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Sample conference paper: instructions for preparing a paper for SMAR 2011 (maximum two rows if needed)

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ABSTRACT: Increasingly glass fibre reinforced polymer (GFRP) rebars are being installed - instead of conventional steel reinforcement - in concrete structures located in corrosive, that is moist and warm, environments. Recent material developments have resulted in much higher tensile strengths and moduli of elasticity compared to GFRP bars of earlier generations. These material developments make newer generation GFRP bars suitable for long-term applications under high sustained stresses. Under these conditions the long-term bond properties of these bars are critical. For the structural design long-term design values of the bond strength must be determined.

The bond behaviour and the bond creep behaviour of reinforcing bars in general are discussed in the paper. The critical issues, especially those applying to GFRP bars, are defined. The results of a test series on the bond durability and a test series on the bond creep behaviour of a newest generation GFRP rebar are presented. Finally, a procedure for the determination of long-term design values of the bond strength using the results of the bond creep tests is explained in detail.

1 INTRODUCTION

Glass fibre reinforced polymer (GFRP) reinforcing bars were first developed as crack reinforcement in North America in the 1980s. Massive problems encountered there due to the corrosion of the steel reinforcement in bridge decks had led to the search for alternative reinforcing materials to conventional steel rebar.

The first materials available on the market had relatively low tensile strengths and moduli of elasticity. The approach at the time was, therefore, to install comparatively large amounts of bars with large diameters (high rebar ratio) in the bridge decks. Thereby the stresses in the bars were kept relatively small while the widths of the cracks in the decks were limited to acceptable sizes. As the corresponding bond stresses on the bars were relatively low bond behaviour was tested only in short-term tests. Little attention was paid to long-term bond behaviour and bond creep behaviour of these bars. (ACI440, CSA S806-02)

In the late 1990s the search for corrosion resistant reinforcing bars began in Europe, where high prices for stainless steel rebar made its installation increasingly uneconomic. Here the focus lay on load bearing reinforcement in relatively thin concrete elements, such as balcony slabs, subjected to high loads.

As the stresses which needed to be permanently sustained by these bars were much higher, durability and long-term behaviour became a central issue in the qualification tests of these bars.

A testing concept was developed to analyse the bond creep behaviour of these bars and determine design values of the long-term bond stress which insure acceptable performance of these bars for service life spans of as much as 100 years.

2 BOND CREEP

2.1 Bond creep in reinforced concrete

Bond creep of steel reinforcement in concrete is defined as the time dependent increase of the slip of a steel reinforcing bar embedded in concrete under permanent load. (Franke 1976)

Bond creep occurs along the embedment length of reinforcing bars as the slip of the bars increases with time. The stresses in the bar and the surrounding concrete change in that region, as a result. Bond creep is one of the reasons for the time dependent increase of the widths of cracks in reinforced concrete elements.

One of the causes of the increase in the relative displacement between the reinforcing bar and the surrounding concrete lies in the visco-elastic and plastic compression of the concrete corbels as local compressive stress peaks occur in the immediate vicinity of the bar ribs. Radial micro cracking of the concrete is most likely more pronounced near the ribs or the reinforcing bar, also contributing to an increase in the relative displacement between the concrete and the reinforcing bar.

2.2 Bond creep in concrete reinforced with GFRP bars

GFRP bars are available from a large number of producers worldwide. A large number of different materials (fibres and resins) are used in their production. Their geometry and surface properties and therefore their properties in concrete vary greatly. Whereas bars, especially those of earlier generations, are often laid, newer generation bars, conceived to sustain higher permanent tensile stresses, are usually produced in a so called pultrusion process. In this process the bars are pulled through the machinery at high tension. This ensures a nearly perfect linear and parallel alignment of the fibres in the bars.

Bar surfaces also vary greatly. A number of producers sand coat the finished bars to insure bond, others apply ribs to the core of the bars during the production process or after hardening of the bars, others cut ribs into the hardened bars.

