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Durability issues of FRP rebars in reinforced concrete members

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Abstract

The use of fibre reinforced polymers (FRPs) as rebars in reinforced concrete (RC) elements is a viable means to prevent corrosion effects that reduce the service life of members employing steel reinforcement. However, durability of FRP rebars is not straightforward as it is related to material properties as well as bar–concrete interaction. A state of the art of durability of FRP rebars is presented herein in order to highlight issues related to the material properties and interaction mechanisms which influence the service life of RC elements. The design approach implemented in international codes is discussed and the reduction factors taking into account the durability performances are summarized.

Keywords: Durability; FRP bars; Environment effect; Long-term behaviour; Thermal effects

1. Introduction

The increasing use of fibre reinforced polymers (FRPs) as rebars in reinforced concrete (RC) structures has been supported by the ‘‘durability’’ of this novel material. However, the high durability of FRPs has been defined only with regard to that of steel rebars. The latter are detrimentally affected by corrosion phenomena governing the effective life of structures and their maintenance costs. Unfortunately durability of FRP rebars is a not straightforward subject; it tends to be more complex than corrosion of steel reinforcement, because degradation of the material could depend both on resin and fibres and on their interface bond behaviour. Furthermore, the types of rebars available on the market are various and the commercial products are continuously changed. Different fibres are characterized by different behaviour under high temperature, environmental effects and long-term phenomena. In addition concrete could be an unfavourable environment due to alkali and moisture absorption.

The durability of FRP materials has not been yet assessed thoroughly and hence reliable design rules for RC structures are still lacking. Nevertheless, it has been observed [69,60,33,7,37] that the durability of concrete members reinforced with FRP rebars depends on the effect of concrete environment for the composite material and cracking and concrete–bar bond. The latter is of paramount importance and depends on the rebar surface adopted by the manufacturer to improve bond (e.g. sanded, ribbed, etc.). It has also been noted [42] that crack openings are generally higher than in RC members with steel rebars, being the Young's modulus of FRPs lower than in mild steel, thus reducing the protection due to concrete.

Recently, many studies have been carried out on durability of FRP bars [6,25,26,32,36,38,53,69]; however, there are still many aspects to be investigated to provide reliable design rules to be implemented in codes of practice.

The durability may be defined as the capacity of a material or a structure corresponding to the initial performance and is kept constant during time. In structural engineering durability is thus the property related the effective life of the construction. Materials and structures can be characterized in several manners. Variations of mechanical

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properties as Young's modulus, tensile strength, interlaminar shear and bond strength are the most suitable indicators of FRP deterioration. Considering the interaction with concrete, durability is also the ability to prevent cracking, chemical degradation, delamination, wearing, and similar effects of ageing with time, under the conditions of sustained loads and/or design environmental conditions.

In this paper a state of the art of durability of FRP rebars is dealt with. The adopted framework can be divided in three parts: effects of external and concrete environment, long-term effects, influence of concrete–FRP mechanisms.

Experimental results relative to the effects of temperature, chemical agents and moisture are presented to compare different types of fibres and resins. Long-term phenomena are also discussed and the role of fibres type and the consequences on RC elements are presented. Finally, direct influence of interaction mechanisms between concrete and rebar, especially due to bond, are outlined.

References to specific provisions available in the technical literature and/or codes are introduced, as appropriate, for each of the features influencing the durability.

2. Durability of FRP material

Experimental tests to investigate durability have long durations and require accelerated methods to activate the environmental effects. Thus the accuracy of the results in terms of real time performances has to be determined. There is no full agreement about the test procedures; the topic is further complicated by the variability in FRP products and their use in concrete members.

It is essential in structural applications to identify standard test procedures that could be confidently recommended for materials.

FRP bars include two different phases, a resin matrix and unidirectional fibres. As a result, the properties of both components and resin/fibres interface have to be investigated with special emphasis on the influence of environmental and mechanical parameters. All the above components play a role in defining the characteristics of the composite material and can be susceptible to attack by various aggressive environments, so that the adequate performance of all three elements has to be fully warranted throughout the design life of the structure.

Matrix protects fibres and transfers uniformly stresses between them, therefore the type of resin and the quality of its realization are fundamental. The effectiveness of the resin depends on its continuity of surface and absence of defects. For example, cuts at the ends of composite expose directly fibres to external environment giving undesirable effects in a durability viewpoint. In such regions environmental effects can produce damage of the fibre/matrix bond, because of the exposure of the fibres along their length, matrix and the resin/fibre interface of internal parts to direct attacks from the environment.

The characteristics of resins that could reduce durability of FRP materials, independently from resin and fibres type are:

- Resin wet out (how well the fibres are covered by resin);
- Absence of cracks (either surface or through thickness);
- Absence of voids (generally smaller and well distributed is preferable);
- Degree of cure of resin (if the production process was not well controlled the resin may be insufficiently cross-linked to provide the designed protection).

  Other qualities of resins are significant for durability, but can be controlled by selecting the type of resin:
- Resistance to alkali and chloride attack;
- Toughness to resist microcracking;
- Impermeability to environment penetration to the interior;
- Easy manufacturing to minimise quality variations;
- High compatibility with fibres to ensure a strong fibre/matrix bond.

Fibres provide stiffness and strength to composite material, i.e. the performance of structural systems depends on their main mechanical properties and durability behaviour. The durability of glass, aramid and carbon fibres, that are the most common types used in civil engineering applications, are different and have to be underlined for all the effects assessed hereafter. In general glass fibres, that are largely used also because are the cheapest ones, are less durable when used as rebars in concrete, due to high chemical sensibility to alkali environment. However, these observations should lead to a review of the existing design process to consider that improving of performances can arise by optimizing the manufacturing techniques and coupling with various resins.

