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STAINLESS STEEL-FRCM SYSTEM FOR STRENGTHENING OF RC BEAMS: TOWARDS A SUSTAINABLE STRENGTHENING TECHNIQUE

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Abstract.

Fabric-Reinforced Cementitious Matrix (FRCM) systems for strengthening concrete structures are an alternative to traditional techniques. The FRCM system is a composite material consisting of two or more layers of cement-based matrix reinforced with dry fibres in the form of open mesh or fabric. When adhered to concrete structural members the FRCM system acts as supplemental external reinforcement. Many existing Reinforced Concrete (RC) members exhibit degradation due to the carbonation of concrete and/or corrosion of internal reinforcing steel bars. These RC members can be strengthened using stainless steel, in strip format (unidirectional fibres), embedded in a cementitious based matrix. The system, named Stainless Steel-FRCM, can be applied according to the Externally Bonded (EB) technique. In order to reduce times and costs of intervention, number of used materials, as well as the amount of chemical compounds, a novel Inhibiting-Repairing-Strengthening (IRS) technique is proposed and experimentally tested. Using a suitable matrix (thixotropic mortar with passivation properties) the main three operations of steel bars corrosion inhibition/protection, restoring of deteriorated concrete, and installation of the external strengthening can be carried out in one-step. For evaluating the effectiveness of both new strengthening system and installation technique an extensive experimental investigation was planned and developed. A part of the experimental research includes two groups of three RC beams (3.00 m and 4.80 m long): one strengthened with IRS technique, one strengthened with EB technique and one control beam. These beams were tested under monotonic loading. Further two beams, one beam for each group, strengthened according to IRS technique, were also tested under cyclic loading. The experimental results show the validity of the proposed solution in terms of structural performance and environmental sustainability.

Keywords: Innovative materials, repair, strengthening.

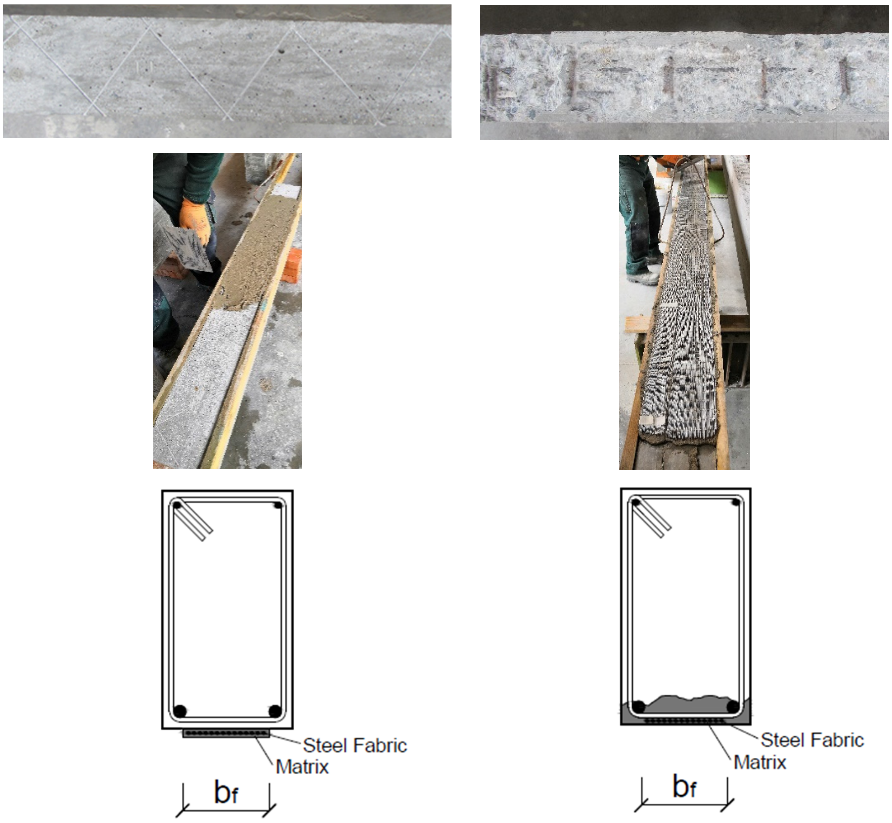
1. Introduction

The repair and rehabilitation process of Reinforced Concrete (RC) structures and infrastructures is become a fundamental target in last years. Several approaches for strengthening concrete members by composites have been developed and increased significantly as an alternative to traditional methods. Combining fibres of different origin with inorganic cementitious matrices new class of composite materials were defined under the acronym Fabric-Reinforced Cementitious Matrix (FRCM) or similar names as Textile-Reinforced systems. Lightweight and high strength of FRCM systems fit perfectly in the rehabilitation process.

