

REGULAR ARTICLE

Effect of marine environment on the behaviour of concrete structures reinforced by composite materials

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Abstract. This study deals with experimental investigations of beam performances in a marine environment. Two kinds of concrete beams, unreinforced and reinforced with carbon plates and carbon rods, are being tested. The first one is stored in a laboratory, the other is exposed to a marine environment located in the north of France. After 12 months, all beams are tested via a four-point bending test in a laboratory. Results obtained have shown that beams stored in marine environment have a better behaviour than those stored in laboratory. It should be noted that no damage has occurred on these beams. However, we observe a significant increase of load of about 32% to 48% causing the first crack observed on the beams stored in marine environment compared to those stored in the laboratory. This means that beams in situ offer increased stiffness and a slight gain of failure loads. This may be due to the development of living organisms (in a marine environment) which acted as additional adhesive and sealing, providing a protection of concrete structures against damage.

Keywords: Composite material / marine environment / durability / concrete

1 Introduction

Port and river infrastructures are an important heritage in France, 60% of these infrastructures are over 50 yr old. They are subjected to different loads caused by mechanical, chemical, biological and climate-related effects. The development of organisms living on the concrete surface has an influence on concrete's preservation; these organisms could either be beneficial or dangerous. Some organisms such as algae are often seen on works' damp and submerged parts. They coat the concrete and block the passage of gases and oxygen lowering the carbonation and reinforcements' corrosion. Nevertheless, other types of living organisms such as mollusks take root in the concrete and can destroy it. Furthermore, they can release carbonic acid and carbon dioxide during the day [1]. An excess of these organisms increases the weight and area of some protruding structural elements and can generate significant static overloads. When the outdoor temperature drops below -3°C , moisture contained in the concrete's pores freezes starting from the cladding's largest pores. When water freezes, it increases its volume by about 9% and generates hydraulic pressure in the porous granular network [2]. If the pressure exceeds the concrete's tensile

strength, it causes cracks in the concrete's mass. Concrete damage depends on the rate of cooling, cycle numbers, minimum temperature reached and freezing period length.

The concrete interstitial solution offers a protection to armatures against corrosion due to its high alkalinity [3]. This high alkalinity forms a passive layer on the armature surface preventing the development of corrosion [4,5]. Nevertheless, this layer could be altered by the carbonation and ingress of aggressive agents such as chloride ions in particular [6]. In a marine environment, structures in a drawdown zone are especially susceptible to corrosion because of a strong chloride concentration as well as a minimum amount of oxygen. The drawdown zone is an area defined by the change in water level. This zone is covered and uncovered depending on sea level (drawdown area determined by high and low tides). In this zone, the concrete is repeatedly subjected to the wetting drying cycle. A high concentration of chloride ions and a sufficient amount of oxygen are present in this area causing the corrosion of reinforcements. This area represents the most unfavourable zone for the lifespan of structure. In addition to these constraints, the structure is also subjected to a freeze-thaw cycle in this area.

When concrete pores are saturated with water, as it is the case for submerged structures, carbon dioxide ingress is extremely low and carbonation is virtually nonexistent. Similarly, if the concrete is in a very dry environment, the amount of water is insufficient to dissolve carbonic gas, and

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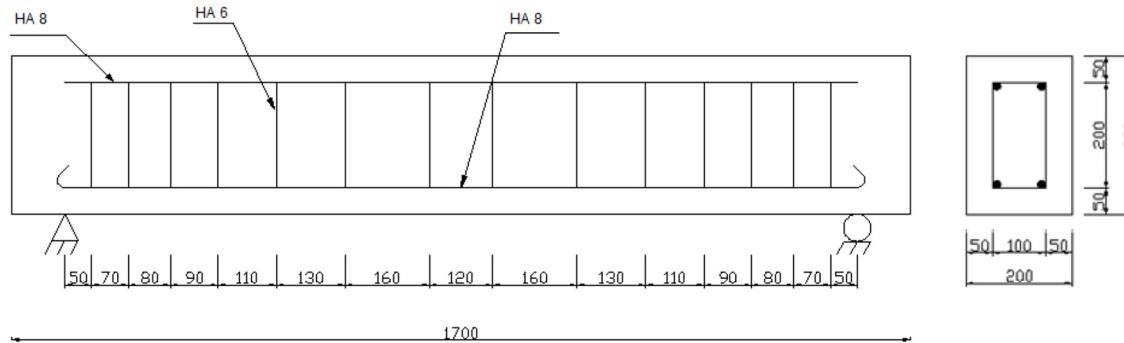


