Damaged Concrete Viaduct in an Italian Highway: Concrete Characterization and Possible Strengthening Techniques by FRP Applications in Comparison

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Abstract. The “Fornello” viaduct in the Italian Orte-Ravenna highway (E45) is seriously damaged. In this paper, the concrete of the reinforced slab has been widely characterized to evaluate the level of damage and to identify the causes of degradation. No-destructive tests, as those based on ultrasonic waves, as well as chemical, physical and mechanical destructive tests have been carried out on specimens drawn from deteriorated and not deteriorated zones of the R/C bridge decks. Into the slab thickness, the concentration distribution of main anions has been quantified by ion chromatography. Porosimetry tests have been carried out to detect the resistance to freeze-thaw cycles of cement paste. Possible strengthening techniques by FRP applications have been compared.

1. Introduction
Damage of reinforced concrete in structures like bridges and highways is related to low fatigue level due to cyclic loads, thermal loads, construction technologies, seismic events and environmental aggression. Chemical and physical agents may induce a gradual increase in concrete porosity and permeability causing a decrease in concrete integrity and corrosion of steel bars [1,2]. Since the cost of repairing reinforced concrete structures during the induction period of degradation is much lower than the rehabilitation cost during the propagation period, additional prevention methods should be adopted when severe environmental conditions occur on structures requiring long service life. Cathodic protection, the high corrosion resistant but very expensive stainless steel rebars, galvanized reinforcement thanks to sacrificial corrosion [3], corrosion inhibitors [4], hydrophobic coatings or admixtures, due to their ability to make concrete less susceptible to water saturation [5-7], can give an adequate level of protection in relation to the structure service life.
On the contrary, in Italy, many of bridges and highways built in the early seventies have not been provided of additional protection methods. Therefore, now, they are in poor condition of conservation and they need urgent interventions of structural rehabilitation.

In this paper, the seriously damaged reinforced concrete slab of a viaduct in an Italian highway has been considered. The aim is to evaluate the level of concrete damage and to investigate the causes of degradation by chemical, physical and mechanical characterization of specimens drawn from damaged and undamaged regions of the R/C bridge decks. Finally, possible strengthening techniques by FRP applications have been compared.

2. Materials
The object of the present study is the "Fornello" viaduct (Figure 1), of the Orte-Ravenna highway (E45), Italy, managed by the National Organization for Highways (ANAS). The highway winds along a mountain route and the structure, built in the early seventies, is seriously damaged. In the specific case of the Fornello viaduct, the slabs show very poor conditions of preservation and requires urgent structural rehabilitation interventions. The viaduct has four spans 32 m long, and 9.5 m wide in each direction. The deck consists of four pre-stressed reinforced concrete girders and an R/C slab with average thickness of 200 mm (Figure 2). Bars with round and square cross section constitute the steel reinforcement in the longitudinal and transversal direction.

In this work parts of the viaduct slab (Figure 2), after removing rebars and the upper incoherent concrete layer, are transferred to the research laboratory, for experimental investigation.

Twenty-one concrete samples 500 mm x 1800 mm in size (Figure 3) are taken out from the removed slab. For mechanical, physical and chemical characterization, concrete cores of 10 cm diameter are drilled from the samples extracted from the slab (Figure 3). In particular, three types of concrete cores are considered: those drilled from the least (Core 1), an average (Core 2) and most deteriorated part of the samples (Core 3), respectively.
3. Concrete characterization: tests and results

3.1. Mechanical tests
Ultrasonic pulse velocity tests are carried out on the cores (d = 10 cm) drilled from the slab samples [8]. The calculated elastic dynamic modulus, averaged among the values obtained in three specimens of the same type, ranged from 38 to 43 GPa. Compression tests show compressive strength values ranging from 23 to 33 MPa (Table 1). It is evident that the actual mechanical properties of the concrete are rather constant along the slab height and consistent with the original concrete quality.

| Table 1. Results from mechanical characterization tests |
|---------------------------------|
| Rc (MPa) | Ed (GPa) |
| Core 1  | 30 | 40 |
| Core 2  | 33 | 43 |
| Core 3  | 23 | 38 |

3.2. Chemical tests
To detect a possible chemical cause for concrete deterioration, Ion chromatography (IC) is carried out on water leachate of powder samples collected in the cores at increasing depths from the slab intrados; 0-2 cm, 2-4, 6-8, 8-10, 10-12, 14-16, 16-17 cm, respectively, to obtain the concentration profile of soluble anions in the slab. The values reported in Figure 4 are the average of the values obtained in three powder samples collected at the same depth in the cores.

Sulphates and chlorides are the most abundant anions. In particular, soluble sulphates, caused by sulphation occurring on the cement paste due to the dry and wet deposition of sulphur oxides as atmospheric pollutants [9-11], concentrate just in the slab intrados, probably due to water percolation effect. Moreover, the slab intrados is more exposed to the polluting emissions of vehicles than the slab extrados that is additionally protected by a bituminous layer.