Durability of a composite material is related not only to the properties of its constitutive materials (fibres and matrix), but also to the integrity of the interface between these two components. Bond of FRP reinforcement relies upon the transfer of shear and transverse forces at the interface between bar and concrete, and between individual fibres within the bar. These resin-dominated mechanisms are in contrast to the fibre-dominated mechanisms that control properties such as longitudinal strength and stiffness of FRP bars. Environments that degrade the polymer resin or fibre/resin interface are thus also likely to degrade the bond strength of an FRP bar.

Usually a strong fibre/matrix interface is needed and inadequate selection of fibre or matrix types or incorrect processing can lead to a weak interface to environmental attacks. A deterioration of this interface reduces the capacity of load transfer between fibres with a consequent weakness of the composite material [26]. The use of a coupling agent on the fibre surface improves the strength of the interface, and protects the fibres against environmental attack or reaction with moisture or alkalis. However, the chemical bond between the coupling agent and the surface of glass fibres is not stable in the presence of moisture and alkalis that gradually destroys this bond, causing damage to the interface.

Combined with chemical attacks, a high level of sustained mechanical loading increases the degradation of the fibres/matrix interface.

2.1. Environmental influences

FRP bars are susceptible to changes of strength and stiffness in the presence of environments prior to, during, and after construction.

The external environment is characterized by many chemical and physical actions, but only some of them could give important effects on FRP materials modifying their mechanical performances, thus reducing durability of structure. The most important are generally those discussed in the following, although their influence depends on the type of composite material (type of resin and fibres).

One of the most important effects of external environment is the variation of thermal conditions. In a polymeric composite the matrix properties are more affected by the increase in the temperature than the fibre properties. The glass transition temperature (T_g) of the matrix is a key parameter, since it defines a topic point generally corresponding to significant changes with considerable reduction of the mechanical properties.

The elastic modulus and strength of an FRP bar decrease with the increase in temperature under high temperature and sustained load. In the short-term, an increase in temperature between 30 and 40 °C, that is a significant condition in the life of a structure, does not significantly affect the strength or the elastic modulus of the most of commercial fibres. However, long thermal ageing at a high temperature combined with sustained loading may cause deterioration in the properties of the matrix.

Under service temperature of concrete structures (from −20 to +60 °C) the reduction in Young's modulus is negligible for CFRP, however slight reduction occurs for AFRP and GFRP (Fib technical report [17]).

A reduction of ultimate load capacity in presence of high temperature is caused by modification of matrix properties and in consequence of interface fibre–matrix, limiting the effectiveness of fibres strength.

In many civil engineering applications, RC members are subjected to high number of freezing/thawing cycles, that are mostly combined with water and chloride ions penetration into the concrete, producing degradation of fibres, resin and interfacial bond. Microcraking of resin is particularly influent because reduces the protection of fibres and bond at the resin interface; thus the type of resin is a key parameter for durability of FRP as further discussed in the next section.

As far as very high temperature is concerned, i.e. fire resistance, polymeric materials are usually flammable or harming in the case of fire, therefore, basically resin determines the temperature/fire resistance of FRPs. Resins soften, melt or catch fire above 150–200 °C. Fibres themselves are more or less able to resist to higher temperatures: aramid to 200 °C, glass to 300–500 °C while carbon in non-oxidizing environment up to 800–1000 °C (Fib technical report [17]). Due to the temperature independence of carbon fibres themselves, CFRP shows the most favourable behaviour.

In Fig. 1 [64] experimental variation of Young's modulus and tensile strength at increasing temperature is shown for various types of aramid and carbon rebars. In the first graph the reduction of Young modulus as a function of the room temperature is depicted for three types of aramid and carbon rebars; the higher reduction for aramid is shown. The same results are found also in the second graph where the value of the tensile modulus is plotted. Finally in the third graph the strength reduction is shown for one aramid

