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Short term and long term properties of newly developed bent GFRP reinforcing bars

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Abstract: Steel has been the primary reinforcing material of concrete structures for decades. However, Glass Fibre Reinforced Polymer Reinforcement (GFRP) is becoming increasingly common when corrosion, magnetism, thermal and electrical conductivity are important issues. This paper is focused on the latest generation of GFRP bent bars, which have long been cited as a weakness of GFRP reinforcement because of their reduced strength and stiffness. Strength at the bent location has often been determined by relevant codes to be in the range of 40-50% of the straight bar strength. Recent developments, however, have resulted in improvement of GFRP bent bars, with a stiffness of over 55 GPa and a long-term design strength of over 200 MPa. The ultimate and characteristic tensile strengths are respectively >550 MPa and 250 MPa. The long-term behaviour of GFRP bent bars has been determined following the recommendations of the Durability Concept proposed by The International Federation for Structural Concrete. These recent developments on the technology of manufacturing of GFRP bent bars and results from completed and ongoing tests are presented in this paper.

1 Introduction

GFRP reinforcement has been increasingly used as a non-corrosive, thermally and electrically non-conductive, and non-magnetic alternative to steel reinforcement. In order to be a complete reinforcement alternative it has to include straight bars as well as bent bars. However, unlike steel, GFRP bent bars do not have the same properties as the straight ones. They have a lower stiffness and strength compared to straight bars, and they cannot be bent on site, but need to be manufactured and delivered as such. These are considered as drawbacks of GFRP reinforcement, and bent bars are avoided wherever possible, being replaced with headed bars, other reinforcement configurations, or other types of reinforcement. This makes the improvement of mechanical properties of bent bars an important issue, for a wider use of GFRP reinforcement.

2 Analysis of Bents

Bending of a steel rebar, for example with a typical diameter of 5 times the diameter of the bar, results in strains of more than 15% on both sides of the bar, compression on the inside and tension on the outside of the bend. This high strain value is made possible by yielding of steel, a property not present in case of GFRP rebars, where fibres would break at lower values of strain.
Since bending is not possible for any cured composite rebar, this process has to be completed before the curing process.

What happens to the fibres during the bending process?
Ishihara et. al. (1997) and Morphy (1999) have shown that fibres do not experience high elastic strain. If fibres are not held together aligned along the axis of the rebar, the whole deformation takes place by compression of the inner fibres of the bent section, since the outer fibres are not being stretched while bending. For a bending diameter equal to 7 times the diameter of the bar, the compression strain is in the order of 20%. Buckling of the fibres is the only possible way to achieve this deformation, as shown in Figure no. 1.

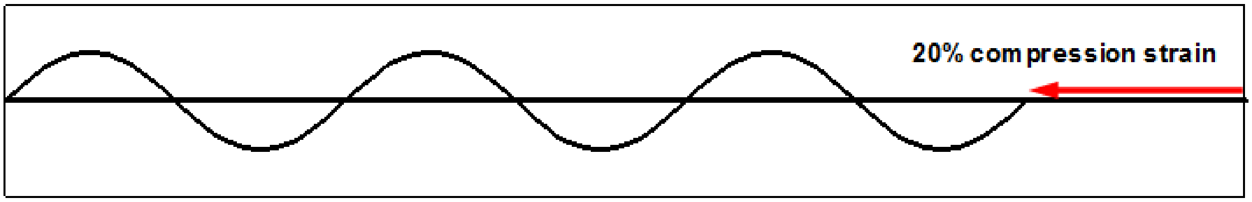

Figure 1: Fibre deformation in compression

For a bend with a diameter equal to 7 times the diameter of the bar and a sinusoidal buckling shape, as shown in Figure no. 1, the amplitude would be 15% of the wavelength. This means that if fibres buckle every 10 mm, the amplitude would be ±1.5 mm, and deviation angles from the axis would be more than 30^{o}. Such laminates are now much weaker and less stiff than parallel unidirectional laminates.

