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ENDURANCE LIMIT OF FRP COMPOSITES USED FOR REINFORCEMENT OF CONCRETE STRUCTURES

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Abstract: *FRP reinforcement subjected to a constant load over time can suddenly fail after a time period called the endurance time. This phenomenon is known as creep rupture. Carbon fibers have a very good resistance to creep rupture. Aramid fibers are more susceptible to this phenomenon and glass and basalt fibers are the most susceptible ones. Results of various previous experimental programs showed the ratios of stress level at creep rupture to the initial strength to be in range of 0.18 to 0.93 for different types of FRP reinforcement. Simple example was chosen to calculate supposed stresses in reinforcement and according to results, only calculated values for CFRP reinforcement are lower than the 50-years residual stresses according to aforementioned experiments. The values of residual stresses are only extrapolated from short-term tests and real experience in time is needed to decide about real long-term degradation of these materials.*

Keywords: FRP reinforcement, Creep rupture, Stress limitations.

1. Introduction

During renovation and execution of concrete structures, non-metallic reinforcing materials are increasingly used considering their appealing advantages like low weight, high strength and easy application. The significant difference between steel and composite reinforcement is the long-term behavior. FRP composites can be subjected to creep rupture. That is why stress level under sustained load should be limited as the portion of the short-term strength of FRP reinforcement. Long-term properties depend both on fibers and matrix used in FRP. The best long-term properties are reported for carbon FRP, the worst ones for glass and basalt FRP.

2. FRP reinforcement

FRP reinforcement is anisotropic in nature and can be manufactured using a variety of techniques such as pultrusion, braiding and weaving. The characteristics of FRP reinforcement are dependent on factors such as fiber volume, type of fiber, type of resin, fiber orientation, dimensional effects and quality control during manufacturing. (ACI 440.1R-03) The resin acts as a matrix bonding the fibers together and transferring the load applied to the composite between each of the individual fibers. The resin also protects the fibers from abrasion and impact damage as well as severe environmental conditions (water, salts, alkalis) which affect the durability of FRP products. (Benmokrane, 2015) To the commonly used fibers carbon (CFRP), glass (GFRP), aramid (AFRP) and basalt (BFRP) fibers belong.

Glass fibers are the cheapest ones but the less durable due to high chemical sensibility to alkali environment. Carbon fibers tend to show the best resistance. CFRP and AFRP reinforcement is also insensitive to chloride ions. Carbon and glass fibers do not absorb water which affects in better fatigue strength. The most discussed problem of non-metallic reinforcement is the behavior during elevated temperature – which is the problem of resin. Carbon fibers themselves are not sensitive to high temperature and that is why CFRP shows the most favorable behavior. CFRPs are in addition not affected by ultraviolet rays.

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Durability of FRP reinforcement is not only influenced by component properties but also by the interface between them. The transfer of shear and transverse forces at the interface between reinforcement and concrete, influencing the bond, and between individual fibers within the composite are the resin-dominated mechanisms. Fiber-dominated mechanisms control properties such as longitudinal strength and stiffness of FRP reinforcement. (Ceroni, 2006)

3. Long-term properties of FRP reinforcement

FRP reinforcement subjected to a constant load over time can suddenly fail after a time period called the endurance time. This phenomenon is known as creep rupture. The endurance time of FRP reinforcement decreases as the ratio of the sustained tensile stress to the short-term strength increases. The endurance time also decreases with the effects of high temperature, ultraviolet radiation exposure, high alkalinity, wet and dry cycles, and freezing-thawing cycles. (ACI 440.1R-03) Carbon fibers have a very good resistance to creep rupture. Aramid fibers are more susceptible to this phenomenon and glass and basalt fibers are the most susceptible ones. Nevertheless, the susceptibility of the resin is the biggest problem.

The viscoelastic response and temperature sensitivity of polymeric resins make an FRP material more sensitive to creep and other rate-dependent phenomena than metallic materials. A typical creep history of a structure reinforced with FRP composites consists of three different regions, as it is shown in Fig. 1. In the primary region, creep grows faster in time. In secondary region, the creep strains do not grow and structure remains serviceable. The tertiary region means a damage of material in structure. (Banibayat, 2014)

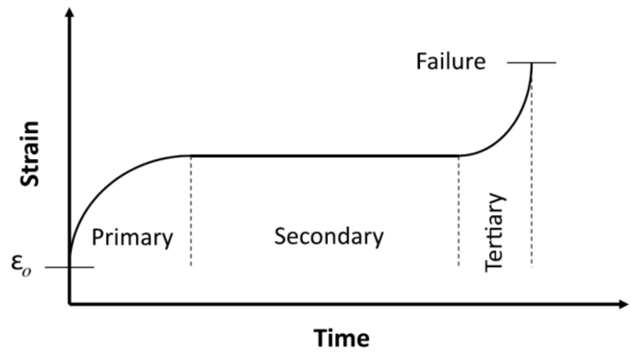

Fig. 1: Creep strain of FRP reinforcement (Banibayat, 2014).