The improvement in terms of performance of strengthened local members with FRCM composites was experimentally confirmed by several researches [1–6]. In this context, Steel-Fabric Reinforced Cementitious Matrix (S-FRCM) strengthening system has proven to be one of most effective innovative reinforcement used in the civil engineering field [7].

As well as the structural aspect, the use of environmentally sustainable repair and reinforcement techniques and materials is becoming increasingly important. So eco-friendly geopolymeric matrices act as corrosion inhibitor and together to the repair of the cover concrete with inside the steel strengthening fibre represent a new effective application [8–10]. This latter technique, alternative to the traditional Externally Bonded (EB) application, is proposed with the name of IRS (Inhibiting/Repairing/Strengthening) because of it includes these three operations in one. The effectiveness of this methodology of strengthening has been experimentally evaluated on the basis of obtained test results.

The IRS strengthening procedure is a novel eco-friendly intervention and can be representing the best choice when considering the structural effectiveness as well as sustainable development. In fact, the use of this technique does not require passivating materials of the internal reinforcements (applying geopolymeric matrices), shorter execution times of the intervention (strengthening and restoration/repair of the surfaces in one step), reduced intervention times and consequently less use of skilled manpower. The economic



a) b)

Figure 1. Preparation of the surfaces and cross-section after the strengthening process: a) EB-FRCM system and b) IRS-FRCM system.

advantage therefore represents a key aspect in the study and development of this IRS innovative technique.

In order to compare the flexural capacity of beams with the two applications of reinforcement techniques (EB and IRS), an experimental flexural test was carried out. The specimens are formed by two groups of beams (A and B) with a length of 3000 and 4500 mm, width of 150 mm for both, 250 and 400 mm of height. The beams were supported by simple supports and a total of eight beams have been tested under four-points bending, subjected to monotonic and cyclic loading.

2. Application techniques

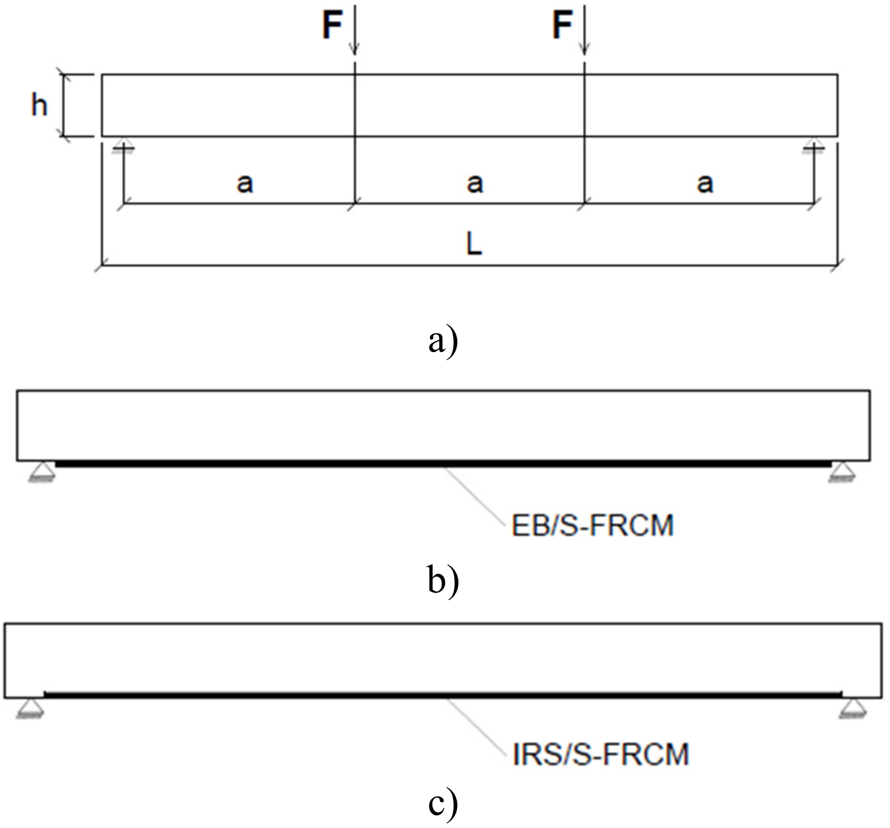
The preparation of the surfaces and the technique of applying the composite material represents a fundamental phase of the strengthening process. According to the traditional strengthening technique (EB) after the restoration of the cover concrete, if necessary, two layers (of about 5 mm each one) of cementitious matrix are applied. A new innovative application (IRS) was experimentally tested with effective results. It consists to restore the deteriorated concrete and to apply external strengthening in one step with installation of the stainless-steel strip in the cover concrete with reduction of time and cost of the intervention. The final layer of mortar shows more consistent thicknesses ($30 \div 35$ mm). Details of the two techniques EB-FRCM and IRS-FRCM are outlined in figure 5.