2.a - Bending diameter = $4d_b$

2.b - Bending diameter = $7d_b$

Figure 2: Longitudinal section of GFRP bent bars

In Figure no. 2, longitudinal sections of two different GFRP bent bars are shown. Both bars are of the same diameter and same fibre content, and the only difference is the bending diameter. The bar shown on the left has a bending diameter of $4d_b$ and the bar on the right has a bending diameter of $7d_b$, where d_b is the diameter of the bar. On the right side the fibres are almost parallel with the bar axis, while on the left side buckling of inner fibres is clearly observed. This would result in a higher reduction in strength and stiffness on the bend with lower bending radius because the fibres would not attract forces uniformly along the cross section of the bar. The outer fibres would break before the inner fibres start being stressed in tension.

The reduction in strength and stiffness is not only dependant on the bending radius, but also on the fibre content of the bar. From Figure no. 3 it can be observed that the strength of the bent portion decreases considerably with the increase of the deviation angle from the bar axis. This effect is higher for higher fibre content. A bending diameter equal to 7 times the bar diameter is a good compromise between the loss of strength and the applicability of bent bars (Bank 2006).

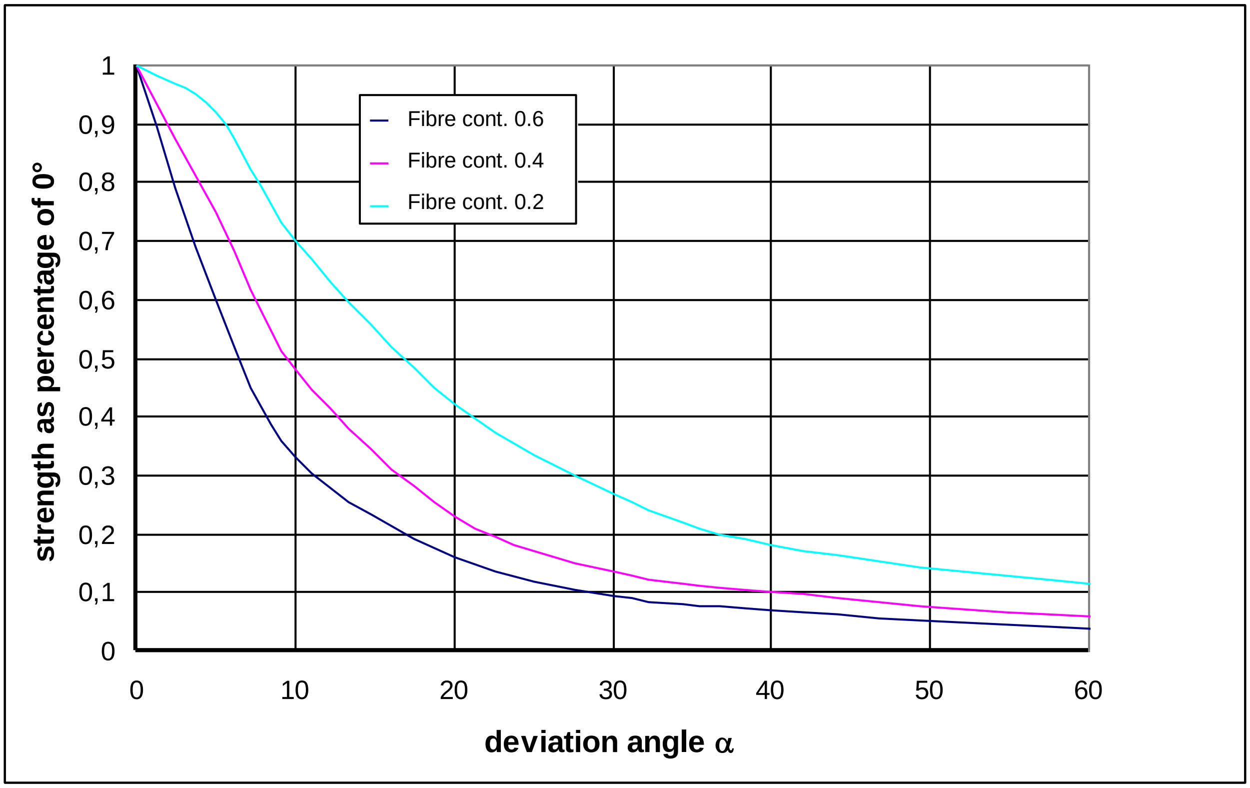

Figure 3: Influence of deviation angle on strength of UD laminates for different fibre contents (Menges, 1980)

3 Manufacturing

