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CRACK WIDTH CONTROL IN CONCRETE STRUCTURES WITH FRP REINFORCEMENT

R. Sonnenschein*, J. Bilcik, K. Gajdosova*****

Abstract: *Traditional material for concrete reinforcement is steel. In recent times, non-metallic fibers (steel, glass, aramid, carbon, polyethylene and polypropylene) as dispersed short fibers (together with different structures such as yarn, chopped yarn, strings, nets, fabrics, and polymer composite material reinforcement (bars and cages)) have been intensively investigated and some of them used for construction of structures. FRP rebar stress-strain curves have almost linearly elastic behaviour. The paper presents the mechanical properties and durability of different types of FRP rebars and calculations of the required reinforcement area in connection with the crack widths limitations for GFRP and steel reinforcement.*

Keywords: FRP composites, crack width, minimum reinforcement area

1. Introduction

Non-metallic fiber reinforced polymer (FRP) reinforcement is being used as an alternative to steel reinforcement in concrete structures, especially in aggressive environments, mainly due to its high corrosion resistance, and its high mechanical performance. (Pendhari, 2008)

FRP composites are durable materials which are different from the steel reinforcement for their resistance to the electrochemical corrosion. The advantages of FRP composites are high tensile strength, low density, electromagnetic neutrality and non-conductivity. With respect to steel, different mechanical behaviour of non-metallic reinforcement; however, involves some drawbacks- namely the lack of thermal compatibility between concrete and FRP reinforcement. Due to the difference between the transverse coefficients of thermal expansion of FRP bars and concrete, the temperature increase is inducing tensile stresses within the concrete member. These tensile stresses may cause splitting cracks within the concrete and eventually lead to degradation of the member's stiffness. As a consequence, important thermal strains occur just after the appearance of the first cracking of concrete which occurs in case the thermal stress within the concrete around FRP bars, in different locations, reaches the tensile strength of concrete (f_{ct}). These thermal cracks may cause degradation of the bond between FRP bars and the surrounding concrete, and eventually, failure of the concrete cover if the confining action of concrete is not sufficient (Zaidi, 2006).

Extensive analysis of cores removed from GFRP reinforced structures has confirmed that structures with small covers show no cracks despite being in service for 6-8 years. The studies also confirmed that no damage due to freeze-thaw cycles was experienced by the GFRP-reinforced structures. In light of the above discussion, the requirements for cover to FRP reinforcement shoul remain unchanged. (Mufti et al., 2007).

High tensile strength and lower modulus of elasticity cause that the decisive criteria for the design of the required area of FRP reinforcement is usually the serviceability limit state, not the ultimate limit state.

* Ing. Robert Sonnenschein, PhD.: Fakulty of Civil Engineering, Department of Concrete Structures and Bridges, Slovak University of Technology, Radlinskeho 11; 810 05, Bratislava; SK, robert.sonnenschein@stuba.sk

** prof. Ing. Juraj Bilcik, PhD.: Fakulty of Civil Engineering, Department of Concrete Structures and Bridges, Slovak University of Technology, Radlinskeho 11; 810 05, Bratislava; SK, juraj.bilcik@stuba.sk

*** Ing. Katarina Gajdosova, PhD.: Fakulty of Civil Engineering, Department of Concrete Structures and Bridges, Slovak University of Technology, Radlinskeho 11; 810 05, Bratislava; SK, katarina.gajdosova@stuba.sk

2. Composition, distribution and characteristics of FRP composites

There are several types of the composite reinforcements. Their common feature is that they consist of two components: the fibers and matrix. The fibers constitute 50 to 70% from the volume of the composite. (CNR-DT, 2006) They ensure its strength and stiffness, as well as electromagnetic neutrality, corrosion resistance and low weight. (ACI 440, 2006) The fibers can be made from carbon (CFRP), glass (GFRP), aramid (AFRP) or basalt (BFRP). The fibers are embedded in the polymer matrix that has a low modulus of elasticity. Matrix has more functions in the composite. It ensures the position and alignment of the fibers, protection from damage during manufacture and manipulation, durability of the composite as well as the protection from influence of external environment. It is also responsible for the distribution of the loads on the individual fibers. (fib No. 40, 2007) In the building industry the most commonly used are the thermosetting matrices based on epoxy, vinyl ester and polyester resins. Different types of the FRP composites have different characteristics resulting from the use of chosen type of fibers and matrixes.