The beams were prepared with the EB technique through the cleaning of the surfaces from any type of material (dust and other substances) and subjected to light mechanical scarification and small mechanical carvings. With reference to the IRS technique, the specimens were cast in the form work without the cover concrete. The idea is to simulate the existing RC elements with damaged cover concrete, which in the strengthening phase is totally removed. The surfaces were wet to avoid absorption of the mixing water of the matrix. In figure 5 the state of the surfaces before and after the strengthening process is reported.

3. Experimental Programme

3.1. Test specimens

Starting from previous research [1], eight RC beams subjected to four-points bending were tested in the laboratory of the Department of Civil Engineering at University of Calabria. The beams were designed to fail in flexure before in shear, using appropriate internal shear reinforcement (stirrups). Two types of concrete beams with different amounts of internal steel reinforcement were used. Two 16 mm and



a)

b)

c)

Figure 2. Geometry of control and strengthened beams: a) RC control beam; b) EB technique and c) IRS technique.

Group	L [mm]	b [mm]	h [mm]	L/h [-]	a [mm]	a/d [-]	A_s[a] [-]	ρ_s[b] [%]	A'_s[c] [-]	Stirrups [mm]
M-A	3000	150	250	12	900	4.1	2⌀12	0.6	2⌀8	⌀8/150 mm
C-A							2⌀14	0.9		
M-B	4800		400		1500		2⌀16	0.7		
C-B							2⌀14	0.5		

[a] A_s: tension steel reinforcement.
[b] $\rho_s = A_s/(bd)$: internal tension steel ratio.
[c] A'_s: compression steel reinforcement.

Table 1. Geometrical properties and internal steel reinforcement of tested beams.

12 mm steel bars were used as bottom reinforcement in the monotonic tested beam (Group A and B, respectively) and 14 mm in the cyclic tested specimens. The shear reinforcement consisted of 8 mm steel stirrups placed at intervals of 150 mm and two 8 mm steel bars as top reinforcement to hold the stirrups for all beams. The aim is to investigate the structural performance of the EB-S/FRCM and IRS-S/FRCM systems considering two large-scale RC beam groups (3000 mm Group A and 4800 mm Group B). Some geometrical dimensions of the two groups have been changed in order to evaluate potential scale effect.

Beams referred to as M were tested under static monotonic loading; the character C indicates the beams subjected to static cyclic load. To complete the label of the specimens, the abbreviations EB and IRS indicate the reinforcement technique used. The internal and external reinforcement ratios and geometry of the beams are presented in figure 2 and table 1. The complete labels of the beams were reported in table 5 (see later). The width (b_f) of S-FRCM fabric was equal to 100 mm and 150 mm for the beams of the groups A and B respectively, in order to keep equal the strengthening ratio $\rho_f = (b_f\, t_f)/(bd)$. Where t_f is the thickness of the external strip of steel reinforcement.