Consolidation and curing are performed in two different steps, allowing the application of a third intermediate step in which the bar can be deformed into the required bent shape. However, in the case of a closed mould pultrusion this is not possible because both steps are performed in the closed heated tool. In addition, the grinding of ribs which is a simple and well automated and controlled process for straight bars, would be extremely complex for curved geometries. Consequently, a totally different process had to be developed, with the following goals:

- Hold all fibres at their original aligned position while being bent, to avoid deviation of the inner fibres from the axis of the bar
- Achieve a bonding strength comparable to that of the straight bars with mechanically ground ribs
- Be a simple process

The envelopment of the fibres using a corrugated pipe which is flexible longitudinally, but stiff radially, has resulted to be a successful solution. This method is simple, guarantees the parallel alignment of the fibres, and provides a high bonding strength due to the corrugated shape which imitates the ribs of the straight bars.

4 Test Method

Being a different manufacturing process, all main properties have to be determined; the most important ones being strength and stiffness, in the short-term as well as in the long-term.

Different test setups have been recommended by the codes to test the properties of bent bars. In Ahmed et al. (2010) the B.5 setup defined in ACI 440.3R-04 (which is virtually the setup of CSA S806-12) has been found to be superior to the simpler B12 setup.

The authors recommend the following setups, shown in Figure no. 4, as a simplified alternative of B.5. Straight portions of the rebar have been de-bonded to allow transfer of forces directly to the bent portion.