Chlorides, as a result of the great use of de-icing salts in winter, decrease from the outer to the inner layer of the slab. In particular, the concentration of soluble chlorides exceeds the chloride threshold value of 0.4% by cement weight and it is therefore capable of inducing corrosion of steel reinforcements [12]. However, a visual observation of the deteriorated viaduct does not evidence a deep corrosive attack of reinforcements (Figure 1).

Chlorides and sulphones are followed in order of abundance by organic anions such as formate and acetate. Organic anions could be the result of biological weathering and/or deposition of primary pollutants due to the incomplete combustion of fossil fuels and of secondary pollutants from the photochemical oxidation of olefin compounds [10, 11]. Moreover, IC revealed the presence of nitrate...
which is the final product of the oxidation-hydration of NOx present in polluted atmospheres [10, 11]. Similarly to sulphates, also organic anions and nitrates concentrate in the slab intrados.

![Concentration of soluble anions as a function of the slab depth.](image)

**Figure 4.** Concentration of soluble anions as a function of the slab depth.

X-ray diffraction analysis (Figure 5), carried out on powder samples collected from the cores, does not reveal a significant presence of compounds coming from the chemical degradation of concrete, but just of quartz and calcite that are typical components of ordinary concrete.

![X-ray diffraction analysis on a powder sample collected at 0-2 cm from the slab intrados](image)

**Figure 5.** X-ray diffraction analysis on a powder sample collected at 0-2 cm from the slab intrados (Q = Quartz, C = Calcite).

Finally, phenolphthalein colorimetric tests (Figure 6), following the Italian Normative UNI 9944:1992 and carried out on the cores drilled from the slab samples, does not reveal a deep carbonation depth in the concrete slab (pink color indicates not carbonated concrete), therefore, the sound original concrete, due to its alkalinity, is potentially still able to protect reinforcements from corrosion.

![Carbonation test on a core section drilled from the slab.](image)

**Figure 6.** Carbonation test on a core section drilled from the slab.
3.3. Porosimetry tests
Mercury porosimetry was carried out on small pieces of cement paste extracted from the least (Core 1), an average (Core 2) and most deteriorated (Core 3) cores drilled from the slab samples. In particular, for each core type, three pieces extracted at high, medium and low height in the core are analysed, respectively but no significant differences are observed. The results reported in Figure 7 are averaged among the values obtained from three samples collected from the same type of core. They show a relative low total porosity of about 12%, regardless of the drilling location. However, generally, the critical diameter ($\phi_{cri}$), defined as the largest among the diameters that represent 90% of the cumulative pore volume, is generally lower than 0.5 µm. This is the threshold value distinguishing frost sensitive materials ($\phi_{cri} < 0.5$ µm) from uncertain ones ($1.8 \mu m \leq \phi_{cri} \leq 0.5$ µm). In no frost sensitive materials, $\phi_{cri}$ is $\geq 1.8$ µm [13]; therefore, the viaduct damage has been most probably induced by freeze-thaw cycles.

|     | Total Porosity (%) | Average pore radius (µm) | $\phi_{cri}$ (µm) |
|-----|--------------------|--------------------------|-------------------|
| Core 1 | 12.6 | 0.394 | 0.592 |
| Core 2 | 12.2 | 0.390 | 0.206 |
| Core 3 | 12.7 | 0.447 | 0.133 |

Figure 7. Results of porosimetry tests.

4. Strengthening by FRP applications: tests and results
The performed experimental tests showed that concrete damage is prevalingly superficial, limited to the concrete cover depth of the slab upper side. Except for this area, the actual mechanical properties of the concrete are rather constant along the slab height and consistent with the original concrete quality. The good preservation of the slabs lower side concrete suggests that strengthening of the slab by bonding external FRP reinforcement on this side while replacing the upper side damaged concrete and rebar is possible [14, 15].

An interesting issue concerns also the possibility of bonding the FRP reinforcement on restored concrete. Therefore, in this study, the possibility of bonding the FRP reinforcement on the original concrete of the slab’s lower side is compared with that of bonding the FRP reinforcement on restored concrete of the slab’s upper side.

To this aim, prismatic specimens (100 mm x 180 mm x 500 mm) are cut from the concrete slab. The upper side damaged concrete is completely removed by means of a needle hammer and the rusted steel rebars are extracted (Figure 8).
Concrete restoration (Figure 9) is carried out by making use of two different mortars. A commercial single component mortar with limited shrinkage and high strength is applied to 12 of the cured specimens. As certified by the technical notes of the producer, the 28-day average strength of this mortar is around 60 MPa. A standard mortar with 3 parts of CEM II/A-L 42.5 R cement, 2 parts of sand and 1 part of acrylic emulsion in water dispersion is applied to 12 of the cured specimens. The average 28-day concrete cylindrical strength is estimated around 32 MPa.

Finally, FRP reinforcements based on carbon fibers are applied on the cured concrete surfaces by means of an epoxy resin (Figure 10). As comparison, identical 50 mm x 400 mm FRP strips are applied on lower side concrete surfaces of other 12 specimens by epoxy resin, where the original concrete support was previously arranged with a simple surface brushing. As certified by the technical notes of the producer, the average tensile strength and elastic modulus of this carbon tissue are respectively around 3500 MPa and 230 GPa.