3.2. Material properties and characterization

In order to evaluate the mechanical properties of the concrete, compressive and tensile tests were carried out on cylindrical samples (150 mm of diameter × 300 mm of height). The average compressive strength (f_{cm}) at 28 days was 16.8 MPa for Group M and 33.5

Mechanical property	M beams	C beams
Compressive strength, f_{cm} [MPa]	16.8	33.5
Tensile strength, f_{ctm} [MPa]	1.7	3.7

Table 2. Mechanical property of concrete.

Mechanical property	M beams		C beams		
Diameter ⌀[mm]	⌀8	⌀12	⌀16	⌀8	⌀14
Yield strength, f_{ym} [MPa]	543.8	367.1	492.0	510.6	501.2

Table 3. Mechanical and geometrical property of internal steel reinforcement.

Stainless-steel fibre		Geopolymeric matrix	
Nominal thickness, t_f [mm]	0.24	Compressive strength, f_{cmm} [MPa]	≥ 45
Tensile strength, f_f [MPa]	1470	Flexural tensile strength, f_{tfm} [MPa]	≥ 6
Ultimate strain, ε_{fu} [%]	2.0		
Elastic modulus, E_f [GPa]	190		

Table 4. Mechanical properties of S-FRCM system.

MPa for Group C; whereas 1.7 MPa and 3.7 MPa the average tensile strength (f_{ctm}), respectively. The average yield strength of steel (f_{vm}) of bars ⌀8 (Group M), ⌀8 (Group C), ⌀12, ⌀14, and ⌀16 mm was 543.8, 510.6, 367.1, 501.2, and 492.0 MPa, respectively. Moreover, a summary of used concrete and internal steel properties are given in tables 2 and 3.

S-FRCM composite material system was used for strengthening the beams. It consists of stainless-steel strips embedded in an inorganic geopolymeric matrix. The unidirectional reinforcing strip is made of stainless-steel cords, particularly resistant to corrosion, suitable for interventions on substrates subject to rising damp and/or exposure to aggressive environments. The matrix is a polymers-based inorganic mineral with the addition of synthetic fibres, suitable for structural repairs of deteriorated cover concrete being able to be applied with thicknesses between 2 and 40 mm. The geopolymeric matrix also act as inhibitor of corrosion and represents an eco-friendly material for green technology.

Table 4 presents the mechanical properties of stainless-steel strips and matrix provided in the technical data sheets of the manufacturer/supplier [11, 12].

3.3. Cyclic loading procedure

Specimens subjected to cyclic loading were tested according to 12 monotonous cycles, as shown in figure 3. The periodic amplitude was selected on the basis of the theoretical yielding loads (Fy) of the Group C, using four levels of load corresponding around to 25% ($F_y/4$), 33.33% ($F_y/3$), 50% ($F_y/2$) and 75% ($3F_y/4$) of them.

From the theoretical calculations, the yield loads of C-A-IRS and C-B-IRS beams are almost equal. With reference to the theoretical average yielding load of the two strengthened beams and taking into account the applied load before test (self-weight of the beams and the heavy equipment) the values of the load cycles according to the percentages above described were defined. The values of the load cycles correspond to 12, 18, 30, and 42 kN, respectively. The load history was repeated three times for each step and later the beams were monotonically loaded until failure.

3.4. Test set-up

Each beam was subjected to two equal loads applied symmetrically to the mid-span as shown in figure 2. The shear span (a) was 900 mm and 1500 mm for Group A and B, respectively. The distance from support to point load was chosen to have the a/d ratio equal to 4.1 in all tested specimens.

The load was monotonically applied to the beams of Group M by means of a hydraulic actuator and recorded manually using a 300 kN load cell. The specimens of Group C were loaded by using hydraulic unit that controls a 140 kN jack and 160 kN load cell, with a frequency acquisition of 2 Hz. This equipment allows to apply a load and keep it constant. The load equipment was connected to a rigid steel frame for the application of the load on the elements.

