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Ferrocement, an historical material to build shell and spatial structures

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Abstract
Ferrocement is a type of thin wall reinforced concrete composed of hydraulic cement mortar reinforced with several layers of small size steel wire mesh. The material is used as a low-cost construction and retrofit solution and allows the creation of very thin elements. In the past, the material was also used for the construction of some structural engineering masterpieces that currently face preservation challenges. Pier Luigi Nervi largely used it in his structures built after the second world war. Despite the use of the material, few studies have analyzed its durability with respect to corrosion, especially for preservation purposes. The paper presents the results of a testing campaign on ferrocement mockup specimens subjected to a corrosive environment. The aim is to assess the performance of historical ferrocement exposed to degradation due to corrosion; this can be useful to identify the best procedures to protect and preserve it, as well as evaluate its performance over time.

Keywords: Ferrocement, Durability, Corrosion, Cementitious composites, Chlorides Ingress; Historical structures; Pier Luigi Nervi

1. Introduction
Building shells and spatial structures have always presented technological and design challenges requiring sophisticated structural or constructional solutions. In the first decades of the 20th century, concrete had already emerged as an alternative to steel or masonry and was regarded by many structural designers as a liberating material in terms of form possibilities. The 20th century was a thriving period for developing new solutions in the civil construction field. In the continuous research of the optimal form using the minimum amount of material, the structural designers of the time pioneered and developed the techniques of thin-shell concrete construction.
However, the continuous experimentation carried out with new materials whose durability had never been tested (reinforced concrete was regarded as an eternal material) has spawned degradation and preservation issues that are also often highlighted by the spasmodic and often daring research (developed both mechanically and empirically), perpetuated by engineers, of the materials and shapes optimization, according to a performance-oriented design philosophy (e.g., minimum amount of materials, minimum weight, uniform resistance, maximal ductility etc.) Romeo [1], Capomolla [2], Rega [3]. The aim was to obtain the most daring and performing structures by using as little amount of material as possible. Nervi was one of the leading structural designers exploring these problems, together with Eduardo Torroja, Sergio Musmeci, Nicolas Esquillan, Heinz Isler, and many others (Addis [4], Boller and D'acunto [5], Trovalusci and Tinelli [6]).

Among the research of the optimal form, Pier Luigi Nervi accompanied his experimentation by introducing in his construction (and subsequently patented) the ferrocement: a thin cementitious composite with layered wire meshes that allowed the construction of elements with minimal thickness.

The technological innovation Nervi introduced contributed to redefining the Art of Structural Design of the time, allowing him to explore innovative spatial solutions without neglecting cost and time aspects. From the late 40s, Nervi widely used ferrocement in his buildings and became part of his personal construction system.
However, due to its construction features, such as the high surface area of the reinforcement, the limited cross-section of the concrete cover, ferrocement may present durability issues.
The paper focuses on ferrocement elements exposed to corrosive environments, like the ones employed for unprotected roofing systems, which are affected by various degradation phenomena causing corrosion deterioration. In particular, the paper deals with durability investigation, one of the first applications of ferrocement by P.L. Nervi, and thus with a high historical value. The aim was to assess the behavior of historical ferrocement and its durability and identify the best procedures to protect and preserve it.

2. Nervi's Ferrocement

Ferrocement is part of that series of materials and technological solution that was pioneered during this period. The *ferrocemento* is a composite construction material that consists of multiple, closely spaced layers of mesh or fine rods completely embedded in cement mortar. According to the ACI committee 549 [7], [8], ferrocement behaves differently from conventional reinforced concrete in strength, deformation and potential applications, and thus is classified as a separate, distinct material. It can be formed into thin panels or sections, usually less than a few cm thick, with only a thin mortar cover over the outermost layers of reinforcement. Unlike conventional concrete, ferrocement reinforcement can be assembled into its final desired shape and the mortar can be plastered directly in place without the use of a form.
Ferrocement was invented by Frenchmen Joseph Monier, who dubbed it "ciment armé" (armored cement) and Joseph-Louis Lambot, who constructed a boat with the system in 1848, Naaman [9]. Apart from hulls and boats, the main worldwide applications of ferrocement construction to date had involved silos, tanks and roofs. Ferrocement has a very high tensile strength-to-weight ratio and superior cracking behavior in comparison to conventional reinforced concrete. This means that thin ferrocement structures can be made relatively light and watertight. However, its employment in civil construction was very limited; at the beginning the material was used to build boat hulls, water container, and plant pots, until Pier Luigi Nervi recognized the possible advantages of the material.
Nervi started experimenting with the material in the forties, by changing the percentage of cement and the amount of reinforcement in the chosen element. The aim was to develop a new construction solution by offering a light, user-friendly, low-cost material, and that at the same time could minimize the use of steel and wooden formwork. By using ferrocement it was possible to manufacture very thin slabs of only a few centimeters, which were very ductile, elastic and crack-resistant, and not only possessed an impressive litheness that ensured easy transportation and installation, but also allowed shapes to be made in any desired configuration (Greco [10], Greco [11], Chiorino and Leslie [12]). His experiments on boats and small-scale buildings (such as the shed in via della Magliana), culminated with different patents, but it was in the Torino Esposizioni pavilions, built between 1947 and 1953, that Nervi had the chance to apply his new material for the construction of a large structure [13]. After their construction, Nervi was consecrated as one of the most innovative designers of the world, and his legacy today is still admired and studied.