Fig. 1. Details of the beams reinforcement.

concrete only carbonates moderately. These phenomena have an impact on both mechanical properties and damage of concrete structures. The degree of damage is more or less important depending on whether the concrete is completely or partially immersed. To improve the lifetime and increase the ultimate strength, reinforcement or repair should be conducted in order to maintain the performance of structures [7,8]. Several repair techniques are used, such as structural reprofiling, shotcrete, epoxy injection and chute method [9–14], but these conventional techniques are not sustainable because of the marine environment that produces highly corrosion of materials.

Composite materials are increasingly used to reinforce or repair concrete structures in civil engineering due to their favorable mechanical and thermo-mechanical properties such as lightness, ease implementation, and the high resistance to chemical attack [15–17]. The lightness of composites and its capacity to adapt to complex shapes allow a substantial time saving during repair operations. Fazli et al. [18] studied the effects of marine environmental conditions on the bonded and bare surfaces of concrete slabs by means of the pull-off test. They observed that 12 months of exposure in a marine environment has a low effect on the epoxy performance between carbon fibre-reinforced polymer composite and concrete. Fibre-reinforced polymer is considered as an alternative to steel reinforcement due to many advantages of light weight, high strength and their non-corrosive properties [19–21].

The aim of this work is to study adhesive properties and the interface behaviour between composite and concrete beams in a marine environment. A total of 18 concrete beams non-reinforced and reinforced by carbon plates and carbon rods were built. Nine beams have been stored in a laboratory and 9 beams have been exposed in a drawdown zone to a marine environment in Dunkerque (France) for 12 months. Then, all beams were tested via a four-point bending test in the laboratory.

2 Experimental investigation

The main aim of experimental tests was to study the damage and behaviour of concrete beams in a marine environment. The experimental campaign has involved testing 18 beams, grouped in 3 series:

- Series 1: including 6 non-reinforced reference beams
- Series 2: including 6 carbon plate reinforced beams

- Series 3: including 6 beams reinforced by inserted rods

Beams were stored in two different locations: 3 beams of each series have been stored in a laboratory and 3 in a drawdown zone in a marine environment for 12 months. Test specimens were stored under normal laboratory conditions at a temperature ranging from 18 °C to 22 °C and 50% ± 10% relative humidity for a period of up to 12 months.

At the end of the ageing process, these beams were tested via a four-point bending test to measure and compare flexural strengths. This process will allow to quantify the eventual loss of resilience and to verify the durability of the reinforcement process.

2.1 Materials

2.1.1 Reinforced concrete

The reinforced concrete beams have 1700 mm length with a cross-section of 200 × 300 mm². The beams are reinforced with two longitudinal bars of 8 mm diameter at the bottom and top zones, and stirrups of 6 mm diameter (Fig. 1).

In this study, beams were placed in a marine-drawdown environment, the most unfavourable one, and concrete corresponds to the XS3 exposure class according to the NF EN 206-1 standard [22]. The selected cement is intended for a marine-environment use; it is a CEM III 42.5 N CE PM CP2 cement made of sand 0–4 mm and crushed gravel with a maximum diameter of 11.2 mm. Mixing ratios for cement: sand: gravel: E/C ratio are: 1: 1.90: 2.47: 0.39. In compressive test, three cylindrical specimens of 160 mm diameter and 320 mm high have been tested. The average compression strength of concrete at 28 days is equal to 32.65 MPa.