A few series of creep rupture tests were conducted on FRP reinforcement with different fibers (carbon, aramid, glass, basalt). Usually the tests lasted for a time of 100 h and the results were linearly extrapolated to 500,000 h (more than 50 years).

Results of the experimental program of Yamaguchi et al. (1997) showed the ratios of stress level at creep rupture to the initial strength to be 0.29 for GFRP, 0.47 for AFRP and 0.93 for CFRP. In another extensive investigation (Ando et al. 1997) the percentage of stress at creep rupture versus the initial strength after 50 years was found to be 0.79 for CFRP and 0.66 for AFRP. Seki et al. (1997) reported the ratio of 0.55 for GFRP. A 50-year ultimate creep rupture strength coefficient of 0.18 was found by Banibayat and Patnaik (2014) to be suitable for BFRP reinforcement.

There are two possibilities to avoid creep rupture – adjust the material resistance of FRP reinforcement or limit the stress level in FRP reinforcement under sustained stresses.

4. SLS – stress limitations

High levels of creep can cause unacceptable effect on the function of the structure. That is why codes used in current practice limit stress levels in materials. To avoid non-linear creep behavior of concrete, the compressive stress in concrete under quasi-permanent combination of actions is limited to 45 % of concrete compressive strength in Eurocode 2. Under this value linear creep can be assumed.

The durability of FRP composite materials is generally good until the fibers are protected by the resin. At high stress levels, however, micro-cracks can appear in the resin. This is a very uncertain situation for fibers, in particular glass, because they can be damaged by moisture and the alkaline concrete environment. (*fib* Bulletin 40, 2007)

Recommendations on sustained stress limits imposed to avoid creep rupture are provided in design section of ACI 440.1R (2003).

Tab. 1: Allowable stresses in FRP reinforcement to avoid creep rupture (ACI 440.1R-03).

Fiber type	GFRP	AFRP	CFRP
Creep rupture stress limit $f_{f,s}$	0.20 f_{fu}	0.30 f_{fu}	0.55 f_{fu}

5. Example

For illustration of FRP composite reinforcement action in a simply supported one-way reinforced concrete slab, the example shown in Fig. 2 was chosen.

The input parameters:

- slab thickness: 250 mm
- reinforcement bars diameter: 6 mm
- reinforcement characteristics: see Tab. 2
- concrete cover: 20 mm
- concrete class: C25/30
- effective span of a slab: 6000 mm

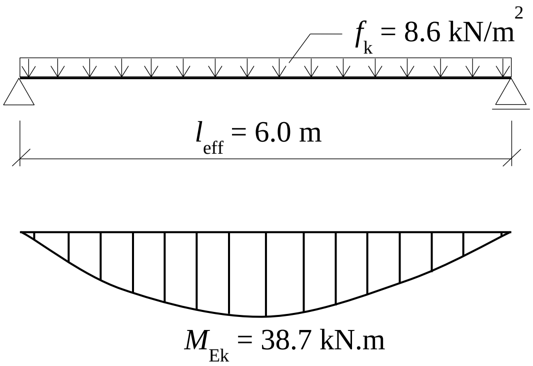

Fig. 2: Example of a one-way slab.

In serviceability limit state, from characteristic combination of action, the stresses in reinforcement were calculated and compared with allowed values stated before (Tab. 3).

Tab. 2: Properties of FRP reinforcing bars.

	CFRP	**GFRP**	**AFRP**	**BFRP**
Tensile strength [MPa]	3100	1000	2100	1500
Modulus of elasticity [GPa]	170	50	83	41
Limit strain [%]	1.20	2.20	2.90	2.50

6. Conclusions

FRP reinforcement subjected to a constant load over time can suddenly fail after a time period called the endurance time. This phenomenon is known as creep rupture. The viscoelastic response and temperature sensitivity of polymeric resins make an FRP material more sensitive to creep and other rate-dependent phenomena than metallic materials. To avoid creep rupture of FRP composite, the stress level in FRP reinforcement under sustained stresses should be limited. From the results of the chosen example it can be seen that only calculated values of stresses in CFRP reinforcement are lower than the 50-years residual stresses according to ACI code and other authors` experimental investigations. Nevertheless, it cannot be stated that other FRP composites will not reliably satisfy their function in the structure and that structures with other FRP reinforcement types will fail before reaching their service life because the values of residual stresses are only extrapolated from short-term tests and we need real experience in time to decide about real long-term degradation of these materials.

Tab. 3: Comparison of calculated stresses in reinforcement and the creep rupture stress limits according to various authors.

	CFRP		**GFRP**		**AFRP**		**BFRP**	
Calculated stress in reinforcement:	1638.5		592.2		1280.5		892.8	
	Stress limits [MPa]							
ACI 440.1R-03 (2003)	1705.0	+4.1 %	200.0	–66.2 %	630.0	–50.8 %	–	
Yamaguchi et al. (1997)	2883.0	+76.0 %	290.0	–51.0 %	987.0	–23.6 %	–	
Ando et al. (1997)	2449.0	+49.5 %	–		1386.0	+8.2 %	–	
Seki et. al (1997)	–		550.0	–7.1 %	–		–	
Banibayat and Patnaik (2014)	–		–		–		270.0	–69.8 %

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