Nervi highlighted the importance of ferrocement in this work, saying: "*ferrocement, due to its independence from formwork, its intrinsic lightness (...) and its resistant capacity, provided the simplest and most satisfactory solution to the complex problem. I would add that, without the constructive qualities of ferrocement, the entire architectural and structural concept of the work would have had to be abandoned or radically changed"* Nervi [14].

In the present paper, the ferrocement under analysis is the one employed by Nervi in the structures of Torino Esposizioni. In both pavilions ferrocement is used in different forms and solutions which Nervi patented in those years. For Pier Luigi Nervi, the Torino Esposizioni represented the first opportunity to apply the principle of his new construction system, which saw his highly personal use of ferrocement with the extensive use of prefabricated elements in a single large-scale vaulted structure. This combined use of two different technologies to construct large concrete shells would become one of the distinctive traits of Nervi's work that would be known as the Nervi system.

Clear proof of how significant the design and construction of both halls had been in Pier Luigi Nervi's development as a builder is the fact that after the completion of both halls, he immediately registered the patents of the solutions he employed during the construction site. In fact, Nervi registered various patents: Patent no. 445781 in Rome on August 26th 1948, entitled "*Ferrocement wave*" and Patent no. 465636 on 19 May 1950, entitled "*Building procedure for creating flat or curved load-resisting surfaces consisting of grids of reinforced concrete ribbing, possibly finished with connecting concrete slabs between the ribs*". These patents would be adopted by Pier Luigi Nervi in the following decades until they became a typical feature of the globally recognized Nervi style (Greco [11]).

2.1. Analysis of the ferrocement

Figure 1 shows some elements of the pavilions where ferrocement was employed. To replicate Nervi's ferrocement, and determine the proper mixture, it was fundamental to study the patents (Nervi [15], [16], [17]) and the writings authored by the designer (Nervi [18], [19], [20]) as well as identifying all the ferrocement elements in the halls and their differences. From the original documentation alone, however, it was not possible to state with certainty the actual mix design of the recipe used by Nervi, especially to assert the one related to the structures under analysis.

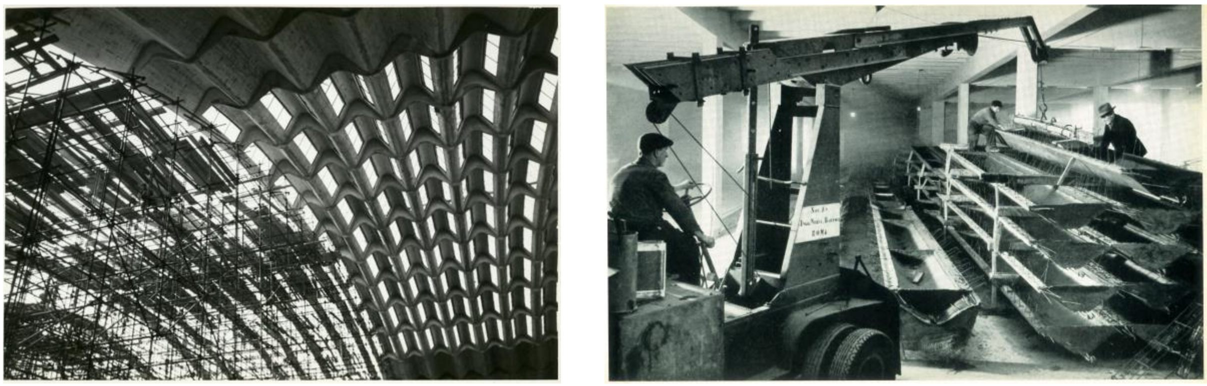


Figure 1: (a) Construction site of Hall B. The construction site's photo shows the mobile scaffolding system used to build the vault (Archivio privato ing. Ravelli). (b) prefabricated undulated beams in ferrocement for Hall C, Nervi [14].