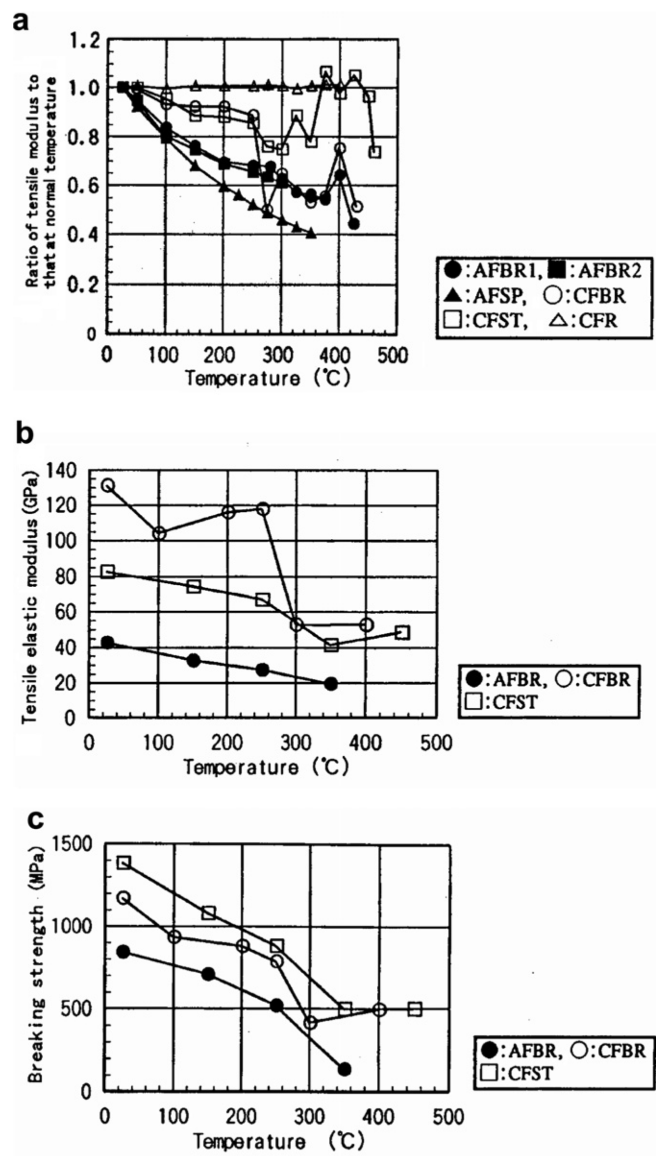

Fig. 1. Effect of temperature [65]: (a) perceptual variation of Young's modulus; (b) variation of Young's modulus; (c) variation of tensile strength.

and two carbon rebars, confirming the superior performance of carbon.

Ultraviolet rays affect polymeric materials that can be considerably degraded [41,7]. Exposure tests have shown [67,23] for AFRP rods around 13% reduction in tensile strength after 2500 h exposure, 8% reduction for GFRP rods after 500 h (no reduction thereafter) and no reduction for CFRP rods. Some results from combined ultraviolet and moisture exposure tests with and without stress applied to the bars have shown tensile strength reductions of 0–20% of initial values in CFRP, 0–30% in AFRP and 0–40% in GFRP [52,71].

Exposition usually does not occur for rebars inside concrete, but attention needs in storage.

For chemical attack, the most important problem could be the effect of acid attack. However, there is a lack of data. Acid attack is more dangerous for concrete, therefore this is more interesting for RC elements when acid resistant cement, such as high-alumina cement, is used with FRP reinforcement.

The degradation process due to chemical actions occurs for combining effects of microcracking in the matrix, due to stress conditions, that favourite penetration of corrosive agents to the core of the bar. There is a stress limit below which microcracking in the matrix cannot occur, and capillary action, related to porosity or imperfections, dominates durability.

2.2. Effects of concrete environment

The most significant problems of steel corrosion in RC elements are related to carbonation that occurs everywhere depending on concrete W/C ratio, cement type, curing, CO_2 concentration and cracking.

Aqueous solutions with high values of pH are known to erode the tensile strength and stiffness of GFRP bars [44], although results vary tremendously according to differences in test methods. Higher temperatures and longer exposure times exasperate the problem.

FRPs are generally not affected significantly by the process of carbonation that reduces concrete alkalinity due to the high calcium hydroxide content of hardened cement stone (pH 12.5–14), therefore the usual benefit of concrete in protecting reinforcement could cause a reinforcement degradation when FRP rebars are used.

On the other hand, alkalinity may affect glass fibres unless suitable polymer resins [60] protect them. The interface between glass fibres and the resin controls the resistance of the GFRP bars to the alkalis [69].

Experimental data [36] showed that resin properties may strongly influence the durability of FRP reinforcement: particularly GFRP rods are sensitive to alkaline attack when polyester resin is used because does not provide adequate protection to fibres (Fig. 2).

Carbon fibres tend to show the best resistance, followed by aramid and then glass fibres [33].

Carbon fibres cannot absorb liquids and are resistant to acid, alkali [36] and organic solvents, therefore, do not show considerable deterioration in any kind of harsh environments, while deterioration of glass fibres in alkaline environment is well known and the role of resin could be more [60] or less negligible [57,66,71]; in particular vinylester resin offers a greater alkali resistance than polyester resins.

The type of glass fibres, resin and manufacturing process could may lower the tensile capacity in the range of 25–100% [47]. According to the type of glass fibre tensile strength reductions in GFRP bars ranging from 0% to 75% of initial values have been registered [16]. Tensile stiffness reductions in GFRP bars range between 0% and 20% in many cases. Reduction of strength due to alkali can be influenced by high temperature and stress level [38]. In the case of CFRP, the decrease in strength and stiffness may vary between 0% and 20% [63].

Tensile strength and stiffness of AFRP rods in elevated temperature alkaline solutions either with or without tensile stress have been reported to decrease between 10–50% and 0–20% of initial values, respectively [63,47,56].

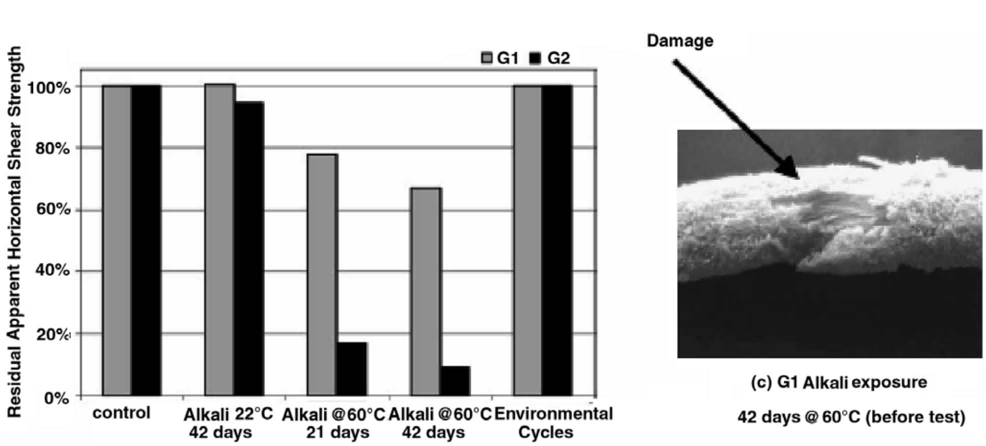

Fig. 2. Degradation of resin caused by alkali (G1: GFRP rebars with thermoplastic resin, G2: GFRP rebars with polyester resin [36]).