2.1.2 Composite materials

Beams have been reinforced by two methods: bonding of carbon composite plates and insertion of carbon rods. The high-performance composite strips were obtained by an arrangement of carbon fibres embedded into an epoxy matrix. The high tensile strength of these strips compensated the lack of tensile strength of concrete. The strips used are manufactured by the pultrusion process and have 50 mm width and 1.2 mm thickness. Carbon rods are installed using “NSM technique—Near Surface Mounted”.

Table 1. Mechanical characteristics of composite reinforcements.

Characteristics	Carbon plates	Carbon rods
Modulus of elasticity	>165 000 MPa	>140 000 MPa
Tensile strength	>2800 MPa	>2800 MPa
Fracture strain	>17%	>1.70%
Percentage of volume fibres	>68%	
Density	1.5	

Table 2. Characteristics of Sikadur 30 adhesive.

Characteristics	Sika 30 adhesive
Modulus of elasticity	12 800 MPa
Compressive strength at 2 days	>55 MPa
Bending strength at 2 days	>30 MPa
Glue density	1.8
Mixture ratio (white resin / hardener)	3/1 (by weight)
Adherence to concrete	>4 MPa

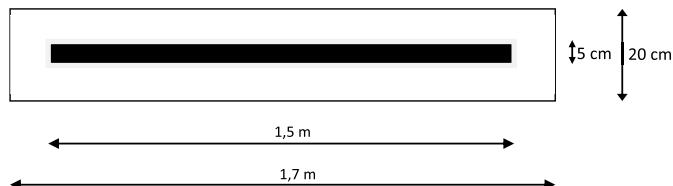


Fig. 2. Reinforcement with bonding of carbon plates.

Rods used for our tests have a circular section of 6 mm diameter. The mechanical characteristics of the composite plates, carbon rods and epoxy-based glue are given in Tables 1 and 2.

2.2 Tests set-up

In this study, two reinforced techniques are considered: reinforcement with carbon composite plates and reinforcement with carbon rods insertion. In the first technique, reinforced concrete was bonded with a carbon strip of 1.5 m length, 5 cm width and 1.2 mm thickness. The dimensions of concrete were 1.7 m length with a cross-section of 20 × 20 cm² (Fig. 2). The second technique used consisted of inserting two carbon rods in adhesive-prefilled concrete grooves. Carbon rods of 6 mm diameter are cut and degreased with a solvent before being placed in the grooves. Grooves must be filled with the extra glue and the surface must be levelled (Figs. 3, 4).

The surface preparations are carried out in order to remove laitance, standing water, grease, oils, old surface treatments or coatings and all loosely adherent particles (Fig. 5). The surface to be strengthened must be prepared

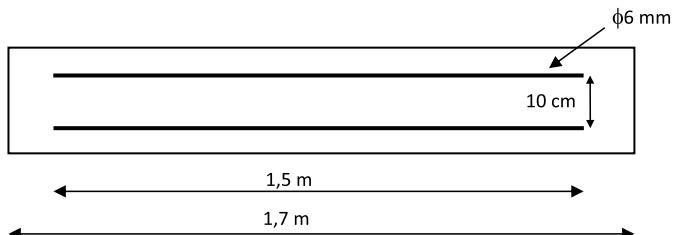


Fig. 3. Reinforcement with rods insertion.



Fig. 4. Insertion of rods insertion.



Fig. 5. Surface preparation.



Fig. 6. Plate rubbing.