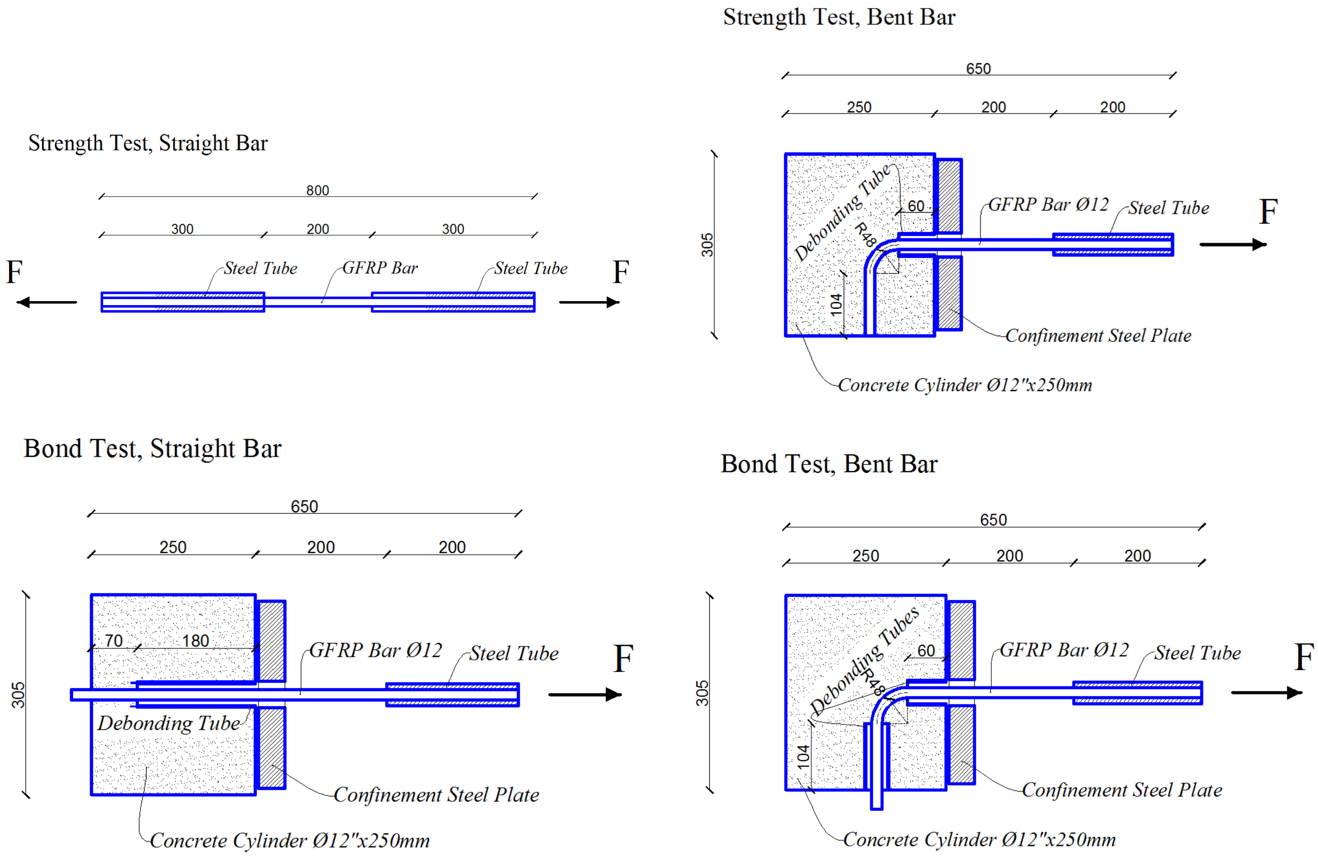

Figure 4: Quarter concrete block setup, similar to CSA S806 setup

Tensile and bonding strength at the bent portion were compared to the respective properties of a straight bar of the same size. Figure no. 5 shows loading setup of specimens.

Figure 5: Test setup

Six additional tests according to the full B.5-type setup have been performed at the RWTH Aachen University with similar results with the simplified test setup, shown in Figure no. 4.
The long-term strength is determined according to the time to failure approach with a specimen similar to the setup shown on the top right “strength test, bent bar”, in Figure no. 4.

4.1 Test Parameters

Quality of bonding between the fibers and the corrugated plastic pipe was expected to considerably affect the performance of the bent bars. For this reason, two series of bent bars were produced and tested: with and without bonding.

5 Results

The mechanical properties at the straight portion were mostly related to the fibre content of the bar. The measured value of 55 GPa of the Modulus of Elasticity, was very close to the theoretically calculated value by considering the fibres modulus and their ratio on the cross section. Strength and stiffness were relatively not sensitive to bonding between fibres and plastic ribs.

The behaviour of the bent portion was more sensitive to the bonding effect. Delamination of the bar without bonding can be clearly observed in Figure no. 7. Such phenomenon is not observed in the case of the bonded bar, shown in Figure no. 6.

Results on the tensile and bonding strength tests have been shown respectively on Tables no.1 and no.2.

Figure 6: Failure of a bent bar with bonding

Figure 7: Failure of a bent bar without bonding

5.1 Long term values

The long-term strength is determined according to the time to failure approach at 60^oC. With a shift to 40^oC by a factor of 100 this method is on the safe side. The long-term strength values are shown in Figure no. 8.