Some experimental studies [37] were performed to investigate the performance of GFRP materials exposed to a concrete environment in built structures. Any degradation was found for GFRP reinforcement (rods and grids) in concrete environment in real-life engineering structures exposed to natural environmental conditions for durations of 5–8 years. The EDX analyses indicated no alkali ingress in the GFRP reinforcement from the concrete pore solution. The results was that, under tension, GFRP reinforcement is durable and highly compatible with the concrete material and results are used for the new addendum of CHBDC [13].

Another environmental problem in RC concrete elements could be presence of chloride in sea construction or de-icing salts that usually accelerate corrosion.

Results vary widely because it is difficult to distinguish the effects of chloride attack and degradation due to moisture diffusion and/or alkali attack of the fibres. CFRP and AFRP reinforcements are insensitive to chloride ions. Experimental studies demonstrated that GFRP reinforcements can be seriously damaged in marine environment or in presence of de-icing salts [48].

During casting of concrete, FRP rebars can absorb water causing a chemical reaction. The moisture absorbed by the composites, combined with the temperature of exposure, induces stresses in the material with consequent damage of fibres, matrix, and their interface and decreasing of the strength of FRP material with time.

Moisture can be absorbed by capillary uptake along any pre-existing crack or interface between the fibre and resin matrix. The effect of moisture on composites is a mass uptake, followed by the plasticization of the matrix and a decrease in the glass transition temperature. Moisture can act as a plasticizer disrupting Van-der-Waals bonds in polymer chains [7] and producing fibre–matrix de-bonding [21]. The phenomenon is emphasized for polyester resins and high temperature (>60 °C) (Fig. 3).

Carbon and glass fibres cannot absorb water [74]. Conversely, water absorption in aramid fibres causes reversible decrease in tensile strength, Young's modulus or relaxation and irreversible decrease in fatigue strength [43]. Decrease in characteristics of AFRP due to water absorption is

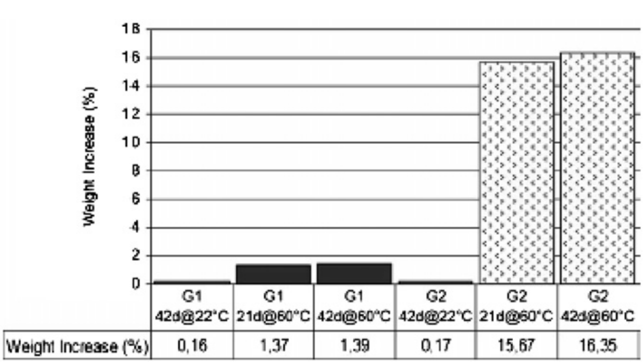

Fig. 3. Absorption capacity (G1: GFRP rebars with thermoplastic resin, G2: GFRP rebars with polyester resin [36]).

about 15–25% [20]. According to swelling of AFRP reinforcement, bond cracking can be induced by wet/dry cycles (e.g. in splash zones of marine structures) that cause deterioration and points out that aramid fibres are inapplicable in marine environment [58,59] although the low sensitivity to chloride.

A synthetic scheme of the meaningful issues of FRP rebars durability in concrete is represented in Table 1.

2.3. Mechanical properties time depending

The most important time depending properties are: creep, relaxation and fatigue.

Creep phenomena in FRP rebars include: the creep strain under sustained load and the long-term tensile strength under sustained load (often called stress rupture, residual strength or creep rupture strength) that can be suddenly attained after a period of time called "endurance limit". Creep failure strength can be defined as the tensile stress causing failure after a specified period of time after starting of a sustained load.

This type of failure depends on the fibre and resin types: considering that carbon and glass fibres have excellent resistance to creep, while most of polymeric resins can be very susceptible, the creep performance of FRP bars strictly depends on orientation and volume fractions of fibres.

The endurance limit decreases as the ratio of the sustained tensile stress to the short-term strength increases. High temperature, exposure to UV radiation, high alkalinity, wet and dry cycles and freeze-thaw cycles may reduce the creep rupture strength and the endurance time.

It was experimentally observed that creep rupture [11] does not occur if sustained stress is lower than 60% of the short term strength. Therefore this phenomenon is relevant for prestressed element, while in the RC elements the low level of stress in FRP rebars at serviceability loads does not cause the possibility of creep rupture.

Experimental results [27] on GFRP, AFRP and CFRP bars, evidenced a linear relationship between creep rupture strength and the logarithm of time, for period up to 100 h. By extrapolating the results to 500,000 h (57 years) the ratios of creep strength rupture to the short-term strength of bars were linearly extrapolated to be 0.29, 0.47 and 0.93 for GFRP, AFRP and CFRP, respectively. Test on commercial twisted CFRP bars and AFRP bars with an epoxy matrix at room temperature to determine the endurance time[5] showed that the estimated retained percentage of short-term strength after 50 years was 79% for CFRP and 66% for AFRP. Tests on GFRP bars with vinylester matrix at room temperature [55] evidenced a creep strength rupture equal to 55% of the short-term strength for an extrapolated endurance time of 50 year.

