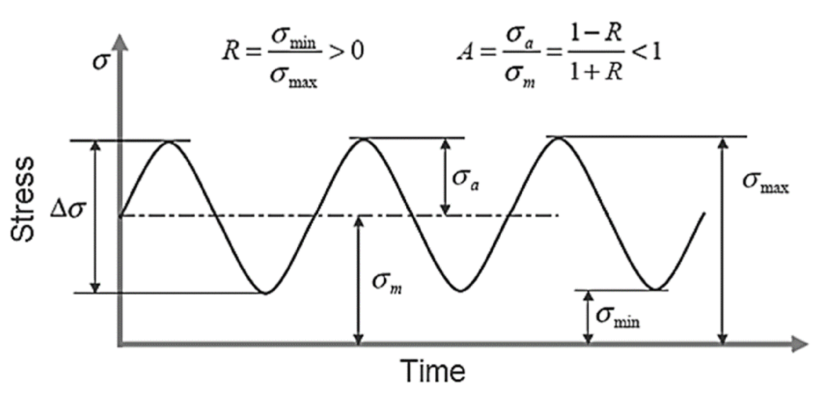
EXPERIMENTAL PROGRAM

- **Seismic behaviour**: cyclic tensile tests;

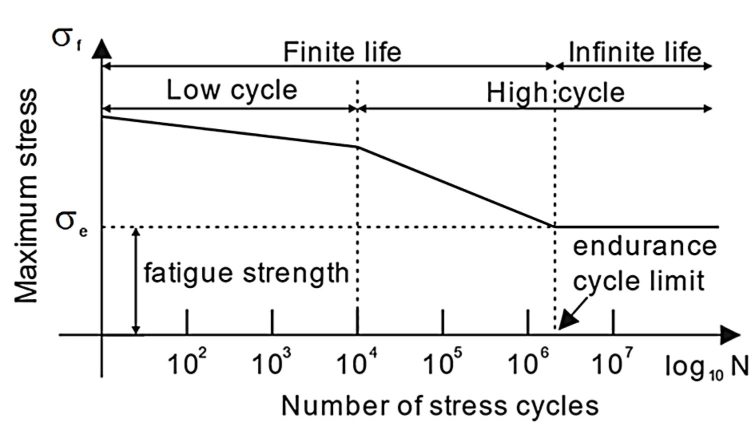
Duration: 15 cycles, load amplitude: 5%-90%*$\sigma_{u,k}$, load frequency: 1Hz.

- **Fatigue behaviour**: cyclic tensile tests;

Duration: 2x10⁶ cycles, load amplitude: 6%-60%*$\sigma_{lim,conv}$ load frequency: 3 Hz and 10 Hz.



Wöhler diagram



In the Wöhler diagram, 3 fields are distinguished:

- $N_f < 10^{3\div4}$: quasi-static resistance;
- $10^{3\div4} < N_f < 10^6$: resistance to finite fatigue;
- $N_f > 10^6$: resistance to infinite fatigue.