The bond between a reinforcing bar and the surrounding concrete is ensured via three mechanisms: adhesion, shear (force transfer in to the concrete corbels parallel to the bar) and friction between the bar and the concrete. All three mechanisms are strongly influenced by surface geometry, texture and consistency. As GFRP bars contain linearly oriented fibres, they are, unlike steel, not isotropic. As a result, their bond behaviour is additionally controlled by the inter-laminar shear properties of the material itself (transfer of forces along the interface between the ribs and the core cross section of the bar).

As a result of all these considerations the bond and bond creep behaviour of the various GFRP bars available on the world market differ significantly. Detailed and strenuous short- and long-term bond and bond creep testing is required to determine safe design values of the bond stress for each individual bar.

3 TESTING BOND CREEP BEHAVIOR OF FRP REBARS

3.1 Intent of testing series

In conjunction with the applications for general construction authority certifications of a newest generation pultruded GFRP reinforcing bar in Germany and in The Netherlands (DIBt 2008, KOMO, KIWA 2009) a testing scheme was developed to determine the allowable design value of the long-term bond stress sustainable by these bars. The behaviour of the bars after the concrete has cracked and their bond creep behaviour in higher grade concretes were to be studied in an extensive testing series using this scheme.

3.2 Test specimen

Eighteen (18) test specimen were prepared according to the RILEM testing recommendation RC 6. GFRP rebars with a core / nominal diameter of 8, 16 and 25mm were tested. The concrete cubes had side lengths of 150mm and 250mm respectively. The bars were located in the center of the concrete cubes. The bottom end of the bars extended beyond the face of the cube to allow for the measurement of the slip at the unloaded bar end. The embedment length of the bars was four or five times the bar diameter. The rest of the bar length was covered by plastic pipes to debond the bar. (Weber 2009)

Figure 1: Curing of test specimen in water.

The concrete recipe was devised so as to obtain a compressive strength of 75MPa (grade C50/60 according to EC-2). The specimen were cast horizontally and tested vertically. This configuration corresponds to the concreting direction in real life near-surface installations of the bars. Each prism was reinforced with two closed carbon steel stirrups (d = 6mm, grade 500 steel) located at the beginning and in the middle of the embedment length. The specimen were cured in water at room temperature. They were at least 28 days old when tested.

3.3 Testing concept

The central idea behind the testing scheme is to study the behaviour of the bars in cracked concrete under extreme yet realistic environmental conditions.

To simulate these conditions alkaline concrete (Portland cement) was used on all specimen. The specimen were pre-loaded to a strain of 1mm at the free bar end at room temperature. For the long-term bond creep tests the specimen were heated to 60°C and were kept water saturated at all times. This environment simulates real life conditions for service life spans as they are required in real life projects. The load was sustained on the bars for at least 2000 hours without them showing any signs of increasing slip due to bond creep.

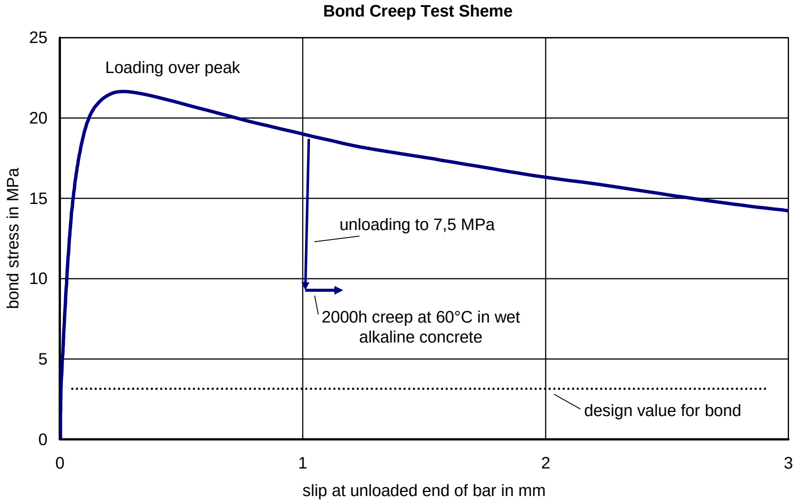

Figure 2: Concept of bond creep testing.