Tests focusing on the durability of E-glass/vinylester FRP bars in alkaline and de-ionized water under sustained tensile stress (or no stress) at ambient and elevated temperatures up to 608 °C for periods of up to 14 months

Table 1
Effects of environmental agents in concrete

Effect	Aramid	Carbon	Glass	Influencing parameters
Alkali exposition	Strength reduction 0–20%	Strength reduction 0–20%	Strength reduction 0–75%	Resin type, temperature, tensile stress
Chloride exposition	Low sensitivity	Resistant	Sensible	
Moisture	Decreasing of fibres mechanical characteristics	Damage of resin	Damage of resin	Resin type, temperature

evidenced that the creep strain in the 9.5 mm bars was less than 5% of the initial value after 10,000 h of sustained tensile loading [39]. This value was obtained under high tensile stress of 38% of the guaranteed tensile strength.

A test method to characterize creep rupture of FRP bars was proposed by Japan Society of Civil Engineers (JSCE-E533 [29]), while ACI 440.3R-04 [3] proposed a "Test Method for Creep of FRP Bars". These test methods are aimed at evaluating the load-induced tensile strain at imposed ages for FRP bars under a selected set of controlled environmental conditions and the corresponding load rate.

CFRP shows excellent behaviour with regard to the strains due creep. It can be stated that creep strain of CFRP, at room temperature and humidity, remains under 0.01% after 3000 h at a tensile stress of even 80% of the tensile strength [33,49,68]. AFRP and GFRP give much higher creep strain than CFRP: 0.15–1.0% for AFRP and 0.3–1.0% for GFRP at the same conditions above described [20,33,43].

The relaxation phenomenon of an FRP bar is defined by the time dependent decrease in load of the bar held at a given constant temperature with a prescribed initial load applied and held at a given constant strain [22,34]. Usually relaxation is defined after 1 million hours. A test method for long-term relaxation of FRP bars has been suggested by JSCE (JSCE-E 534 [30]) and by the ACI sub-committee 440 K [4].

Experimental studies have been performed on different FRP products considering various load durations [5]. Test results indicate that at increasing the temperature, the relaxation rate becomes greater and this tendency is stronger for AFRP bars. Relaxation after 1000 h can be estimated as 1.8–2.0% for GFRP tendons, 0.5–1.0% for CFRP tendons and 5.0–8.0% for AFRP tendons, while relaxation of GFRP, CFRP and AFRP tendons after 50 years of loading can be estimated as 4.0–14.0%, 2.0–10.0% and 11.0–25.0%, respectively, depending on the initial tensile stress [6].

A summary of time-depending phenomena described above is reported in Table 2.

Fatigue is a degradation of the integrity of a material caused by repeated applications of a large number of loading cycles that reduce meaningful mechanical properties such as strength and stiffness. A loss of strength causes a premature failure of the component, because occurs at a small fraction of the static strength of material.

Evaluation of fatigue resistance in FRP materials is complex due to several damage mechanisms at many locations in the composite element: matrix cracking, fibre breaking, crack coupling, delamination initiation and delamination growth [53], so that the FRP components fail due to a series of interdependent damage events. Unidirectional FRP composites possess high fatigue resistance with linear behaviour up to failure, while in presence of angle-plies localized damage mechanisms can occur making non-linear the stress–strain response [22].

Fatigue resistance of GFRP is usually less than that of prestressing steel [74,33,34].

The fatigue stress limit is the stress level below which a material can be stressed cyclically for an infinite number of times without failure.

Individual glass fibres, such as E-glass and S-glass, are generally not prone to fatigue failure; individual glass fibres, however, have demonstrated delayed rupture caused by the stress corrosion induced by the growth of surface

Table 2
Range of time-depending effects

Phenomenon	Aramid (%)	Carbon (%)	Glass (%)	Influencing parameters
Creep strain under sustained load (i.e. 80% tensile strength after 3000 h)	0.15–1.0	<0.01	0.3–1.0	Temperature, humidity
Creep failure strength after about 50 years	47–66	79–93	29–55	Resin type, volume fraction and orientation of fibres, environmental conditions
Relaxation				
1000 h	5.0–8.0	0.5–1.0	1.8–2.0	Temperature, initial tensile stress
50 years	11–25	2.0–10	4.0–14	

flaws in the presence of even minute quantities of moisture in ambient laboratory environment tests [35].

GFRP bars may loose approximately 10% of the initial static strength per decade of logarithmic lifetime [35] in presence of cyclic tensile loading. Environmental factors aging contemporaneously to cyclic load can influence the fatigue behaviour of GFRP bars due to sensibility of glass fibres to moisture, alkaline and acidic solutions.

CFRP composites are the least vulnerable to fatigue failure: the fatigue strength is 3–4 times higher than that of prestressing steel [68,49,50]. At one million cycles the fatigue strength (residual strength after being subjected to fatigue) is usually between 50% and 70% of the initial static strength, and is low dependent on environmental conditions, unless the resin or fibre/resin interface is substantially degraded by the environment. Fatigue of CFRP seems to be independent of stress level and amplitude [70].

In general fatigue behaviour when FRP rebars are embedded in concrete is influenced by concrete environmental that results in negative effect reducing fatigue life (Fig. 4 [45]).

In the case of CFRP bars encased in concrete the fatigue strength further decreases when the temperature increases from 20 °C to 40 °C [1]. Therefore the endurance limit is inversely proportional to loading frequency and decreases due to the higher mean stress or a lower stress ratio (minimum stress/maximum stress) [49].

