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Universal durability concept for FRPs in harsh environments

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ABSTRACT: Properties of advanced composites are normally much higher than for conventional materials. But some of them are time and temperature dependant. It is well known that properties as the tensile strength and the modulus change after ageing in harsh i.e. alkaline environment of concrete. In addition for composites creep rupture can occur at stress levels under the short term strength. Nevertheless in most codes the design values are derived from short term tests. Long term limits are derived from literature as percentage of the short term strength. Accelerated durability tests aiming at the chemical deterioration at a certain practical strain level have to be passed in addition.

For normal conditions this seems to be safe. But now the question is: Is this safe under all conditions, also in warmer climate at higher humidity? If yes: Is this still economic to have such a high safety factor? Long term field tests in Canada have shown excellent long-term properties of certain bars, while the results of tests on the same materials in the Arabian countries are inferior.

The first coherent approach bringing together the results of the various test series was developed for the fib bulletin 40. Now this approach is adopted by the German and Duch certification organisations as well as by the CSA in the new S806-10 Code for FRP reinforced structures. This semi-probabilistic approach is based on the strong log. load/log time to failure correlation for each FRP material. In this procedure a secure, yet not exceedingly conservative, design value of the tensile strength for any FRP material is derived for any given environmental condition found between Canada and the Arabian Gulf region in typical member geometries.

1 INTRODUCTION

Current experience-based durability concepts specify fixed percentages of the short term strength of FRPs as long term design values. This approach leads either to uneconomic or to unsafe designs especially if climatic properties differ from the conditions of the country the test guide comes from. The new comprehensive durability concept was devised to derive safe design values of the tensile strength for service lives up to one hundred years.

In this time-to-failure concept a series of bars is tested in highly alkaline water-saturated concrete at room temperature, 40°C and 60°C until failure occurs. The time to failure line of the material over time is described by the logarithmic temporal slope (R_{10}) and the one thousand hour strength (f_{F1000h}). Both values are derived for different temperatures from the results of test series at those temperatures.

Based on this data, characteristic values of the tensile strength for a specific design service life and a defined set of environmental conditions can be calculated. The concept ensures the same level of safety for any service life and any environment. It allows for potentially much higher design values than existing codes and guidelines do, resulting in more efficient and economical designs of FRP reinforced concrete structures.

The concept applies to any FRP reinforcing bar. It has been internationally accepted and adopted by the International Federation for Structural Concrete, fib (fib 2007) and the CSA 806-10.

2 RESIDUAL STRENGTH CONCEPT

Current international codes and guidelines on FRP reinforcement and the design of FRP reinforced concrete structures require durability tests on the basis of a residual strength approach (CSA, ACI, etc.). Bars are aged either without load or at relatively small loads (strain in the bar at testing according to CSA S807 = 0.2 %) in an alkaline solution for specified periods of time. After the aging process the bars are unloaded and tested according to the particular guideline or code.

This approach was developed at a time when FRP rebars were primarily used as crack or secondary reinforcement and the stress levels in the bars were comparatively small. The stress in the bars over the entire service life was guaranteed to be lower than the stress applied on the bars during the aging process.

The newest generation FRP bars have been developed to serve as long-term structural reinforcement. They are able to permanently sustain stresses far greater than those allowed in the design of older FRP materials.

With this goal in mind the authors began testing their newly developed glass fibre reinforced polymer (GFRP) rebar according to the ACI 440.3R-04.R Guide Test Methods for Fibre-Reinforced Polymers (FRPs) as well as the CSA S806-02 Annexes. The stress during the test, had to be representative of the load in the application, as defined in CSA 806-02. The bars were aged under a wide range of stress levels at elevated temperatures in a highly alkaline solution. They were unloaded, dried and then tested for their residual tensile strength. The tests showed that the residual strength was essentially independent of the stress applied on the bars during the aging process. At low aging stresses it remained in the range of ninety percent of the virgin strength. However, when a certain threshold level of the tensile stress applied on the bars during the aging process was exceeded the bars failed suddenly before their residual strength could be tested. In other words, their residual strength was zero.