The vertical displacements were recorded using three linear variable displacement transducers (LVDTs). Two were placed at mid-span (both in the front and back side) and one at quarter span. Finally, the strain values of all materials (concrete, internal tensile steel reinforcement and external strengthening) were measured by means electrical strain gauges

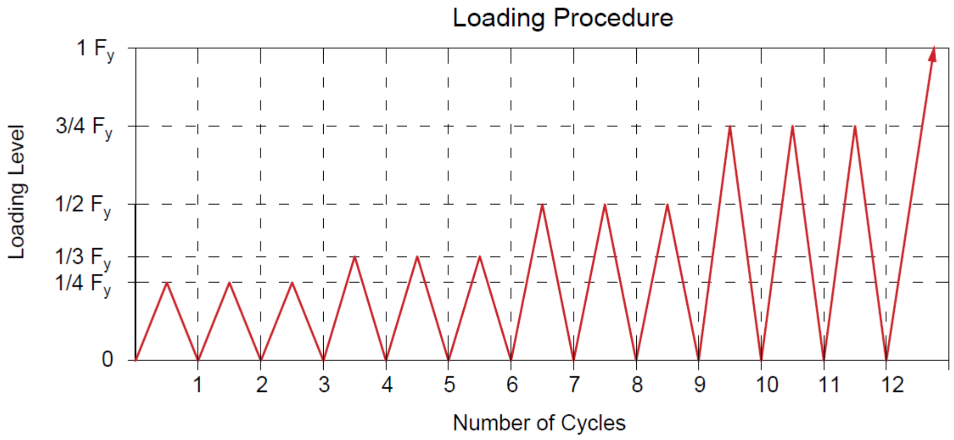
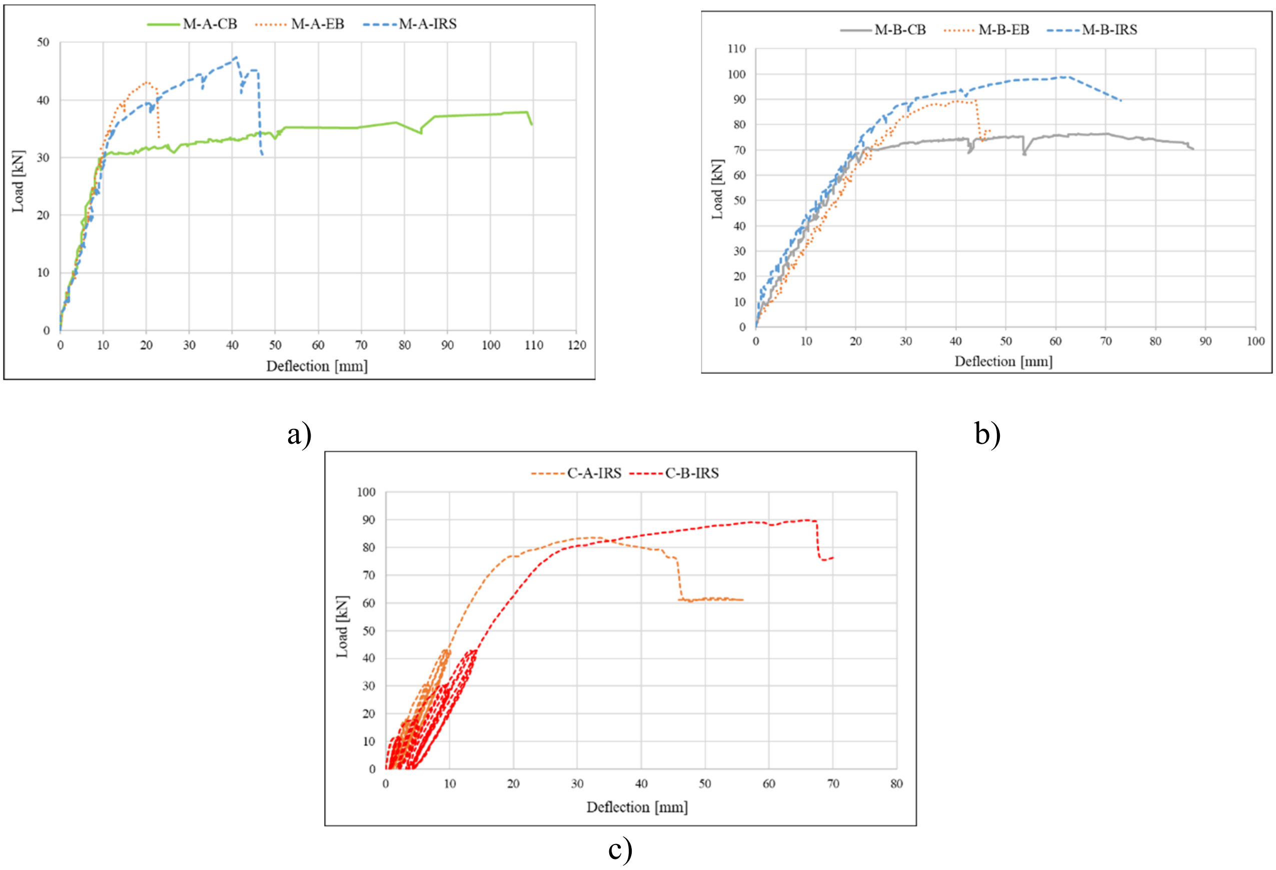