SEISMIC BEHAVIOR

Test results

***Galvanized steel** cords and **lime** mortar*

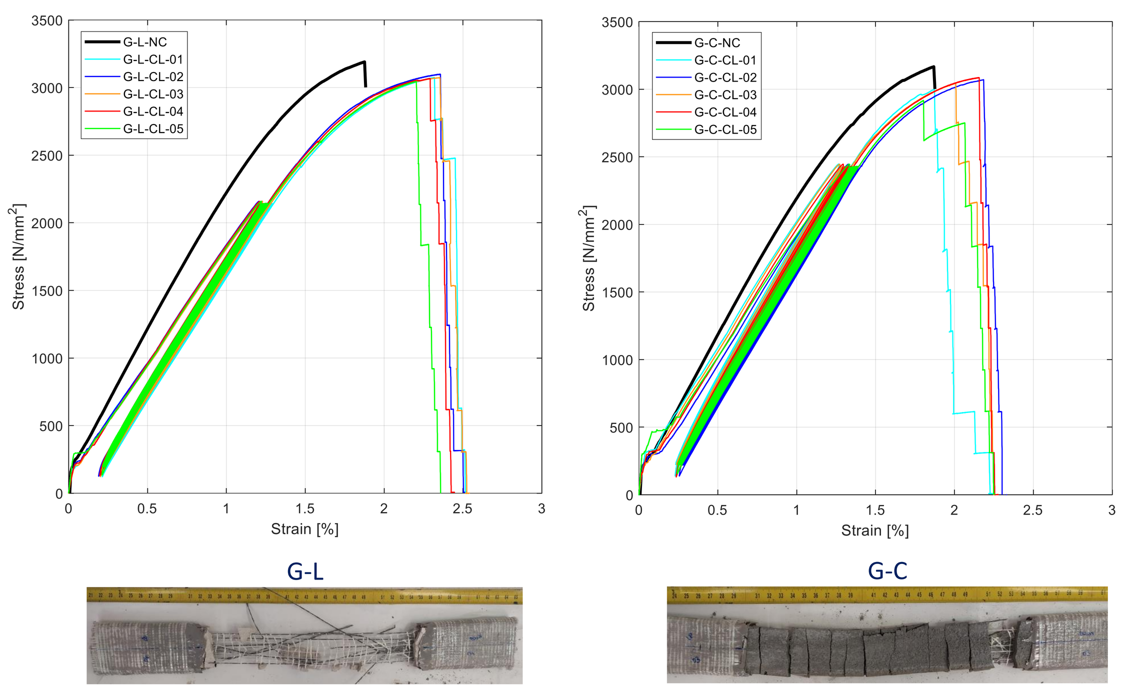
Specimen name	σ_f [N/mm²]	ε_f [%]	E_3 [kN/mm²]
Not Conditioned			
Mean value	**3056.1**	**2.02**	**184.8**
Standard deviation	10.3	0.11	4.4
Characteristic value	**3032.1**		
Seismic Action			
G-L-CL-01	3074.1	2.32	176.3
G-L-CL-02	3099.1	2.36	178.2
G-L-CL-03	3073.6	2.35	176.2
G-L-CL-04	3066.8	2.29	175.3
G-L-CL-05	3045.4	2.20	173.5
Mean value	**3071.8**	**2.30**	**175.9**
Standard deviation	19.2	0.06	1.7
Characteristic value	**3027.0**		

***Galvanized steel** cords and **cementitious** mortar*

Specimen name	σ_f [N/mm²]	ε_f [%]	E_3 [kN/mm²]
Not Conditioned			
Mean value	**3001.0**	**1.95**	**198.9**
Standard deviation	28.3	0.03	7.0
Characteristic value	**2935.2**		
Seismic Action			
G-C-CL-01	2996.8	1.87	188.1
G-C-CL-02	3069.8	2.18	189.5
G-C-CL-03	3044.9	2.01	190.3
G-C-CL-04	3086.1	2.15	191.0
G-C-CL-05	2917.6	1.80	186.5
Mean value	**3023.0**	**2.00**	**189.1**
Standard deviation	67.9	0.17	1.8
Characteristic value	**2864.8**		

Loading-unloading cycles seems to not affect FRCM tensile strength, whereas a sensible reduction of the tensile modulus of elasticity is detected, for both lime-based and cement-based composites.

Stress-Strain response



Mortar type influences the crack pattern and the deformability of the specimens. Indeed, specimens made of stronger mortar matrices (i.e. cement mortar) exhibited a low number of localized cracks, to lower peak strain values corresponded. On the other hand, specimens provided with weaker mortars (i.e. lime mortar) exhibited a more spread crack pattern and achieved higher values of the peak strain.