The conclusion based on these tests is that applying only slightly higher sustained loads on the bars than those tested may result in their sudden creep rupture failure. Figure 1 shows failure points (stress levels) for a large number of residual strength tests after aging at different stress levels (aging at 60°C in artificial concrete pore solution, ph: 13.7). While the residual strengths of bars aged at stresses up to 350MPa were all in the range of 90% of the virgin strength, bars failed during aging at 400 and 430MPa. Under high stresses local failure within the bar leads to even higher stresses in the remaining fibres within the bar. Therefore, the probability of another local failure occurring is increased. A chain reaction is set off.

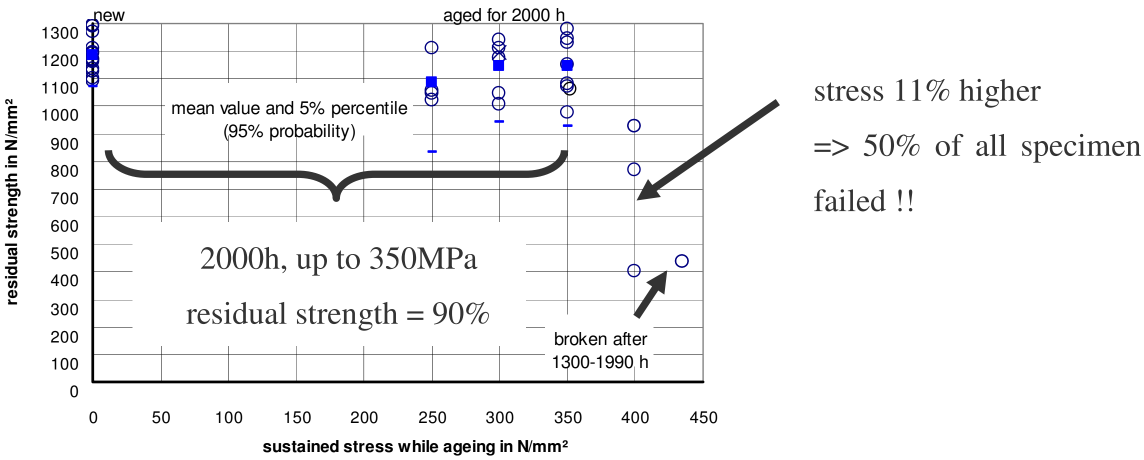

Figure 1. Stress Threshold in Residual Testing

2.1 Conclusions from residual strength testing

A high percentage of residual strength allows not for any conlusion to a higher stress level or a longer testing time. The interesting fact is the load while testing and time and temperature during the test. A low residual strength can be a sign of weak chemical durability in artificial pore solution.

3 TIME TO FAILURE OR CREEP RUPTURE DURABILITY CONCEPT

In polymer technology it is common knowledge that, unlike steel, the long-term strength of polymers under load decreases with time. This is the case for fibre reinforced as well as non reinforced polymers. Furthermore, the rate of decrease of the sustainable tensile stress of FRPs is known to be a function of the prevalent environmental conditions: the mean temperature of the material, the amplitude and frequency of temperature changes and the moisture level surrounding the bars.

The experts involved in the certification processes of polymeric reinforcing materials in Germany and in the Netherlands agreed that it was necessary to apply this knowledge to the durability testing concept for FRP bars (Weber, Volkwein 2007). As a result, a different performance based durability testing concept was developed which guarantees the same level of safety in any design of FRP reinforced concrete members while allowing for efficient and economic FRP reinforced structures.

This is achieved by recognizing that the long-term tensile strength of FRPs can not be determined on the basis of test results of short-term tensile tests, but must, rather, be extrapolated from the results of long-term durability tests. Whereas current codes treat the tensile strength of FRPs, their alkali resistance and their creep rupture behaviour as three separate phenomena, the comprehensive durability concept defines a procedure for accelerated long-term tests, measuring the effects of the interaction of these three phenomena. On the basis of the results of these tests it is possible to define the long-term failure line of the FRP material.