Regarding direct investigation on the material, it was not possible to carry out a proper diagnosis on-site, apart from endoscopies and partial scarifications, due to the fact that ferrocement elements were presented a thickness below the minimum one requested by the most common non-destructive tests (such as ultrasonic pulse velocity, and rebound tests); another issue for investigating the material on-site was the fact that some ferrocement elements were often used as formwork, where concrete was poured over them, and consequently it was not possible to investigate it.

When partial scarification was performed at the surface level, it exposed the first mesh layer of the ferrocement element. Usually, on visual analysis, the first layer of mesh was found to be corroded.

Considering the historical value of the analyzed structures and since the ferrocement elements are extremely thin, to investigate the durability of this material, small-scale ferrocement mockups were built in the laboratory, starting from a small sample collected on-site. More specifically, the sample was collected from one of the ferrocement beams elements of Hall C, which elements are better described in Lenticchia et al. [21]. The sample was used to determine the matrix composition of the concrete (both chemical and petrographically) and identify the wire characteristics. The collected sample was extracted in an area presenting some detachments of the painting, probably due to water infiltrations. Before collecting the sample, an endoscopy and scarification of the surface were carried out (Figure 1a). The thickness of the ferrocement element was determined to be approximately 25 mm, in line with the original design. Each layer of metal mesh was carefully removed from the cement matrix by using a hammer, chisel, and a Dremel. After removal, all layers extracted were documented and cataloged. The four layers of wire mesh all presented an advanced state of corrosion (Figure 2b).

Figure 2: (a) Surface scarification of the ferrocement element before the extraction of the sample. It is possible to see the detachments of the painted surface due to possible water infiltrations. (b) Collected sample of ferrocement. It is possible to see the various layers of wire mesh and their state of conservation.

3. Experimental procedure

3.1. Sample preparation

For evaluating the performance of the ferrocement, 11 samples are realized with a dimension of 300 mm x 75 mm x 30 mm, each sample included seven layers of metal mesh 270 mm x 55 mm (Vr=3.63%). The dimension of the samples and the number of layers were defined by following Pier Luigi Nervi's design (regarding the volume fraction of steel reinforcement) and in accordance with ACI indications, in order to use the proper dimensions for the mechanical tests.

According to the results of the investigations discussed in section 2, the mockups were reconstructed by using a premixed mortar based on pozzolanic cement. The pozzolanic component (in replacement of bentonite) confers to the mortar a thixotropic consistency, making it suitable to be set and modeled around the metallic net.

Regarding the wire mesh, from the visual analysis of the original sample, the resulting steel meshes consist of woven steel wires spaced 10 mm apart. Thus, smooth steel bars and woven meshes with 1mm diameter and 10x10 mm spacing were selected for the mock-up reinforcements. The samples were poured by using a w/c ratio equal to 0.18, which provided the best workability for this application, and to obtain a good quality compact matrix to ensure good durability as highlighted by Naaman [9], stating that the w/c ratio shouldn't exceed 0.4-0.45 by weight. The samples were cured for 28 days underwater in a humidity-controlled environment for 28 days.

A solution with 3.5% NaCl solved in water is used to accelerate the corrosion process. The aging cycles run for a six-month period alternating wet and dry cycles, where during the wetting day, samples were sprayed continuously for one hour. The drying occurred under natural conditions. After six months of aging, all samples showed evident deterioration on the surface.

3.1. Experimental campaign

Different tests were carried out during the aging procedure to monitor the development of the corrosion phenomena in the samples. In a photographic test campaign, regular and standardized photos were shot on a screen to develop superficial evidence of corrosion or other eventual phenomena on the samples. Half-cell potential test was measured on a regular grill of 20 points on each sample to keep track of the areas with a higher probability of corrosion development by using a standard anode immersed in copper sulfate.