FIGURE 3. Loading history for the C Group beams.



a) b) c)

FIGURE 4. Load-displacement relationships.

Specimens	Failure mode	F_u [kN]	ε_c [‰]	ε_s [‰]	ε_f [‰]	ΔF_u	μ_δ
M-A-CB	Concrete Crushing	37.22	3.67	13.38	-	-	8.64
M-A-EB	End Debonding	43.22	1.50	3.75	1.87	1.16	2.16
M-A-IRS	Intermediate Debonding	47.39	2.63	9.81	11.62	1.27	3.73
M-B-CB	Concrete Crushing	76.33	3.68	17.54	-	-	4.38
M-B-EB	End Debonding	89.52	3.53	12.03	5.99	1.17	1.83
M-B-IRS	Concrete Crushing	98.96	4.65	15.49	10.73	1.30	3.05
C-A-IRS	Concrete Crushing	83.60	1.89	15.31	10.43	-	-
C-B-IRS	Intermediate Debonding	90.00	1.25	6.24	7.26	-	-

Table 5. Experimental results.

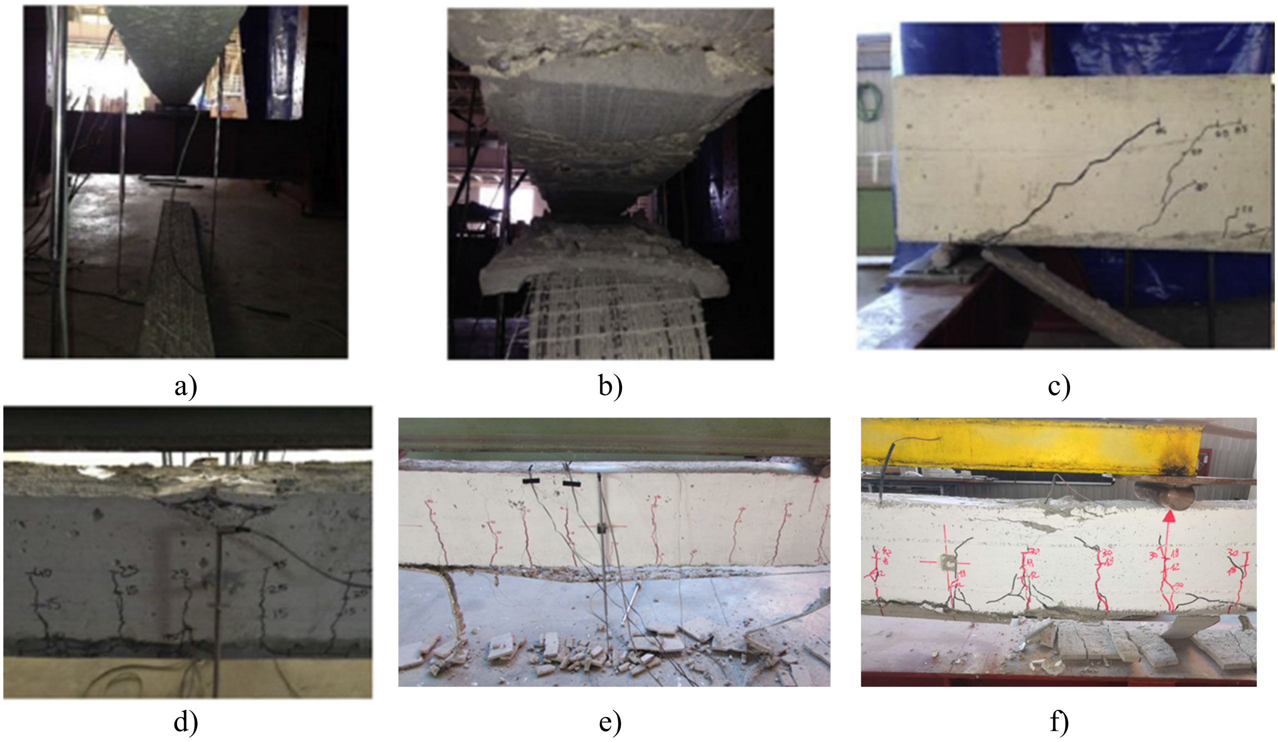

a) b) c) d) e) f)

Figure 5. Experimental failure modes of the beams: a) M-A-EB, b) M-A-IRS, c) M-B-EB, d) M-B-IRS, e) C-A-IRS and f) C-B-IRS.

in the middle section of the beams.

In the specimens monotonically tested the load was periodically paused in order to identify and mark crack formations and growth while in the cyclic tests it was performed at the end of each step.

4. Experimental Results and discussion

Static and cyclic flexural response at failure was experimentally studied. The ultimate load and overall behaviour of all tested beams are analysed and discussed through the comparison of load-deflection curves to measure the influence of the two strengthening methods (EB and IRS) on the flexural capacity.

The load-deflection curves are shown, for all tested beams, in figures 4a, 4b and 4c. The deflection reported represents the average value measured by LVDTs located in the centre of beam span. The classical vertical flexural cracks were observed during the loading and at failure.

Table 5 summarises the failure modes of all specimens, the maximum load (F_u), the strain measured on the top surface of the compressed concrete (ε_c), on the bottom tension steel bars (ε_s) and on the stainless-steel strips (ε_f). ΔF_u indicates the ratio between the ultimate load of strengthened beam and that of control beam; furthermore, for the beams monotonically tested, an evaluation of the ductility in terms of displacement is given as ratio between the deflection in the mid-span section at failure and at yielding of the internal tensile steel (μ_δ).