3.4 *Pre-loading of specimen*

In a first step a tensile load was applied on the bars at room temperature until a total slip of 1mm was measured at the end of the bar opposite to the load application. The slip was recorded as a function of the (bond) force applied on the bars.

The maximum bond stress achieved by the 8mm bars during this pre-loading was between 20 and 26 MPa at a slip between 0.5 and 0.7mm.

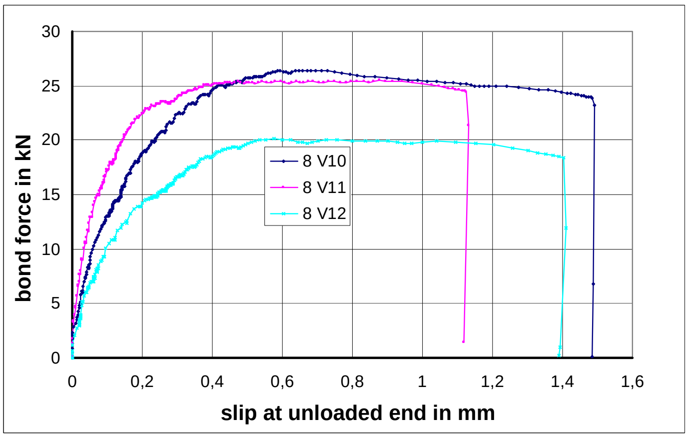

Figure 3: Pre-loading to 1mm slip d = 8 mm ComBAR bars.

The maximum bond stress for the 16mm bars was between 22 and 25 MPa at a slip between 0.1 and 0.4mm.

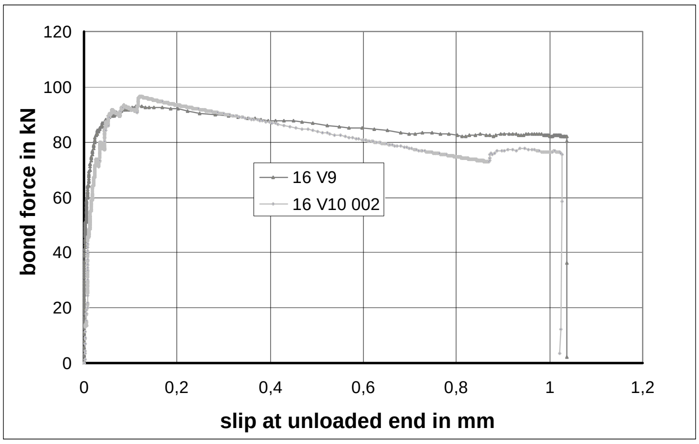

Figure 5: Pre-loading to 1mm slip d = 16 mm ComBAR bars.

The maximum bond stress for the 25mm bars was between 16 and 19 MPa at a slip between 0.3 and 0.4mm.

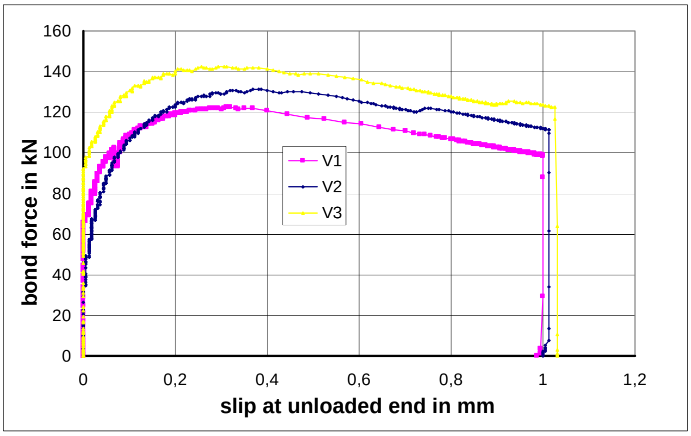

Figure 6: Pre-loading to 1mm slip d = 25 mm ComBAR bars.