In the end, sample performance was evaluated by carrying out four points bending test, according to the ACI Committee 549 [8], [22] standards and measuring the midspan deflection by means of an LVDT. Moreover, a 3D-Digital Image Correlation (DIC) method was employed to assess the four-point tests under stress. The adopted correlation approach is based on monitoring the pattern of gray values in small local regions. The following paragraphs reports the results of each testing stage and its discussion.

4. Discussion of the results

Deterioration or loss of strength due to reinforcement corrosion can indicate relative corrosion damage. In order to evaluate it, all specimens were tested to failure in flexure to evaluate changes in their performance, and consequently the effect of corrosion in the structural response. Flexural tests were carried out with the configuration as required by ACI Committee 549 [8], Naaman [9] with simply supported beam with third-point loading. For aged samples, the tested element was positioned with the side exposed to the aging process downward, subjected to tension state. Figure 3 and Figure 4 depicts the load-deflection pattern for the aged and the non-aged series, respectively. In both figures, the mean value of the series is depicted with a red line, while the blue line always depicts the sample treated with a layer of paint.

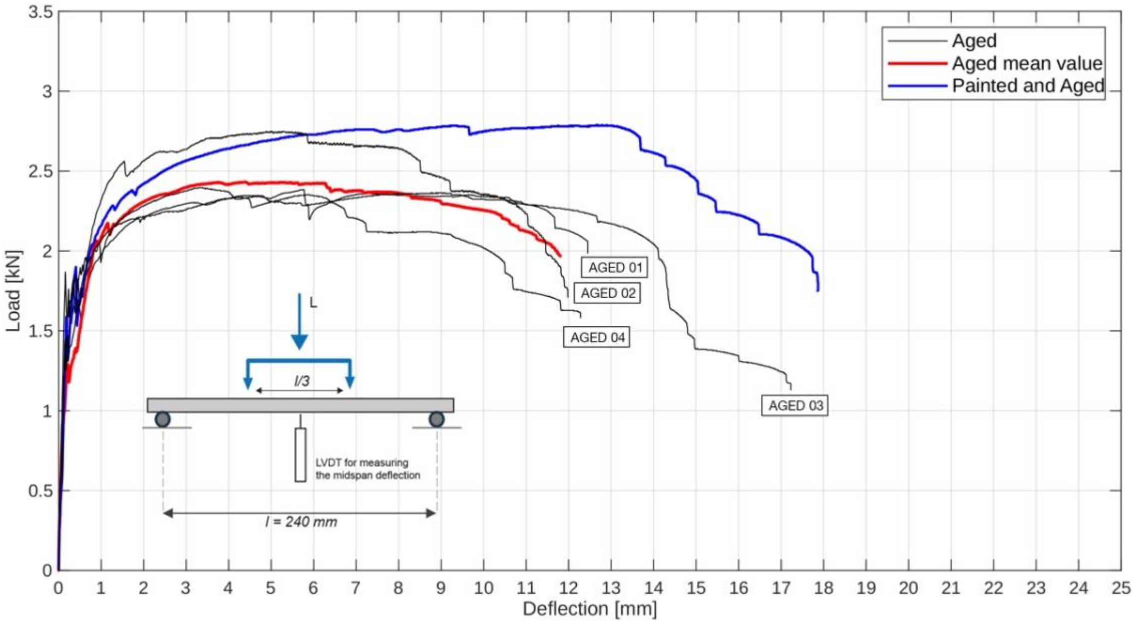


Figure 3: Four-point bending test Load-Deflection pattern, aged + painted and aged samples.