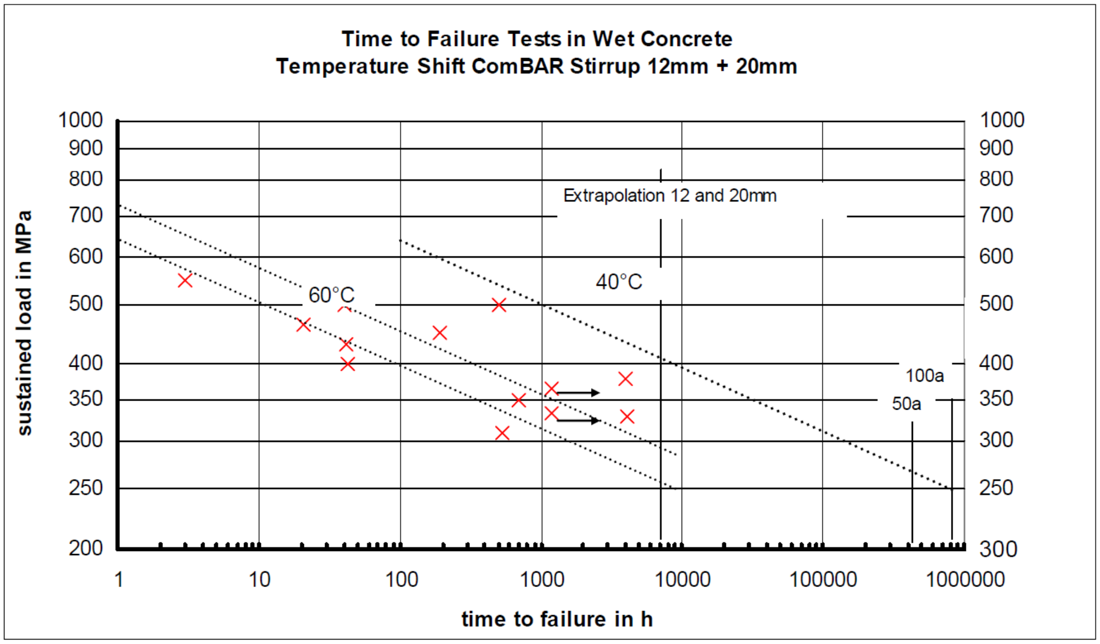

Figure 8: Long-term strength of bent bars

Nom. Diameter	Ult. Tens. Strength	Char. Tens. Strength	Design Tens. Strength	Mod. of Elasticity
Φ12mm	700 MPa	250 MPa	190 MPa	55 GPa
Φ16mm	>600 MPa			
Φ20mm	>550 MPa			

Table 1: Tensile strength of bent bars

Diameter	Straight Section	Bent Section
Φ12mm, Φ16mm	8 MPa	10 MPa
Φ20mm	10 MPa	12 MPa

Table 2: Bonding strength of bent bars

6 Summary and Concluding Remarks

The test program presented in this paper shows that with the introduced technique it is possible to achieve high strength and stiffness not only in pultruded straight glass fibre rebars, but also in bent profiles.

In addition, it has been shown that there are many ways to increase the strength of bent bars, as following:

- Parallel alignment of the fibres.
  Undulated fibres reduce the strength, starting at deviation angles as small as 5^o. At deviation angles of 30^o the strength would be reduced to 10% of the original strength. Solutions to this

issue are a greater bending angle in the range of 7 times the bar diameter, and a rigid envelope which holds the fibres in their original aligned position.

- Bond in the bent portion.
  A slip in the bent portion leads to a bending moment in the beginning of the curvature. This can have a knock-down effect in the already reduced strength of this section. For a smooth section without bond, only one third of the strength of a section with good bonding was measured.
- Durability.
  In short-term tests a part of the load will be transduced by the undulated fibres through the resin. In the long term the creep of the resin leads to redistribution towards the straight fibres. The load on these fibres will increase and the time to failure will be much shorter than for a uniformly loaded section.

These recent manufacturing developments have resulted in improvement of GFRP bent bars, with a stiffness of over 55 GPa and a long-term design strength of over 200 MPa. The ultimate and characteristic tensile strengths are respectively >550 MPa and 250 MPa.

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