by planing, grinding or sanding and dust must be removed by vacuum. This surface should be levelled and checked with a metal batten; the tolerance for 20 cm length is $\pm 2\text{mm}$. If this is not the case, repairs and levelling should be undertaken with structural repair materials such as repair mortar. Before applying adhesive, the substrate is thoroughly inspected and any unsound material (such as areas of damaged concrete or pieces of the original wooden formwork or tie-wires etc.) is removed. Adhesive is carefully applied to the properly cleaned and prepared substrate with a spatula to form a thin layer between 1.5 and 15 mm thick. Strips and rods are cleaned with a solvent dampened cloth before bonding. Carbon plate implementation is carried out using the double-application technique. A thin layer of adhesive is applied to concrete and plate. This double application allows an even coating of adhesive. The adhesive is applied at a temperature between 5 °C and 40 °C on a clean and healthy support with cohesive bond strength at least 1.5 MPa [23]. This adhesive is a 2-component thixotropic epoxy without solvents. It comes as a component A (white resin) and a component B (colour hardener black). Table 2 presents the mechanical characteristics of epoxy-based glue used to reinforce the test specimens. Using a rubber roller, the plate should be pressed in order to remove the excess adhesive (Figs. 6 and 7). The bonded surface should not be disturbed for at least 24 h and any vibrations should normally be kept at a minimum during the curing period of the adhesive. The strength of adhesive is reached after approximately 7 days at 20 °C.

Note that, the negative influence parameters on the mechanical properties are: Air entrapment in the sample, curing temperature / time, contamination of the adhesive. Note that, the mechanical properties are influenced by various parameters such as: air entrapment in the sample, curing temperature / time and contamination of the adhesive.

2.3 Bending tests

Three beams of each series have been exposed in a drawdown zone to a marine environment for 12 months



Fig. 7. Carbon plate reinforced beam.

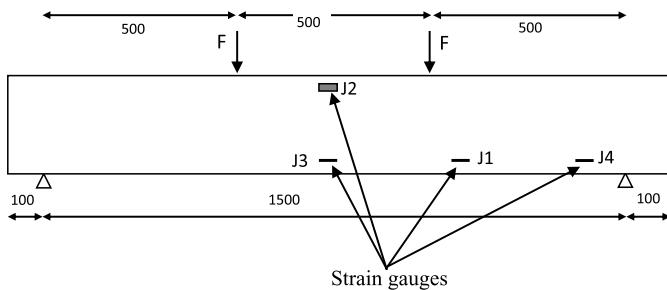


Fig. 8. Beams at the onset of ageing process.

(Fig. 8). At the end of this period, these beams and those stored in the laboratory are subjected to bending tests. The biological growths were removed with a scraper before

Table 3. Designation of beams.

Beams	Designation	Storage conditions
Non-reinforced reference beams	PT3, PT4, PT5	
Carbon plate reinforced beams	PL1, PL2, PL3	Laboratory
Carbon rods reinforced beams	PJ1, PJ2, PJ3	
Non-reinforced reference beams	PT1DK, PT2DK, PT3DK	
Carbon plate reinforced beams	PL1DK, PL2DK, PL3DK	Drawdown zone
Carbon rods reinforced beams	PJ1DK, PJ2DK, PJ3DK	

**Fig. 9.** Four-point bending test configuration.

bending tests. Scraping was done carefully in order to avoid damage of the composite material. Beams were tested in a partially dry condition after 24 h of storage in the laboratory.

Table 3 describes the type of beams, the storage conditions and the designation for bending tests. All beams were subjected to a four-point bending test with a 250 kN capacity press. The distance between the loading points is equal to 500 mm and the load point radius is equal to 0 m. Four displacement sensors were installed on both concrete and composite and were connected to a data acquisition system to measure displacements due to increasing load until failure (Fig. 9). The loading speed was held at a rate of 0.02 mm/s throughout the test.

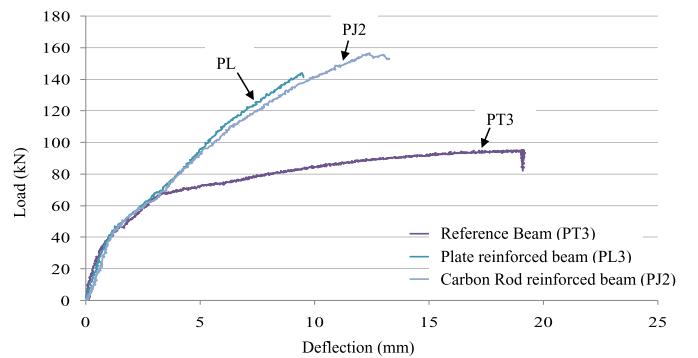
3 Results and discussion

In this section, we present experimental results coming from the measurement of bending tests of reference beams and reinforced beams with carbon plates and carbon rods for both environments.