Fig. 1 shows the relation strength-strain of the various kinds of the FRP composites in comparison with the steel reinforcement.

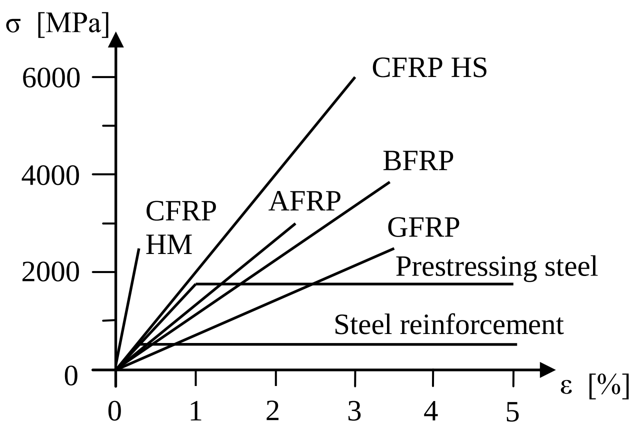

Fig. 1: Stress-strain diagram for the steel and FRP materials (Carolin, 2003)

FRP composites belong among anisotropic materials. Their properties depend on the type, volume and alignment of the fibers, the matrix type, form and quality of the construction. (ACI 440, 2006)

Due to economic reasons, the most commonly used composite reinforcement is from glass fibers. They can be made from the E-glass, S-glass or AR-glass (Alkali-Resistant Glass). The fibers from E-glass are the cheapest and therefore have the widest application. S-glass fibers, on the other hand, have a higher tensile strength and modulus of elasticity. (fib No. 40, 2007) Some environments may have a degrading influence on the glass fibers. Especially degrading is the effect of humidity and alkaline environment within the concrete. The effect of the concrete alkalinity can be reduced by applying a protective coating on the GFRP bars or by choosing the AR-glass fibers which have been created with addition of zirconium (e.g. Advantex and ArcoteX).

In comparison to other types of the reinforcement fibers, carbon fibers have a higher tensile strength and modulus of elasticity. They also appear to be less susceptible to aggressive environments and high temperatures. There are two types of carbon fibers: fibers with high tensile strength (HS) and fibers with high modulus of elasticity (HM). By increasing the modulus of the elasticity, the tensile strength and strain at failure are decreasing. The disadvantage of carbon fibers is their higher price. They tend to be 10 to 30 times more expensive than the fibers from E-glass. Aramid fibers have the best tensile strength to the density ratio. Among all above mentioned types of fibers, aramid fibers are of the lowest density. While resistant to many chemicals, they are sensitive to UV light and humidity, and further can degrade when exposed to certain acids and alkalis. (fib No. 40, 2007)

Basalt fibers are produced by melting of the withered volcanic lava. Their melting temperature is 1450°C, and therefore they are suitable for use in structures which are supposed to be resistant to fire. They have better physical and mechanical properties compared to glass fibers and significantly lower price than carbon fibers. (fib No. 40, 2007) However, their sensitivity to the effect of alkaline environment is considerably higher than that of the glass fibers. (Coricciati, 2007)

3. Serviceability limit state

Serviceability limit state deals with the usual operating conditions which occur within the structure throughout its serviceable life. It follows the criteria of appearance, durability and correct function of the structure. Compared to the steel reinforced concrete, the main difference in SLS criteria calculation for the elements reinforced with FRP lies in offsetting different properties for the FRP reinforcement. (ACI 440, 2006) Compared to steel, FRP reinforcement has a higher tensile strength; however, its modulus of elasticity is commonly smaller. Thus the higher tensile strength of FRP reinforcement cannot be in the design of reinforced elements fully utilized. (Design Manual No.3, 2007)

4. Cracks width control

Crack formation is expected, in case the maximum tensile stress within the cross-section exceeds the actual tensile strength of concrete. The crack width is controlled by the reinforcement area in the cross-section. In case of FRP reinforcement, the properties of the FRP bars such as the surface geometry, the reinforcement diameter and the concrete cover, influence the crack width. (McCallum, 2013) EN 1992-1-1 provides the limiting criteria for cracking together with equations for calculation of their width.