Using this function the characteristic value of the tensile strength of any FRP rebar can now be derived for a defined set of environmental conditions and a specified design service life.

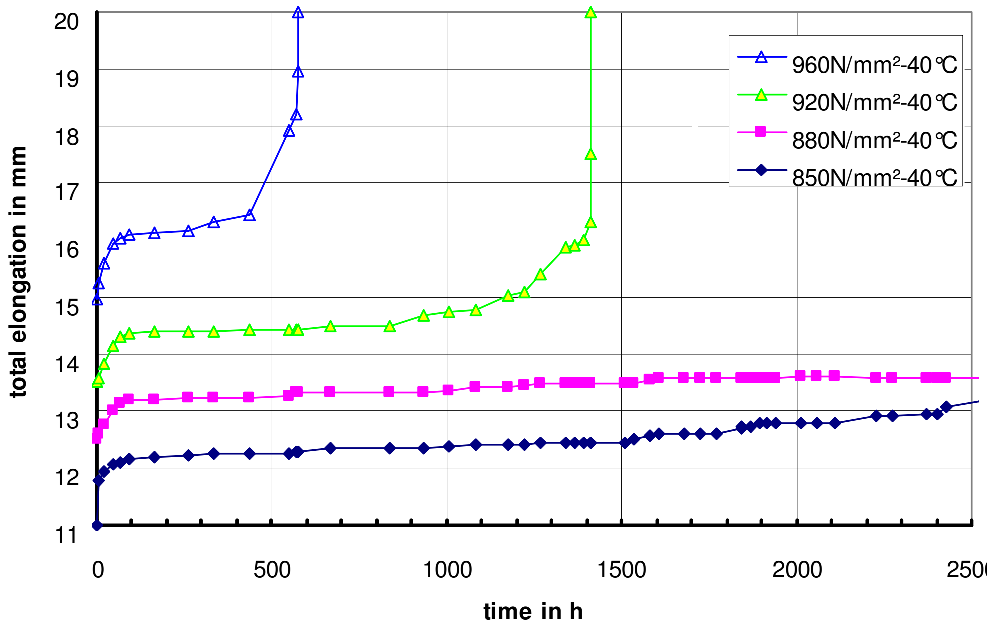

Figure 2: Creep rupture curves for constant Load until Rupture (Ø 16mm bar, wet concrete, 40°C)

In this time-to-failure durability approach, a series of bars is tested in a set-up similar to the test method B.8 of ACI 440.3R-04. In contrast to the ACI-test, where the creep-rupture tests are performed in air aiming to prestressing applications, the comprehensive durability concept requires performing the tests in highly alkaline water-saturated concrete under constant load until failure. Not only is this testing environment much more similar to real-life conditions, but it is also a far harsher environment for FRP reinforcing materials than air. Testing in different media had shown that the environment has a strong influence on the time to failure curve. (Greenwood 2001) In addition, the bars are loaded not only by pure tensile stress but also by typical shear forces generated through the bond to the concrete prism. The time to failure and the corresponding stress are then plotted in a double logarithmic scale. In the subsequent tests the applied stress level is successively reduced until the time to failure of a sufficient number of tests exceeds 2000 hours. To account for the effects of elevated temperatures on the failure line of the bars the tests are run on bars cast into concrete prisms at 23°C, 40°C and 60°C.

Generally, indoor applications are represented by the test series at 23°C while outdoor applications are represented by those at higher temperatures. Measurements and simulations have shown that vertical façade elements or horizontal bridge elements can reach maximum temperatures above 60°C even in countries with a mean annual temperature of 10°C. A detailed analysis of the data using a time temperature shift mechanism based on the three different failure lines showed that, even in such structures, the 40°C line is on the safe side for Central Europe and Canada. For warmer climates like in the Middle East region 60°C is the effective temperature for outdoor applications.