3.1 Beams stored in a laboratory

Figure 10 presents the evolution of the applied load vs. displacement of bending tests. A comparison has been drawn between test results performed on reference and reinforced beams. For reinforced beams, it can be observed in Figure 10 two primary zones, namely:

- In the first zone, results show that behaviour is linear elastic with an absence of any cracked beams.

**Fig. 10.** Load /deflection curves of beams stored in laboratory.

- In the second zone, a second linear phase corresponding to the behaviour of cracked beams. The composite material allows increasing the beam strength to compensate the delamination phenomenon produced between the concrete and steel reinforcement.

For the non-reinforced beams, the two first phases are identical up to reinforced beams, but a third phase appears which corresponds to plastic behaviour of beams. These results indicated that the reinforcement with composite materials increases failure load and decreases mid span displacement. Furthermore, the failure load increased by about 60% between carbon plate reinforced and reference beams and by about 75% between carbon rod reinforced and reference beams.

The formation of first cracks have been detected for a 35 kN load and located at mid span beam deflection of 0.86 mm. Cracks due to the bending moment increase gradually as the applied load increases and the direction of cracks is perpendicular to the beam's axis. Cracks are located in a constant bending moment zone and their opening values are between 3 and 5 mm (Fig. 11). For the carbon plate reinforced beams, initiation and propagation cracks are given in Figure 12. The load corresponding to the initiation of crack is 45 kN. The failure load gain is about 145 kN, which corresponds to 75% of gain compared to the failure load of PT4 reference beam (Fig. 11).

Figure 13 shows the fracture mode of a carbon plate reinforced beams. It can be observed that delamination occurs at the concrete/composite interface. The beam fracture was caused by peeling off [24]. This rupture mode is identical for three composite plates reinforced beams.

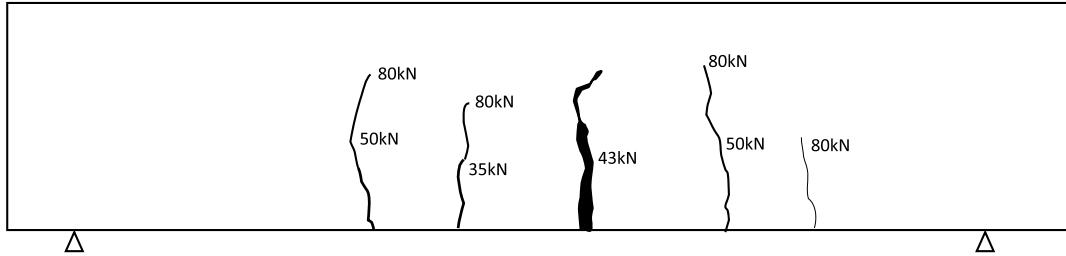


Fig. 11. Cracking of a reference beam stored in laboratory.

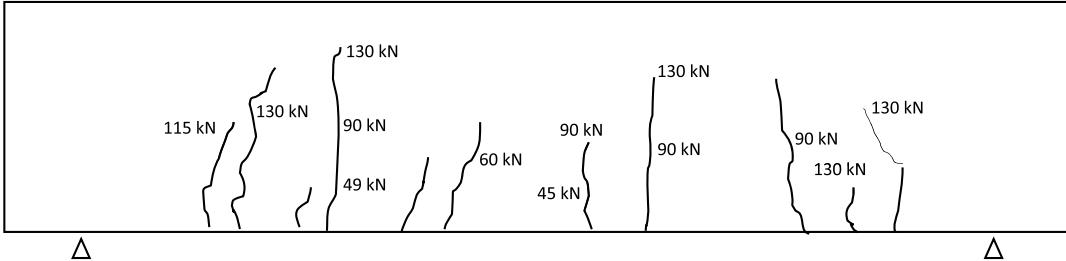


Fig. 12. Cracking of a plate reinforced beam stored in laboratory.