4.1 The calculation of the required reinforcement area in watertight structures – white tanks

In terms of the initiation and propagation of separation cracks, three design strategies are distinguished:

- construction without separation cracks - to be achieved by construction, technology processes, and execution measures,
- construction with separation cracks of limited width - achieved by the design and arrangement of reinforcement,
- construction with separation cracks, without crack control - the cracks are subsequently sealed.

The reinforcement design shall satisfy both the conditions of the serviceability limit state and the minimum reinforcement ratio requirement. The calculated areas of steel reinforcement and several kinds of FRP reinforcement required for the design of a white tank with separating cracks of reduced width will be later compared. The following parameters of the structure were chosen:

- constant parameters: concrete strength class C25/30, cement class S, exposure class XC2, structural class S4, investigation time of 5 days, the maximum permissible crack width $w_{k,max}$ = 0.15mm,
- changing parameters: different types of reinforcement (steel, FRP) and the slab thickness, which was considered between 0.1 m and 3.0 m.

Tensile strength and modulus of elasticity of the steel and FRP reinforcement are listed in tab. 1.

Tab. 1: Properties of the FRP reinforcements

Type of the FRP reinforcement	Tensile strength (MPa)	Modulus of elasticity (GPa)
BFRP	724	40,8
GFRP	1000	55
AFRP	1280	87
CFRP - HS	1400	100
CFRP - HM	1200	165
STEEL	500	200

In compliance with the higher tensile strength of FRP reinforcement, the replacement of the steel reinforcement for the FRP composite rebars has been implemented by the term of similar stresses. That being, a smaller diameter of FRP rebar having similar tensile strength compared to the replaced steel rebar has been chosen. Required reinforcement areas for the steel rebars of Ø16 and for selected types of the FRP rebars of Ø12 are shown in Fig. 2. Depending on the exposure class and the rebar diameter, the concrete cover for the steel reinforcement is 30 mm and for the FRP reinforcement it is 20 mm. From the figure it is clear that the required reinforcement area for a limited crack width increases along with decreasing of the modulus of elasticity.

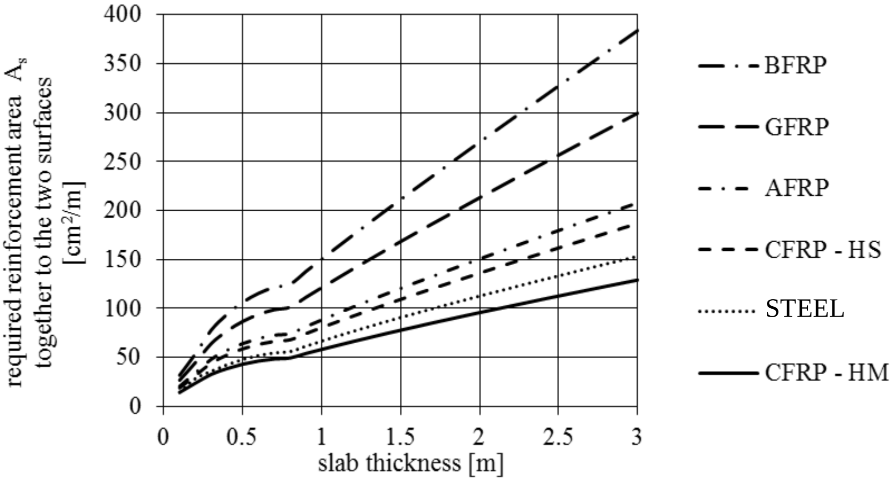

Fig. 2: Required reinforcement area for the limited crack width $w_{k,max}$ = 0,15 mm

5. Conclusion

The traditionally used steel reinforcement can be replaced by composite reinforcement, especially in cases of concrete structures exposed to environments with the increased environmental burden. Serviceability limit state is the deciding criteria for the design of FRP reinforced members. Control of both the limit crack width value and the maximum deflection of the member is necessary. The required reinforcement area for a limited crack width increases along with decreasing of the modulus of elasticity of the reinforcement.

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