Aramid fibres, for which substantial durability data are available, appear to behave similarly to carbon and glass fibres in fatigue. Neglecting the rather poor durability of all aramid fibres in compression, the tension–tension fatigue behaviour of an impregnated aramid fibre bar is excellent. Strength degradation per decade of logarithmic lifetime is approximately 5–6% [46]. While no distinct endurance limit is known for AFRP, but for 2 million cycles the fatigue strength reported is variable between 54% and 73% of the initial ultimate strength [41]. Both GFRP and AFRP show similar dependency of stress level on fatigue strength like prestressing steel does [70].

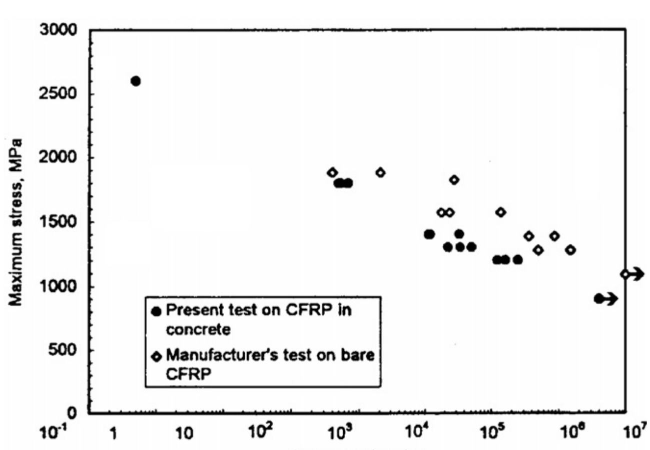

Fig. 4. Comparison of fatigue behaviour of bare and embedded CFRP rebars [45].

Deformations, ribs or wraps on FRP bar surface can induce local stress concentrations influencing the performance of FRP bars under repeated loading: local stress concentrations generate multiaxial stresses increasing the damage mechanisms related to matrix failure degrading the fatigue performance. Construction modality of the FRP bar can activate damage mechanisms related to fibres failure [24].

For FRP rebars used as concrete reinforcement, various types of fatigue testing, such as tension–tension, tension–compression, compression–compression, etc., are possible [61,8,25]. The results indicated that bond strength can either increase, decrease, or remain the same following cyclic loading that means that bond fatigue behaviour has not been sufficiently investigated to date. A test method to determine the fatigue characteristics of FRP bars under tensile cyclic loading has been adopted by JSCE (JSCE-E 535 [31]) and a similar method has been proposed by ACI 440k [4], that is surely a basic procedure for evaluating material characteristics.

3. Influence of concrete–FRP mechanisms

The previous analysis of durability regards FRP rebars alone or in concrete, but does not exhaust durability of RC elements reinforced with them.

Deterioration of strength, stiffness and bond at concrete–FRP interface influences strength and stiffness reductions of RC members. It is, thus, important to highlight the influence of the mechanical problems due to interaction between concrete and FRP [73].

It is worth noticing that the most types of rebars are characterized by Young modulus lower then steel one, thus cracks opening in service conditions are high reducing the protection role of concrete around rebars.

Surface configurations of rebars can modify the bond behaviour of FRP rebars; suitable surface geometry and treatment [72] can reduce crack widths and increase the splitting forces that usually limits the bond strength, allowing the application of rebar near the surface without risk of longitudinal cracks.

However the difference between thermal coefficients (CTE) of concrete and FRP play a very important role when thermal actions occur. In the longitudinal direction of FRP rebars the CTE is strongly dependent on fibres characteristics, but in transversal direction is governed by resin. In Table 3 typical values of CTE are reported evidencing that in longitudinal direction glass fibres result

Table 3
Coefficient of thermal expansion

Direction	Coefficient of thermal expansion ($\times 10^{-6}$/°C)			
	Steel	GFRP	CFRP	AFRP
Longitudinal, α_L	11.7	6.0 to 10.0	−1.0 to 0	−2.0 to −6.0
Transverse, α_T	11.7	21.0 to 23.0	22.0 to 50.0	60.0 to 80.0

similar to concrete but in the transversal one the thermal expansion is much higher for all types of fibres.

Therefore when high temperature variation takes place the large difference between transversal CTE can lead to transversal strain much higher than the concrete ones (Fig. 5), causing radial pressure on the surface of the reinforcement with cracking of surrounding concrete and longitudinal splitting of concrete cover. Therefore the thickness of concrete cover must be generally increased [2].

Experimental pull out tests on embedded CFRP wires [32] have investigated the combined effect of high temperature and concrete cover thickness (10, 20 and 30 mm) on the bond strength. Bond strength increase with the increase of concrete cover up to approximately 100 °C, above 100 °C deterioration of resin matrix is the governing parameter of failure due to a softening phenomenon, while at 200 °C bond strength does not seem influenced by the concrete cover.

Requirement of concrete cover thicker than for steel reinforcement highlights the problem in the case of the innovative technique of strengthening with near surface mounting rebars (NSMB), when the FRP rebars are posed in the cover of the steel ones.

Thermal cycles (also *freezing and thawing*) can damage bond at concrete interface reducing stiffness of the element (increment of deflection) and increasing cracks opening, because, as well-known bond law defines tension stiffening phenomenon.

An important effect on the CTE of rebars is the surface treatment, the effect of spiral wrapping used to improve bond can be relevant; when transversal dilatation occurs a confinement effect of the wrapping reduces the transversal strain and the consequence radial tension on concrete [19].

Also at high temperature and for fire resistance the role of concrete cover is much more important because it represents the protection of rebars, in general less fire resistant than steel.