3.5 *Bond Creep testing*

After this pre-loading all specimen were unloaded and prepared for the long-term test. To simulate real life conditions and to accelerate any aging processes in the bars the specimen were saturated in water and heated to 60°C prior to the application of the load. A constant tensile load was then applied to the bars. The applied loads and the resulting bond stresses are shown in Table 1.

Table 1. Applied constant loads, bond stresses ComBAR

bar diameter [mm]	**specimen designation**	**embedment length [mm]**	**load [kN]**	**bond stress [MPa]**
8mm	V4-V6	40	9.60	9.55
8mm	V7-V12	40	8.07	8.03
16mm	V7-V10	80	30.31	7.54
25mm	V1-V6	100	70.47	8.97

The loads were sustained on the bars for at least 2000 hours. The tests were only declared acceptable if there were no signs of an increase in the bond creep over this period of time. The slip curves are shown in Figures 6 to 8.

The 8mm bars did not pass the test at a bond stress of 9.5 MPa (see Figure 6). They were, however, able to sustain a bond stress of 8.0 MPa for up to 5000 hours.

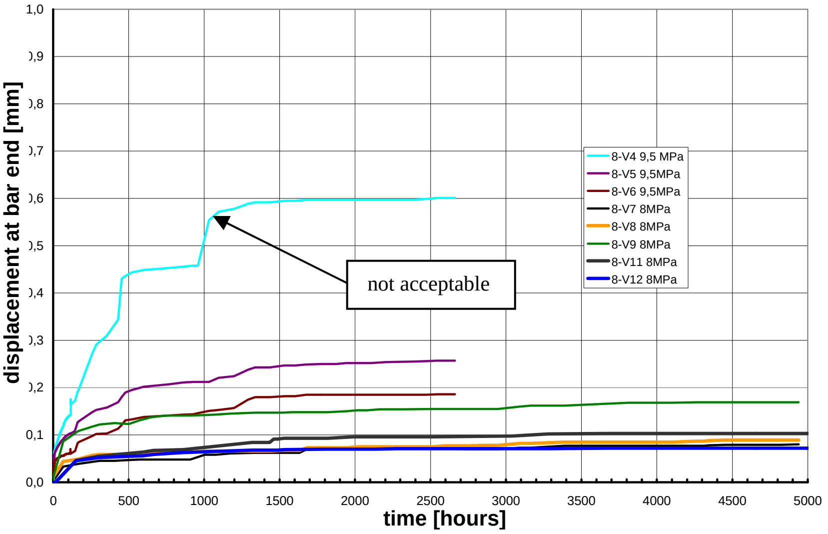

Figure 7: Bond creep curves d = 8mm ComBAR bars at 60°C, cracked concrete.

The 16 mm bars were able to sustain a permanent bond stress of 7.5 MPa without showing signs of growing bond creep.

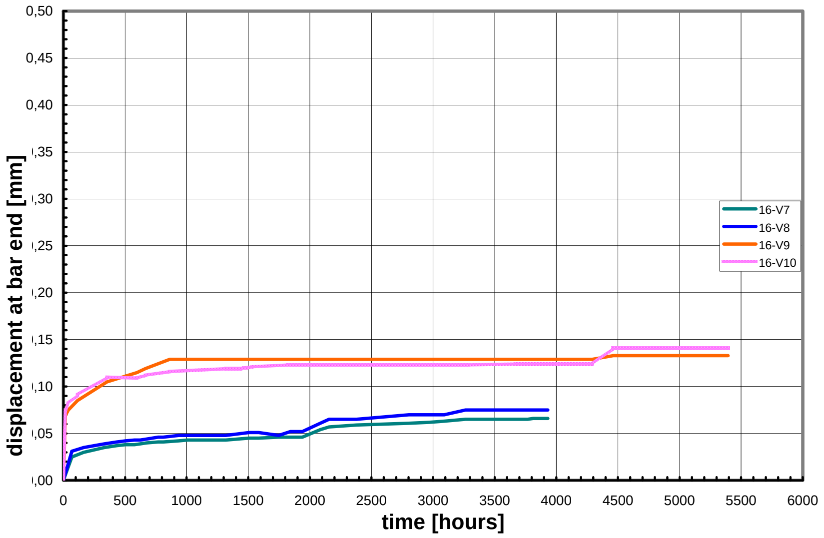

Figure 8: Bond creep curves d = 16mm ComBAR bars at 60°C, bond stress 7.5 MPa, cracked concrete.