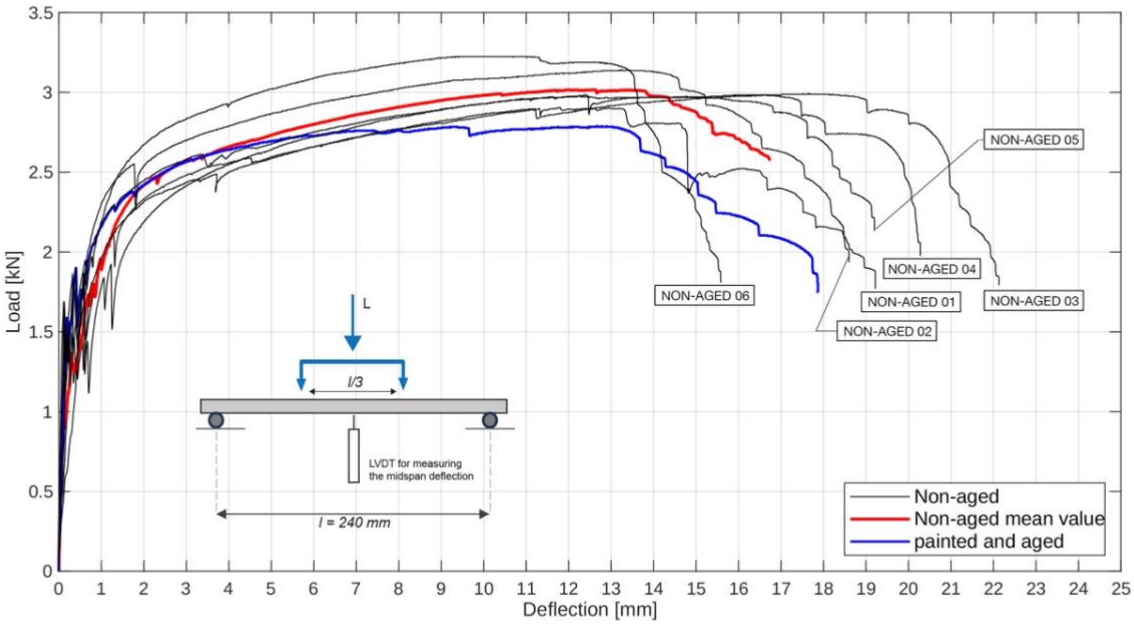


Figure 4: Four-point bending test Load-Deflection pattern, aged + painted and aged samples.

Table 1: Four-point bending test results.

ID	**Ultimate load L_u** [kN]	**Ultimate moment M_u** [kN·mm]	**δu** [mm]
Aged 1	2.385	95.4	5.762
Aged 2	2.352	94.08	5.778
Aged 3	2.396	95.84	3.268
Aged 4	2.748	109.92	4.88
Non-Aged 1	2.904	116.16	11.8
Non-Aged 2	3.14	125.6	13.4
Non-Aged 3	2.992	119.68	17.53
Non-Aged 4	2.984	119.36	16.7
Non-Aged 5	2.984	119.36	12.41
Non-Aged 6	3.224	128.96	9.248
Painted and aged 1	2.788	111.52	12.69

Table 2: Four-point bending test results, mean values.

Mean L_u	**st.dev. L_u**	**Mean δu**	**st. dev. δu**	**Mean Mu**	**st. dev. Mu**
[kN]	[kN]	[mm]	[mm]	[kN·mm]	[kN·mm]
2.470	0.161	4.922	1.022	98.810	6.447
3.038	0.109	13.515	2.847	121.520	4.348
2.788	-	12.690	-	111.520	-

Table 1 reports the results of the flexural tests of aggregated samples in terms of ultimate load and ∂_u (defined as the deflection at the ultimate load). Results are used to evaluate the mechanical properties of the ferrocement samples by comparing the performance of the aged and non-aged ones. Table 2 reports the results in term of mean values and their standard deviation for each parameter (ultimate load, work, and ∂_u). The comparison is done in terms of percentage loss compared to the non-aged samples; it is possible to notice an important difference from the aged and the non-aged series; especially by comparing the medium maximum load and the maximum displacement applicable to the samples.

In particular, with reference to the previous table, it is possible to compute the average loss in ultimate load $\sigma_{u,loss}$ and ultimate deflection $\delta_{u,loss}$ as:

$$\sigma_{u,loss} = \frac{\sigma_{u,nonaged} - \sigma_{u,aged}}{\sigma_{u,unaged}} \tag{1}$$

$$\delta_{u,loss} = \frac{\delta_{u,nonaged} - \delta_{u,aged}}{\delta_{u,nonaged}} \tag{2}$$