Figure 3 shows the results of a number of tests performed on ComBAR bars with a core diameter of 16 mm at 60°C. The mean value line (black line) of the test results is superimposed on the data points, as is the corresponding 5% quantile line (grey line). The relationship between the applied stress and the time to failure is linear (double logarithmic scales). Both lines are computed by the least square method. The slope, the starting point as well as the stress at a given time are the output parameters of this calculation. Data points with very short times to failure were not included in the calculation. In this region the failure lines tend to flatten out and approach the short term tensile strength. Also, the variation in the results becomes very large. Therefore, only data points with times to failure greater than on day should, therefore, be considered.

If the statistical parameters show sufficient quality (failure line is linearity), the European Code EN 705 allows for the extrapolation of times to failure.

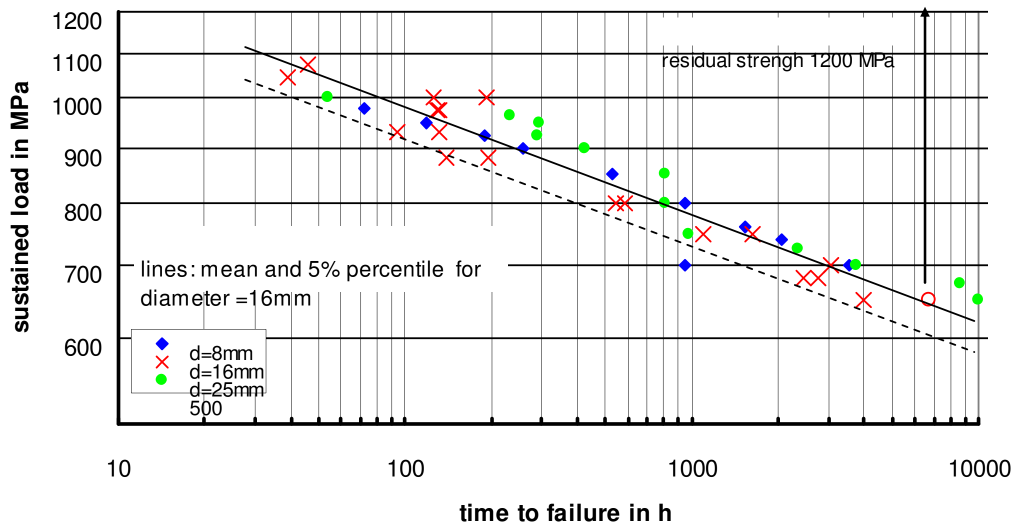

Figure 3. Long-term Tensile Tests under Load: Time to Failure Line (60°C, wet concrete)

The mean value lines (solid lines) for the tests on ComBAR bars at room temperature, 40°C and 60°C are shown in Figure 4. Also shown in this figure are the corresponding 5% quantile lines (characteristic values = dashed lines) for each temperature.

Figure 4 also shows that the rate of decrease of the time-to-failure is virtually identical for tests performed at room temperature and at 40°C. The rate at 60°C, however, is greater. The times-to-failure at elevated temperatures are much shorter than they are at room temperature. The results of the test on ComBAR bars at 40°C were therefore used in the German and Dutch certifications. For the Arabian Gulf region an effective temperature of 60°C has to be chosen.