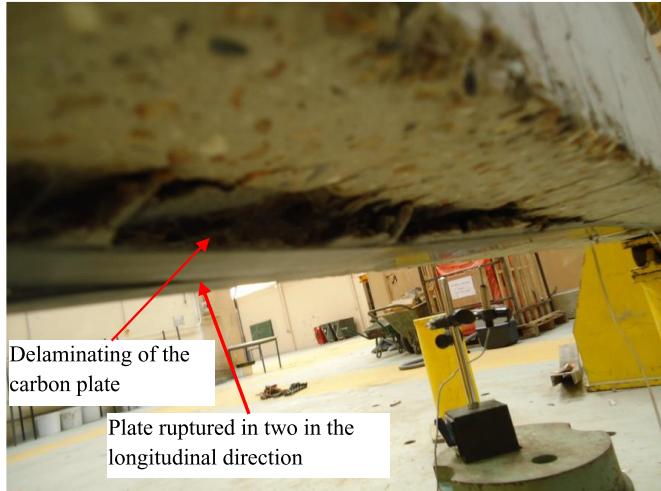


Fig. 13. Rupture of a carbon plate reinforced beam (PL3).

In the case of beams reinforced with composite carbon rods, rupture is sudden demonstrating a high fragility of carbon-rod reinforced beams (Fig. 14). In Figure 15, the initiation of cracks corresponds to a load of 45 kN which is similar to the carbon plate reinforced beams. The failure load is equal to 170 kN corresponding to a load gain of 80% compared to the unreinforced beam. Cracks initiated at the two supports and between these propagate in the direction of the load application point.

3.2 Beams stored in a marine environment for 12 months

Nine beams (non-reinforced reference beams, reinforced beams with a composite plate and rod) were exposed in a



Fig. 14. Rupture of a carbon rod reinforced beam (PJ2).

drawdown zone of the port of Dunkerque located in the north of France. After 12 months of aging, significant biological substance was observed on all beam surfaces. These biological growths are barnacles, algae and molluscs (Fig. 16). A high density of these biological substances has also been observed along the edges of carbon plates, but not on these plate surfaces.

Beams were tested via a four-point bending test in the same experimental conditions than those stored in the laboratory. Figure 17 shows the load evolution in function of the deflection. Failure load was equal to 85 kN for non-reinforced beams. The initiation of cracks was occurred similarly for two unreinforced beams. When the tensile stress reaches the concrete strength, one or more cracks appear. Increasing crack numbers were observed as well as

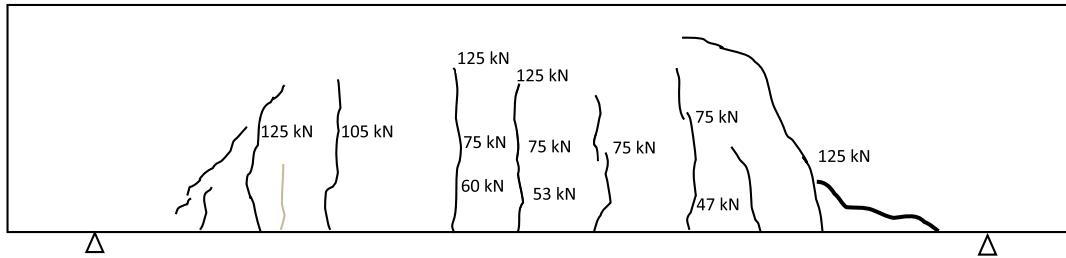


Fig. 15. Cracking of a rod reinforced beam stored in laboratory.



Fig. 16. Development of living organisms on the beams at the Port of Dunkerque.