Tests on beams under high temperature [64] showed the reduction of stiffness and strength is higher when composite reinforcement is used instead of steel (Fig. 6); furthermore the result depends on the fibres but also on the type of rebars [51].

In case of beams fatigue life is related to bond degradation that for FRPs strongly depends on surface treatment. In some cases FRP reinforcement can result in less fatigue degradation [54] than steel, having a bond mechanism governed by more stiff and resistant ribs that result in higher damage of interface during cyclic loads. Therefore it is difficult to evaluate the fatigue strength in concrete because many surface treatment are available with very different bond laws (fib bulletin no. 10 [18]).

Long-term effects of RC elements depends on creep characteristics of reinforcement but also on concrete creep, therefore in general the beam behaviour is similar to that of steel reinforced one and deformability increment in case of FRP reinforcement is not much higher [10]. Moreover it can be observed that low elastic modulus of FRP gives a higher stress in compressive concrete at the same percentage of reinforcement, enhancing the influence of concrete creep. Really the creep effects has to be considered together with shrinkage of concrete, therefore the problem is complex but surely much more influenced by concrete behav-

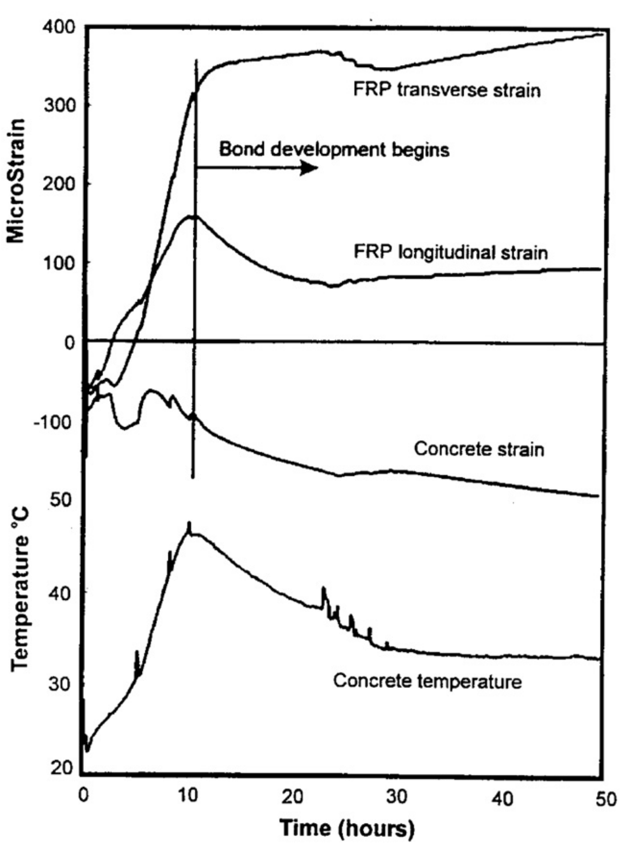

Fig. 5. Strains in concrete and rebars due to temperature [19].

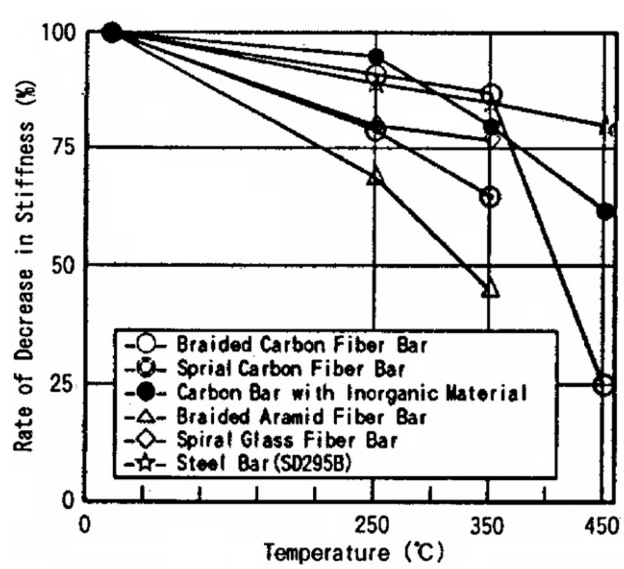

Fig. 6. Stiffness reduction of beams due to temperature effect [64].

iour than reinforcement one. Finally the creep of FRP-concrete bond interface have to be considered, but many type of surface treatments are available and experimental information are lack; considering that FRP bond results in higher stress level of the reinforcement than concrete, compared to steel bond, in general creep could be lower.

4. Design provisions for durability

The alteration of the materials properties in the time is a critical topic for designer, that develop their design for an established service life (usually 50 or 100 years) of the structure. The existing design codes and guidelines (in Japan, Canada, USA and Norway) have been developed to take account of specific environmental and time effects in a similar way. The philosophy identifies the main time depending situations and introduces a series of strength reduction factors to account for potential deterioration of FRP in these conditions. Furthermore in the provisions about constructive details the minimum concrete cover (the concrete thickness covering the rebar) is suggested considering the protection of FRP rebar, the avoiding of splitting failure of bond mechanism, and reduction of concrete cracking due to the different CTE of concrete and rebar. Values of concrete cover should be greater than twice the rebar diameter, d_b, (ACI 440k [4]) or 1.5–1.8 d_b (Canadian Standard Association CAN/CSA-S806-02 [12]) to avoid splitting failure in RC elements, but greater values are required for prestressed elements. In some codes (CNR DT [15], fib technical report [17]), values of concrete cover greater than 25–35 mm are suggested for RC elements and more for prestressed ones.