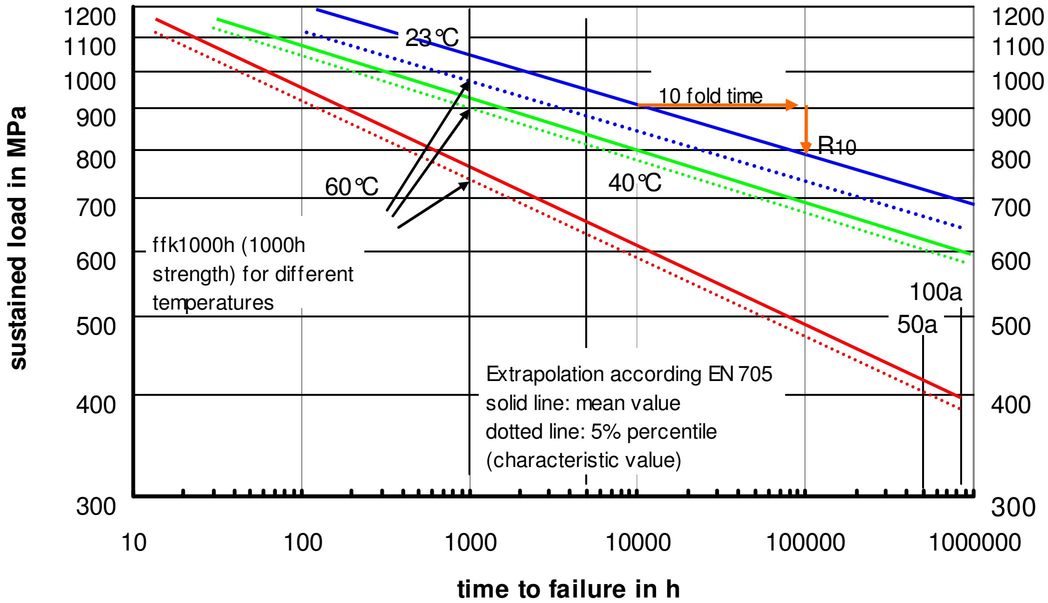

Figure 4. Time to Failure Lines for ComBAR Bars at various Temperature Levels

4 REFINED AND GENERALIZED TIME-TO-FAILURE CONCEPT

The refined concept requires a series of tests to define the material's long-term failure line. This function is defined by the one thousand hour strength f_{F1000h} and the slope of the failure line, the so called logarithmic temporal slope R_{10}. f_{F1000h} is the stress in the bar which results in its failure after a load application for 1000 hours in saturated highly alkaline concrete.

For FRPs the failure function is a linear relationship when the times to failure are plotted versus the sustained stresses on a double logarithmic scale. The elements of the function are explained in Figure 3. The correlation between the failure line of ComBAR at room temperature and at 40°C is also shown in Figure 4.
The characteristic value of the tensile strength $f_{Fk,t}$ for a specific set of environmental conditions and a specified design service life (t) is obtained by multiplying this value by the environmental factor Φ_{env}.

$$f_{Fk,t} = f_{fk1000h} * Ce * \Phi_{mat} \qquad f_{fk1000h} = 950 \text{ N/mm}^2 \tag{1}$$

The environmental factor is defined as

$$Ce = [(100\% - R_{10})/100]^{n} \tag{2}$$

where

R_{10}	logarithmic temporal slope	R_{10} (Example 1): 15%
Φ_{mat}	material factor: including model, geometry and manufcturing tolerances =	0.75
n	environmental exponent	$n = n_{mo} + n_T + n_{SL}$
n_{mo}	moisture exponent	
n_T	effective temperature exponent	
n_{SL}	service life exponent	

The moisture exponent is a function of the prevalent long-term moisture or humidity level of the environment surrounding the FRP reinforced concrete structure. For interior members it is -1. For concrete members submerged in water or wet most of the time, such as sea-front structures, pontoons, and harbour walls, the moisture exponent is +1. The factor for exterior elements which are dry most of the time or dry off relatively quickly (façade panels, etc.) is zero.

moisture condition	n_{mo}
dry	-1
outdoor	0
wet	1

effective temperature (°C)	n_T*
10	0
20	0.5
23 (RT)	0.65
30	1.0
40	1.5
50	2.5
60	3.5
* intermediate values interpolated	

design service life (years)	n_{SL}*
100	3.0
50	2.7
20	2.3
10	2.0
5	1.7
1	1.0
0.1	0.0
* intermediate values interpolated	

As mentioned above, the long-term strength of FRPs depends on the temperature to which the reinforcing bars are exposed. To account for this dependence the effective temperature is defined including the number and the magnitude of the deviations from the mean temperature.

A room temperature of 23°C can be assumed for most interior elements. The temperature of 40°C can be assumed for outdoor applications in Europe and Canada, while 60°C have to be assumed for the Middle East region to be on the safe side. Detailed calculations including exposition angle thickness and colour can lead to different temperatures to optimize the design.