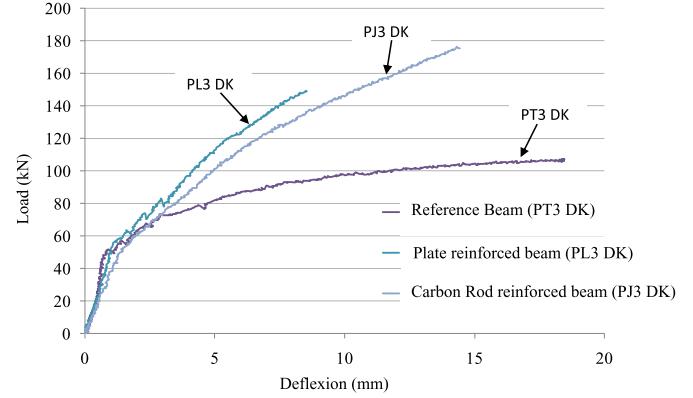


Fig. 17. Load/deflection curves of beams stored in situ (Port of Dunkerque).

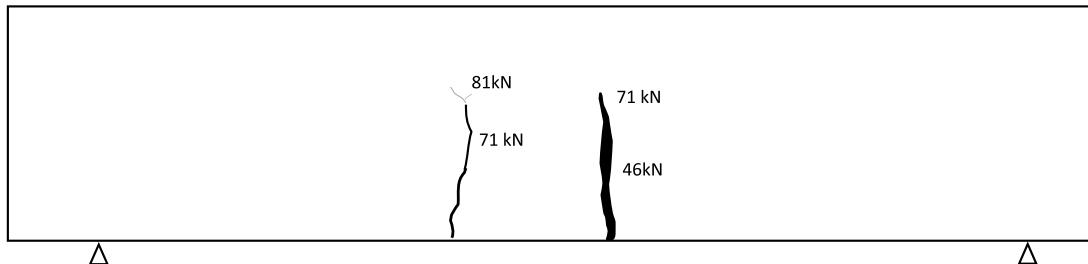


Fig. 18. Cracking of a reference beam stored in situ.

an increase in crack widths between 3 and 5 mm. These cracks propagate progressively according to the applied load in the direction of the upper face of beams (Fig. 18).

For reinforced beams with a carbon-composite plate, a significant cracking occurs at 137 kN. Then, the load decreases according to the initiation of the first crack which is produced at 148 kN. The failure load gain is about 43%, it is lower than that of all beams stored in laboratory (Fig. 19).

Cracks and their distribution appear more diffuse for reinforced beams by carbon plates and exposed to a marine environment. In addition, these cracks are distributed over the beams length (Fig. 20), as in the case of reinforced beams by carbon plates and stored in the laboratory. It has also been noted that the initiation of crack is caused by a stress concentration localized at the plate edges, which in turn leads to plate delamination.

These beams present a similar behaviour as those reinforced by composite rods and stored in the laboratory. It should be noted that a sudden failure of beams is caused by an increased fragility of carbon rod reinforced beams. The initiation crack load is about 56 kN, this value is 2.6 times lower than crack initiation load of beams stored in laboratory. The failure load is about 171 kN, this value is close to that carbon rod reinforced beams stored in laboratory.

4 Conclusion

In the present work, experimental results from bending tests of beams exposed to marine environment for 12 months and stored in laboratory have been presented. Four-point bending tests were conducted on non-reinforced

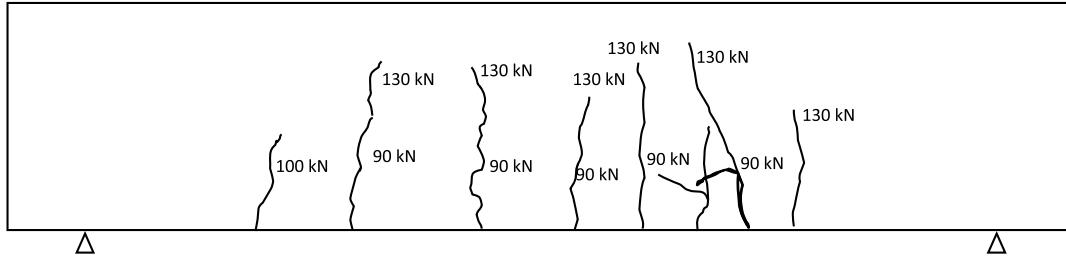


Fig. 19. Cracking of a plate-reinforced beam stored in situ (Port of Dunkerque).