In Table 4, mean reduction factors are listed for various international code and the draft of Italian provisions. These factors introduce in the design the effect of environmental conditions and permanent sustained loads, that reduce the rebars performances during the life of the structure i.e. the durability of the structure.

The design guidelines of British Institution of Structural Engineers (BISE [9]) propose one factor reducing the material strength that takes into account of the effects of environment, sustained stress and other general uncertainties about materials. The JSCE design guidelines (JSCE [28]) provides one factor reducing the material strength and considering several effects including environmental durability, while specific limitations of stresses are given for permanent loads.

On the other hand, other codes (e.g. Norwegian standard NS 3473 [40], STF 22A98741 [62], Canadian Highway Bridge Design Code CHBDC [13,14], CNR DT2005 [15], ACI 440k [4]) suggest specific factors taking into account the deterioration caused by environmental and long-term effects. The Norwegian design provisions (NS 3473 [40]) give reduction factors for stress rupture due to long time load in dry air at room temperature.

The combined effects of environmental deterioration and sustained loads are considered by reducing the material tensile strength using both reduction factors when they are explicitly indicated by codes (ACI 440k [4], NS 3473 [40], CHBDC [13,14], CNR DT2005 [15]) obtaining very high reductions (the minimum value is for GFRP according to ACI 440k [4] provisions). In the case of British and Japanese guidelines (BISE [9], JSCE [28]) all the effects are summarized in the material factor, usually introduced in addition also in the other codes besides the reduction factors.

So high reduction of material properties, especially for glass fibres, in general vanishes the possibility of using high strength performance of FRP material, furthermore it is not possible to differentiate the various types of products available in the market, therefore some researchers consider the approach to much safe and suggest to take into account the parameters influencing the durability.

Reliability of this procedure is related to experimental standard methods to test durability of FRP rebars. ASTM standard are available for matrix and FRP material (water, humidity, corrosion effects) in general but not for bars. About long-term behaviour, the Canadian code (Canadian Standard Association CAN/CSA-S806-02 [12]) suggests testing procedures for long-term relaxation, creep and tensile fatigue of FRP Rods; therefore specific testing procedures are furnished to evaluate alkali resistance and bond strength of FRP sheet bonded to concrete.

However standard procedures are still lack for concrete elements reinforced with FRP rebars, where also mechanical interaction occurs through bond. More studies need in this field to better understand the effective durability of RC elements and not of FRP material.

Table 4
Reduction factors

Factor	ACI 440	NS 3473	CHBDC	JSCE	BISE	CNR
Reduction for environmental deterioration	C_E	η_{env}	Φ_{FRP}	$1/\gamma_{fm}$	$1/\gamma_m$	η_a
	GFRP: 0.7–0.8	GFRP: 0.5	GFRP: 0.75	GFRP: 0.77	GFRP: 0.3	GFRP: 0.7–0.8
	AFRP: 0.8–0.9	AFRP: 0.9	AFRP: 0.85	AFRP: 0.87	AFRP: 0.5	AFRP: 0.8–0.9
	CFRP: 0.9–1.0	CFRP: 1.0	CFRP: 0.85	CFRP: 0.87	CFRP: 0.6	CFRP: 0.9–1.0
Stress limit for permanent load	GFRP: 0.20	Not specified	F	0.8 of creep failure strength	Not specified	η_l
	AFRP: 0.30		GFRP: 0.8–1.0	GFRP ⩽ 0.7		GFRP: 0.3
	CFRP: 0.55		AFRP: 0.5–1.0	AFRP ⩽ 0.7		AFRP: 0.5
			CFRP: 0.9–1.0	CFRP ⩽ 0.7		CFRP: 0.9

5. Conclusive remarks and research needs

Many aspects influence durability of RC elements with FRP rebars depending on reinforcement characteristics and their interaction with concrete. The complexity is due to the variety of products available in the market in terms of constituents (resins and fibres) and surface treatment.

The weakness of FRPs to environmental agents (water, alkali, salt solution) or conditions (temperature) is related to penetration or degradation of resin, that protect fibres and allow their collaboration by bond.

Fibres possess several adequate mechanical properties to be used suitably in various structural applications.

The "endurance limit", i.e. the reduction of tensile strength under sustained load, which may be as high as 50%, is a long-term effect of fibres.

Creep, relaxation and fatigue in RC elements cause effects less relevant than steel reinforcement.

The most important FRP-concrete mechanisms are due to bond and thermal actions, that govern cracking behaviour and in consequence the strength and stiffness of the elements.

In particular, the transversal coefficient of thermal expansion is 5–8 times the concrete one, inducing high tensile radial stresses or reducing bond efficiency. As a consequence, minimum values of concrete cover need to be adopted to prevent splitting failure. The design approach for durability, as implemented in international codes, consists into strength reduction factors to accommodate durability problems and long-term effects. These factors tend to reduce significantly the performances of rebars. However, an alternative approach requires more specific information of the particular product and standard experimental procedures to estimate the properties having a role in durability.

Nowadays the knowledge and continuous evolution of the market does not allow to change the code approach saving simplicity of design method.

Further experimental tests occur to identify the properties of FRP rebars affecting the durability of RC elements, thus leading with an unified approach to allow a generalization for wide categories of rebars. It is also essential to develop procedures for standard tests with accelerated methods to well-assess the experimental data of different researchers and to require that manufacturers may classify the products also in terms of durability.

The more detailed and generalized information may lead to an improvement of the existing design methods decreasing the values of reduction factors and enhancing the design values of properties.

Finally, provisions for details influencing durability especially through cracking of concrete, as concrete cover and crack width limits, are required.

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