4.1 Application and design examples

Example1: Outdoor application in Dubai (concrete exposed to sun radiation, thickness bigger than 6cm, effective temperature to be chosen 60°C)

$f_{Fd,t} = f_{fk1000h} * Ce * \Phi_{mat}$

$f_{fk1000h}$ (Example 1 for 60°C) = 700 Mpa, $R_{10} = 20$

Service life 100 a => n=3 (3 log. Decades from 1000 to 1 Mio.h)

$Ce = [(100 - R_{10})/100]^n = [(100 - 20)/100]^3 = (0{,}80)^3 = 0{,}512$

$f_{Fd,t} = f_{fk1000h} * Ce * \Phi_{mat} = 700\ MPa * 0.512 * 0.75 = 300\ MPa$

Example 2: Indoor application (constant 23°C, dry)

$f_{Fd,t} = f_{fk1000h} * Ce * \Phi_{mat}$

$f_{fk1000h}$ (Example 2 for 23°C) = 950 Mpa, $R_{10} = 14$

Service life 100 a => n=3 (3 log. decades from 1000 to 1 million h)

$Ce = [(100 - 14)/100]^3 = (0.86)^3 = 0.636$

$f_{Fd,t} = f_{fk1000h} * Ce * \Phi_{mat} = 950\ MPa * 0.636 * 0.75 = 453\ MPa$

Examlpe 3: Outdoor application first generation rebar ffu= 650 MPa

$f_{Fd,t} = f_{fk1000h} * Ce * \Phi_{mat}$

$f_{fk1000h}$ (for 60°C) = 200 Mpa, $R_{10} = 25$

Service life 100 a => n=3 (3 log. Decades from 1000 to 1 Mio.h)

$Ce = [(100 - R_{10})/100]^n = [(100 - 25)/100]^3 = (0,75)^3 = 0,42$

$f_{Fd,t} = f_{fk1000h} * Ce * \Phi_{mat} = 200\ MPa * 0.42 * 0.75 = 63\ MPa$

5 SUMMARY

A safe design can be achieved using different approaches. The residual strength approach defines the minimum requirements for chemical durability and creep rupture resistance at low strains in the reinforcement. While the chemical resistance is measured for each product extensively, the creep rupture resistance is considered based on experience based values.

The next edition of the CSA S806 code on FRP reinforced structures will include a time to failure approach, a powerful tool for performance based designs using FRPs. In this concept a safety level is defined according to the internationally accepted semi-probabilistic safety concept. With this approach it is possible to design at the same level of safety for projects in cold and dry as well as in wet and warm conditions. The concept is applicable to permanent and to temporary installations. The number of tests is reduced and the design procedure is simplified.

6 REFERENCES

American Concrete Institute – Committee 440 (2006). Guide for the Design and Construction of Concrete Reinforced with FRP Rebars, ACI 440.1R-06, ACI, Farmington Hills, MI, USA

American Concrete Institute – Committee 440 (2004), Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures ACI 440.3R-04, ACI, Farmington Hills, MI, USA

Canadian Standards Association 2006.CAN/CSA-S6-06 Canadian Highway Bridge Design Code. Canadian Standards Association, Toronto.

Canadian Standards Association 2002. CAN/CSA-S806-02 Code. Design and Construction of Building Components with Fibre-Reinforced Polymers Canadian Standards Association, Toronto, 2002

Canadian Standards Association 2010. CAN/CSA-S806-10 Draft Code. Design and Construction of building structures with Fibre-Reinforced Polymers, Canadian Standards Association, Toronto 2010.

Canadian Standards Association 2010. CAN/CSA-S807-10 Draft Code Specifications for product certification of fibre reinforced polymers (FRPs) as internal reinforcement in concrete structures

EN 705 Plastic piping systems - Glass reinforced thermosetting plastics (GRP) pipes and fittings – Methods for regression analysis and their use. CEN Brussels 1994

Federation international de beton fib . Bulletin 40. FRP reinforcement in RC structures , Lausanne. 2007

Greenwood M. Durability: A Key Value, Composites 2001 October 3-6 Tampa FL USA 2001

Weber A, Volkwein A. Durability based approach for design values of FRP bars, Proceedings FRPRCS 8 Patras 2007