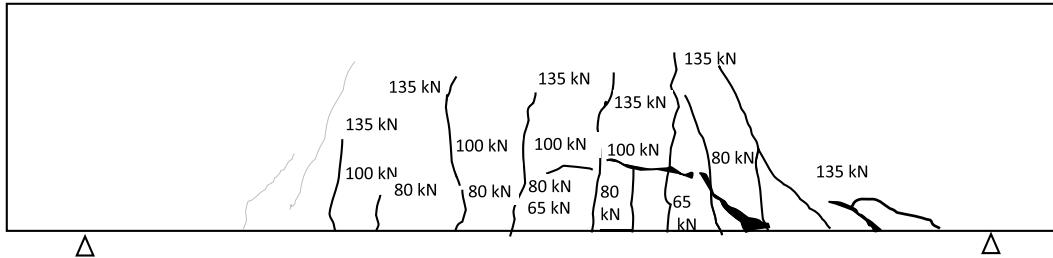


Fig. 20. Cracking of a rod-reinforced beam stored in situ (Port of Dunkerque).

Table 4. Summary of bending test results.

	Beam in laboratory			Beam in marine environment		
	Beam	Load of crack initiation (kN)	Failure load (kN)	Beam	Load of crack initiation (kN)	Failure load (kN)
Non reinforced	PT3	38	95	PT1 DK	50	93
	PT4	35	85	PT2 DK	46	86
	PT5	40	103	PT3 DK	55	107
Reinforced by plate	PL1	47	142	PL1 DK	62	148
	PL2	35	145	PL2 DK	63	151
	PL3	45	145	PL3 DK	63	149
Reinforced by rods	PJ1	33	147	PJ1 DK	60	183
	PJ2	47	156	PJ2 DK	53	171
	PJ3	45	170	PJ3 DK	56	176

beams, carbon plate-reinforced and carbon rod-reinforced beams. Tests have been performed to characterise the mechanical behaviour and to predict the failure load. The comparison between beams stored in laboratory and those exposed to marine environment is presented in [Table 4](#) and [Figure 21](#). Load values are obtained by a simple average of all failure loads of three tested beams for each specimen category. The important points emerging from this study are:

- Reinforcement by plate or carbon rods increases fracture load.
- Fracture load of reinforced beams by two 6 mm diameter rods is more important than that of reinforced beams by a plate of 1.2 mm thick and 50 mm width.
- There are no differences between the fracture modes of beams stored in laboratory and those aged in a marine environment.

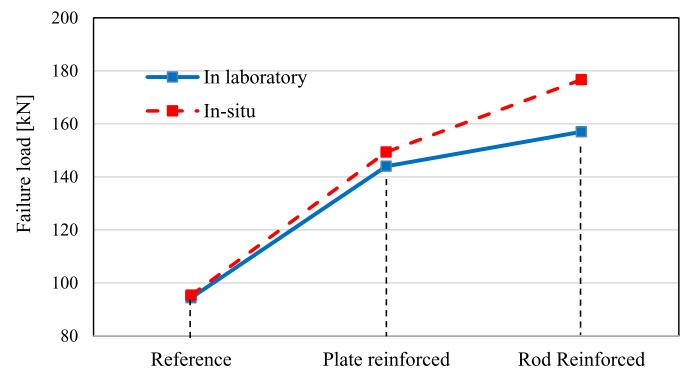


Fig. 21. Comparison of failure loads concerning beams in laboratory and in situ.

- Beams exposed in marine environment have a failure load slightly higher than exposed in laboratory. This may be due to plasticization of the adhesive by water or the

development of living marine organisms that protects the concrete from damage and acts as an additional adhesive or as one layer of waterproof material [2,10]. We have found few references in the literature to explain our present findings.

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