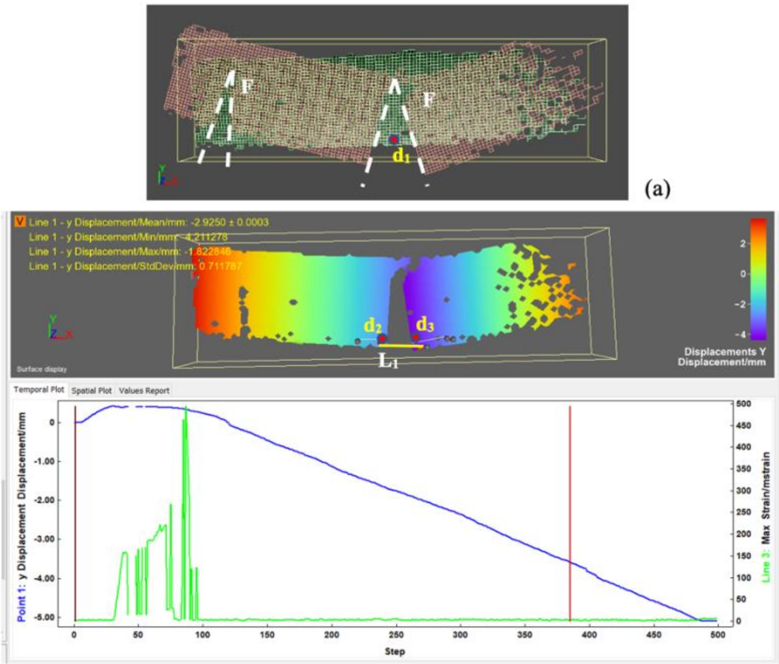
Results are reported in Table 3, and it is possible to notice how aged samples show an important reduction of M_u, of about 18.7%, a significant statistical reduction of δ_u, of about 63.6%, and an average loss of W, of about 69.5% for the aged series. Moreover, the painted sample shows a lower decrease of values of M_u loss, 8.2%, and a notably lower reduction of δ_u (6.1%) and W (8.3%) values compared to aged samples that did not present a layer of paint.

From the results obtained by the experimentations, it can be stated that the sample presenting a layer of paint presents a behavior comparable to the one of not aged samples, with a slight decrease of performances, mostly evidenced by the W loss. This demonstrates very good properties of protection that just a layer of paint can exert on this material. This is important for our observations and analysis, since most of the ferrocement elements located in the case under analysis present at least one of the surfaces protected with a thin layer of paint (Figure 2).

Table 3: Four-Points bending test, percentage of loss of mechanical properties, mean values for series

ID Series	**% M_u loss**	**% ∂_u loss**
Aged	18.688	63.580
Painted and aged	8.229	6.102

This is also confirmed by the results of the 3D DIC tests, where the loss in ductility can also be appreciated by the distribution of the crack pattern, and the crack width in the tensile zone. In fact, the non-aged samples present a more distributed spread with respect to the non-aged ones.



(a)

(b)

(c)

Figure 5: Sample Aged_03. Two main fractures F1 and F2 can be recognized initially (a). Later a third in the left portion will be recognized by recognizing symmetrical behavior. It was placed 3 smart displacement sensors d_1, d_2 and d_3 (b). An additional smart strain gauge (line gauge is positioned). The y displacement of d1 over time is compared with the lager. deformation along x for L_1 (c).