From a first analysis, both strengthening systems of Group M show an increase of the failure load and a decrease of the ultimate deflection and ductility compared to the control beams (M-A-CB and M-B-CB). Furthermore, the structural behaviour of the beams M-A-IRS and M-B-IRS was better compared to the corresponding RC beams strengthened with traditional EB technique (M-A-EB, M-B-EB). From the analysis of deformations and failure modes the IRS solution provided a greater utilization of all the materials, compared to the traditional EB technique. The failure modes of the strengthened beams with S-FRCM strips are shown in figures 5a-f.

On the other hand, the beams of group C (C-A-IRS and C-B-IRS) shown an excellent behaviour under cyclic loads without premature debonding of the reinforcement system until failure. These first results of group C is a part of a wider experimental programme aimed to investigate the performance of full-scale beams strengthened with the traditional (EB) and innovative (IRS) methods in structures affected to variable loads during the service life (such as deteriorated RC deck bridges).

5. Conclusions

This experimental investigation demonstrated the effectiveness of the IRS technique in strengthening of flexural RC members and in reduction of debonding process, showing also an excellent behaviour both under cyclic and monotonic loads. The test results also exhibited that the innovative IRS technique had superior flexural performance to the traditional EB strengthened technique, particularly when considering the economic, eco-friendly, and of environmental sustainability viewpoint.

In detail, the results showed that with EB and IRS technique, the average flexural strength of the beams is improved by around 15% and 30% respectively, compared to control beam under static loading; and great behaviour under cyclic loading for the beams strengthened by means the IRS innovative solution.

Finally, the results obtained from this first phase of the research programme suggest a more interest towards the IRS/S-FRCM applications in enhancing the strength and ductility of the existing RC beams with respect to the traditional EB/S-FRCM strengthening technique.

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