The 25 mm bars were able to sustain a permanent bond stress of 9.0 MPa without showing signs of growing bond creep.

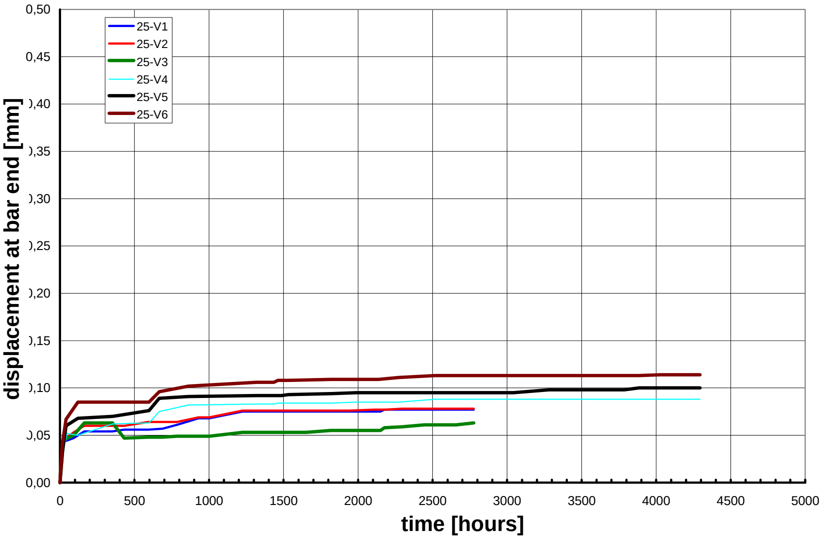

Figure 8: Bond creep curves d = 25mm ComBAR bars at 60°C, bond stress 9.0 MPa, cracked concrete.

3.6 *Inspection of specimen after testing*

One concrete cube from each testing series was cut open after the test to inspect the GFRP bars. Most of the ribs of the 8 and 16mm bars had been sheared off in the tests. On the 25mm tests the concrete corbels had failed.

4 DERIVATION OF DESIGN VALUES OF BOND STRENGTH

Based on the results of these tests, the design values of the bond strength can be specified for the specific GFRP reinforcing bar and for individual bar diameters thereof for service lives up to 100 years.

The characteristic value of the bond stress is derived by statistical means from the bond stress sustained by at least five tests over at least 2000 hours without showing any increase in the bond creep. It applies, of course, only to the concrete grade tested in the series. In Germany a safety factor of 0.65 is applied to this characteristic value to obtain the design value of the bond stress for that particular bar and the specific grade concrete. (Schießl 2008)

In the case of the bar tested in this series the design values of the bond stress in normal grade concretes were found to be essentially the same as those of steel reinforcement as it is commonly used in central Europe.

5 CONCLUSIONS

The bond creep properties of GFRP rebars are a critical measure of their durability and long-term load bearing characteristics. As the materials used in the production of the various GFRP rebars available on the market differ greatly, and the bars themselves have different surface profiles, geometries and textures, their bond properties differ greatly.

A testing procedure has been developed to determine the long-term bond behaviour (bond creep) of GFRP reinforcing bars in pre-cracked concrete sections. In this procedure real life environmental conditions are simulated by testing the bars in saturated highly alkaline concrete prisms. To speed up the testing process and to simulate long-term applications of the bars the tests are conducted at 60°C.

In the tests the characteristic or guaranteed value of the bond stress is determined for the tested concrete for a design service life of up to 100 years. The design value of the bond stress for the particular grade concrete is derived from the results of these tests by applying a safety factor of 0.65.

6 REFERENCES

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