FATIGUE ACTIONS

Test results

***Galvanized steel** cords and **lime** mortar — Mean value*

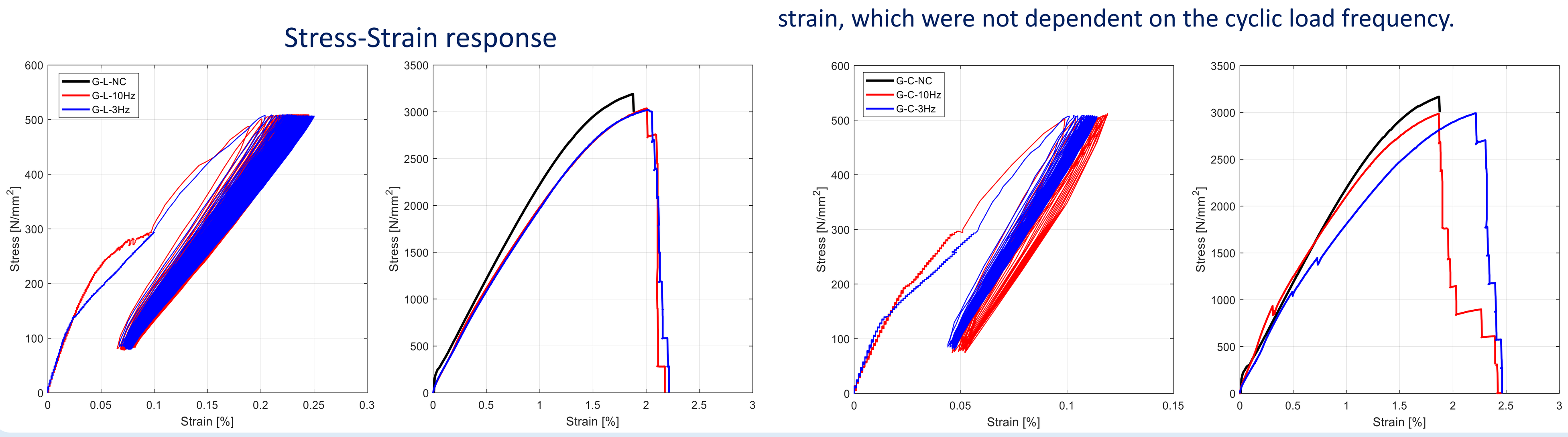
Specimen name	σ_f [N/mm²]	ε_f [%]	E_3 [kN/mm²]
G-L-NC	3056.1	2.02	184.8
G-L-CL_10Hz	3036.3	2.01	160.0
G-L-CL_3Hz	3019.2	2.02	166.2

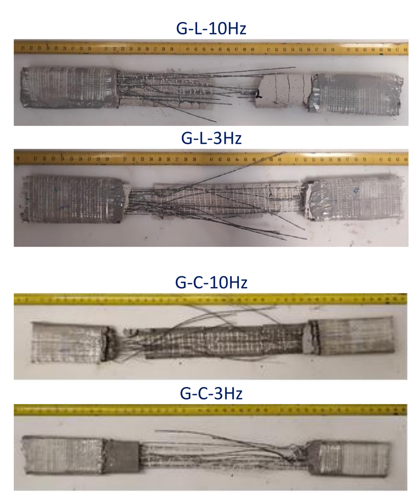
***Galvanized steel** cords and **cementitious** mortar — Mean value*

Specimen name	σ_f [N/mm²]	ε_f [%]	E_3 [kN/mm²]
G-C-NC	3001.0	1.95	198.9
G-C-CL_10Hz	2986.2	1.89	148.4
G-C-CL_3Hz	2991.7	2.21	146.5

Cyclic actions proved to not influence the tensile strength of the FRCM, independently from the type of mortar used, whereas a slight reduction of the tensile modulus of elasticity is detected.
The value of the load frequency only affects the specimen ultimate deformation, depending on the mortar type it is made of. Specimens provided with cement mortar seems to not be able to develop cracks under 10Hz cyclic load; in this case so the overall specimen deformation is lower than that achieved during tests with 3Hz cyclic load, in which the progressive development of the cracks leads to higher peak strain values. On the other hand, specimens made of lime-based mortar exhibited a more spread crack pattern and higher values of the peak strain, which were not dependent on the cyclic load frequency.

Stress-Strain response





PUBLICATIONS AND WORKS

Meriggi P., De Santis S., **Fares S.**, de Felice G., 2020, "Design of the shear strengthening of masonry walls with fabric reinforced cementitious matrix", Construction and Building Materials. *Submitted.*