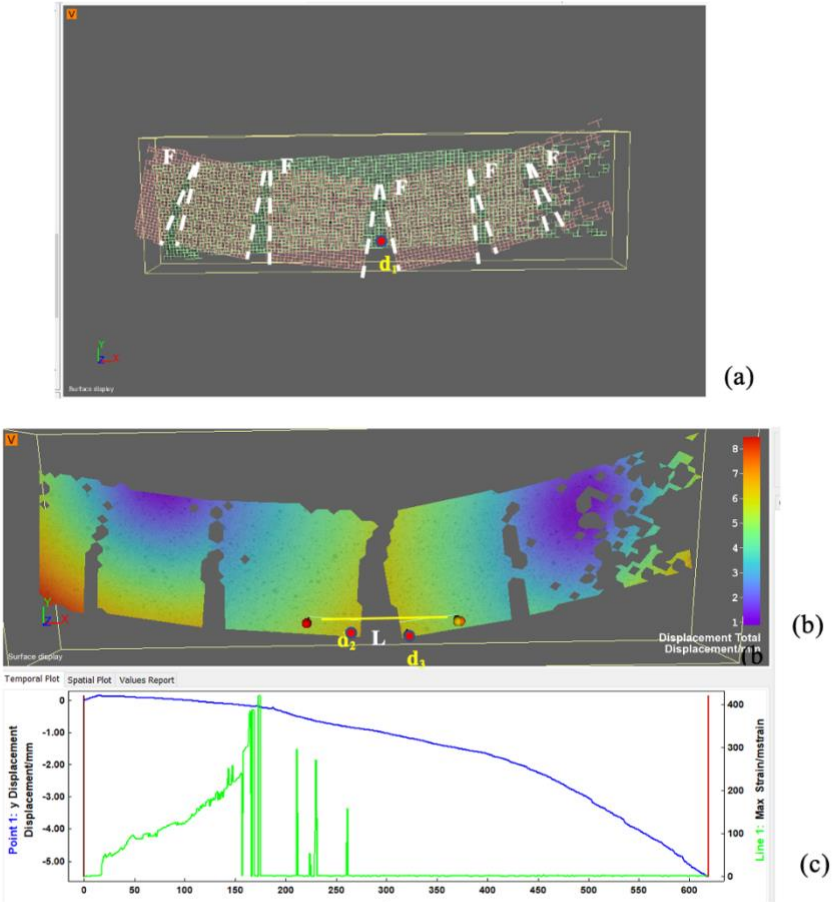


Figure 6: Sample Non-aged_01. Five main fractures F1-F5 can be recognized initially (a). 3 smart displacement sensors d_1, d_2 and d_3 (b) were placed. An additional smart strain gauge (line gauge is positioned). The y displacement of d1 over time is compared with the lagr. deformation along x for L_1 (c).

Similar considerations can be made for specimen Non-aged_01. It, however, does not present any aging phenomenon. In this case, it was possible to recognize 5 macro-cracks on the surface of the specimen and passing through the entire thickness. It is also possible to see by comparing the graphs at letters c in Figure 5 and Figure 6 that for the Non-aged_01 specimen, a more ductile behavior is recognized RBMR Rigid body motion removed in the x-direction for strain (Figure 7) can also be observed. By these graphs, it is possible to recognize in advance the formation of the crack pattern for the two specimens. The crack mouth opening for specimen Aged_03 (aging applied) was equal to 6.31 mm. The crack mouth opening for specimen Non-aged_01 (ageing not applied) was equal to 6.08 mm.

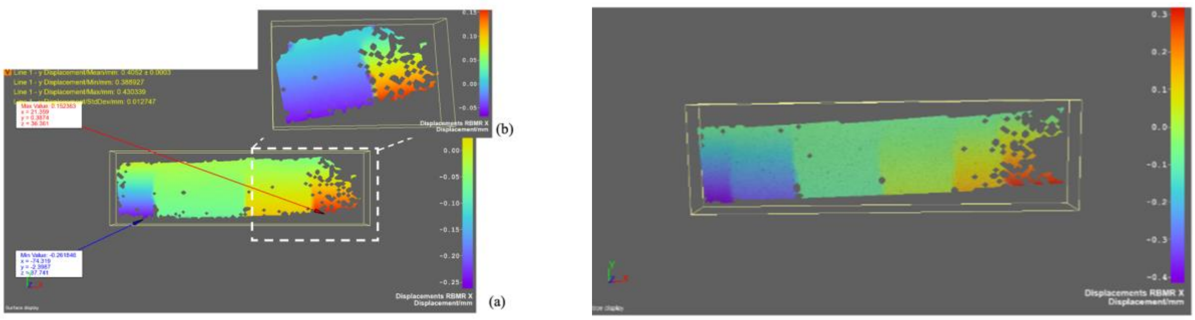


Figure 7: On the left, results of Sample Aged_03: RBMR Rigid body motion removed in x-direction for strain (a). It is possible to recognize a third macrocrack in the left portion with a symmetrical behavior of the specimen before failure (zoom in b). On the right RBMR Rigid body motion removed in x-direction for strain of sample Non-aged_01.

5. Conclusion:

The study presented the behavior of ferrocement subjected to a corrosive environment; in particular, by reconstructing and analyzing the historical ferrocement used by Pier Luigi Nervi in his structures and carrying out both monitoring by means of half-cell potential and bending tests the performance of the material was evaluated. The aim was to understand the effects of aging on this material. The study is of interest since, despite the widespread use of the material, few studies have analyzed its durability for preservation purposes. Through a combination of a specific experimental campaign, which included photographic documentation, half-cell potential monitoring, and mechanical tests, we observed the development of the aging process, and we could evaluate how it affected the performance of the material.

Results of the experimental campaign suggest that a layer of painting, was efficient in protecting the material to the corrosive environment. However, the present work has only considered the degradation by subjecting the specimens to accelerated corrosion due to chloride ingress. Future works should be carried out to evaluate different degradations considering also carbonation. Moreover, other protections measures, such as corrosion inhibitor treatments of various nature, could also be investigated.

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