The fabricated specimens are employed to execute direct bond tests, making use of a force controlled hydraulic jack (MTS 810) with 250 kN load cell (Figure 11).
Figure 11. Strengthening by FRP reinforcements: direct bond test.

On the restored upper side of the slab, superficial de-bonding (SD) (Figure 12), due to the detachment of the FRP strip from the concrete support, and deep de-bonding (DD) (Figure 13) due to shear failure within the original concrete are observed during the bond tests of the restored concrete joints. The last bond failure mode is much less frequent than the previous one.

Figure 12. Strengthening by FRP reinforcements on the restored upper side: direct bond test SD = Superficial Debonding.

Figure 13. Strengthening by FRP reinforcements on the restored upper side: direct bond test DD = Deep Debonding.

In Figure 14, the experimental bond forces of both the previous cases are compared. The bond forces of the joints where the special mortar is applied are about 40% higher than where the standard mortar is applied. This result seems to address this special mortar as much more effective than the standard one. However, if the very high cost of the special product is considered (around 6:1 in weight), this simple effectiveness comparison is meaningful without an accurate analysis of the global cost to benefit ratio.

Figure 14. Comparison of bond forces for concrete restored with different mortars.
In order to evaluate the efficiency of the executed concrete restoration and to assess the validity of this strengthening technique, the experimental values of the bond forces are compared with the theoretical values (Fmax) estimated by means of the Italian design recommendations CNR-DT 200 (2004) [16, 17]. According to these recommendations, the maximum bond force at FRP-concrete interface is given by:

\[ F_{\text{max}} = b_f \sqrt{2 Ef} \Gamma_F \]

where \( t_f, b_f, E_f \) are thickness, width and elastic modulus of FRP respectively. \( \Gamma_F \) is the specific fracture energy of FRP-concrete bond law and it can be evaluated as:

\[ \Gamma_F = 0.064 k_b f_c \sqrt{f_c f_{ct}} \]

where \( f_c \) and \( f_{ct} \) are compression and tensile strength of concrete, respectively, while \( k_b (\geq 1) \) is a shape coefficient depending on the ratio between FRP strip width and surface width of concrete support. In this study, the following efficiency factor (EF) was considered in order to analyze the experimental results: \( EF = F_{\text{exp}} / F_{\text{max}} \), where \( F_{\text{exp}} \) is the bond force experimentally detected.

In Figure 15, the obtained efficiency factors are reported for the bond tests with commercial mortar (a) and standard mortar (b). For both cases, an average efficiency factor very close to 1 is found (0.98 and 0.93 respectively), despite 4 of the 12 bond tests underwent failure with a deep de-bonding failure mode.

The restored joints exhibit bond forces at failure that are in good agreement with the theoretical previsions i.e. the loss of joint efficiency due to concrete restoration is not appreciable. In fact, the standard deviation of the obtained values is around 12%, which is included within the admitted uncertainty due to the rough modality of execution [16].

**Figure 15.** Efficiency factor of the bond tests on restored concrete joints with a commercial special mortar (a) and standard mortar (b). (DD=Deep debonding, SD=Superficial de-bonding, SF=Strip failure).

During the bond tests of the original concrete joints executed at the lower side of the slab, superficial debonding due to the detachment of the FRP strip from the concrete support with coarse aggregates fracture is typically observed (Figure 16) and it shows a surprising high value of the efficiency factor, with mean value 1.4 and standard deviation 3%. (Figure 17).

**Figure 16.** Strengthening by FRP reinforcements on the lower side: direct bond test

SD = Superficial debonding
Figure 17. Strengthening by FRP reinforcements on the lower side: efficiency factor

Perhaps, the significant percentage of coarse aggregates mainly settled in the lower part of the slab due to gravitational effects during the concrete casting (Figure 18), probably contributes to increase the bond strength of the joint with a sort of “strut” effect.

Figure 18. Inert distribution

5. Conclusions
This paper reports the results of an extensive experimental investigation carried out on samples of damaged concrete slab from a viaduct of the Orte-Ravenna highway (E45) in Italy. The study leads to the following conclusions:

- the damage state of the considered viaduct slab is extensive but prevailing superficial, limited to the concrete cover depth of the slab upper side; however, the slab thickness reduction due to concrete damage and the loss of the concrete-steel rebar bond are such that they produce serious structural deficiencies;

- except in the upper part of the slab, the actual mechanical properties of the concrete are rather constant along the slab height and consistent with the original concrete quality;

- the damage was mainly induced by freeze-thaw cycles during the winter season. The lack of maintenance worsened the viaduct conditions;

- the concrete cover restoration results adequate for strengthening the slab by means of FRP external reinforcements;

- the FRP reinforcement applied on the original concrete of the lower part of the slab appears to be particularly effective, producing bond forces +40% than the theoretical expectations.
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