CREATE MORE WITH LESS®

ComBAR® by Fiberline

Technical Information

FIBERLINE COMPOSITES

All test data, values and certificates are provided through the courtesy of Schöck Bauteile GmbH

Table of contents

Page

Glass fibre reinforcement 4

All types at a glance 5

Product description 6

Product data sheet, straight bars 7

Bar end heads 8

Bent bars and stirrups 9

Dowels 10

Certifications and test reports 11

Tests of behaviour in concrete 12

Storage, transportation and machining 13

Applications 14

Tensile strength and modulus of elasticity 15

Durability, characteristic value of the tensile strength .... 16 - 17

Bond behaviour .... 18 - 19

Crack width .... 20 - 21

Deflection 22

Thermal behaviour 23

Fire resistance 24

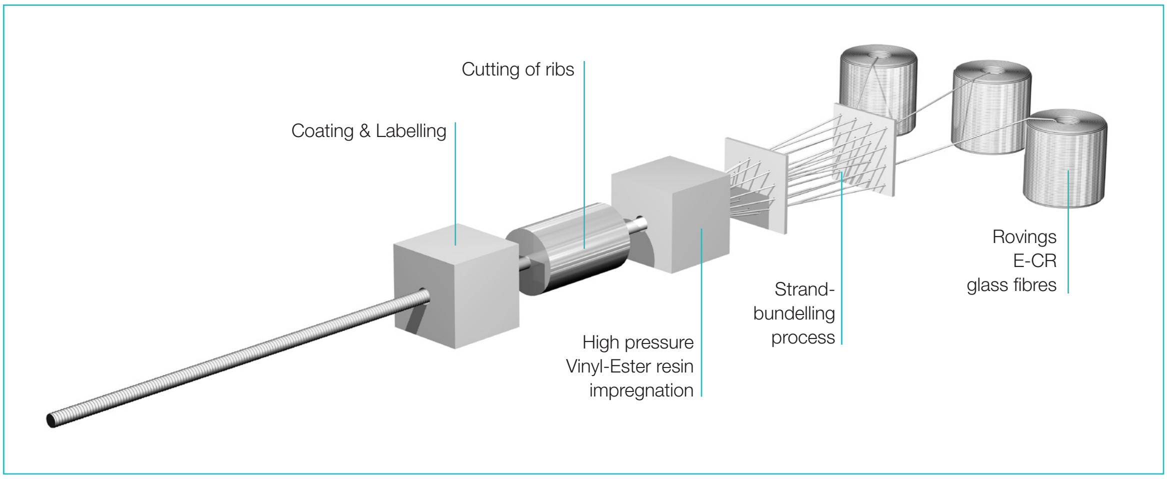
Design recommendations .... 25 - 27

Table 1: Characteristic values long-term tensile strength ComBAR® 28

Glass fibre reinforcement

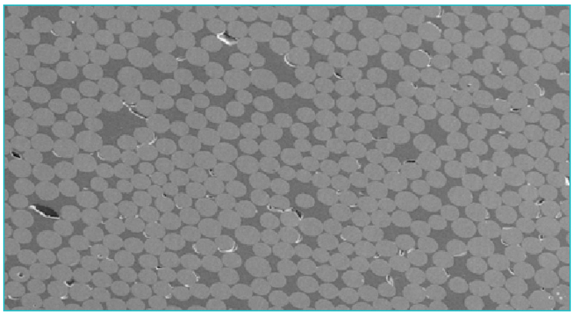
ComBAR® by Fiberline (**com**posite re**bar**) belongs to the class of so called fibre composite materials. In fibre composites fibres are combined with other materials to achieve improved properties and synergy effects. The properties of the resulting material can be customised by choosing specific fibres, by adjusting the fibre orientation and by varying the additive and binder contents.

One of the best known composites is glass fibre reinforced polymer (GFRP). It is being used in many fields, such as electronics and ship building, to produce light weight, high strength and extremely durable components. Glass fibre reinforcing bars are GFRPs of the newest generation. They have a fibre content of more than 85% (weight). As a result, they are much stiffer and stronger than older materials/systems.

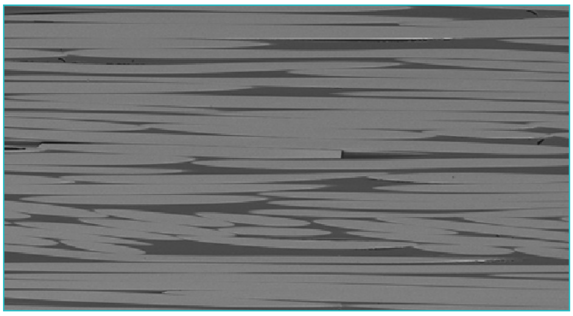


Schematic of the “Pultrusion” process

The composite ComBAR® offers an entirely new range of applications in civil engineering and high rise construction, whenever a high strength, non-metallic, extremely durable, non-corrosive and easily machined reinforcement is called for. The reinforcing bar consists of a multitude of continuous fibres, oriented in the direction of the load, each with a diameter of approx. 20 µm. They are bonded in a highly durable VE resin matrix.
The unique production process guarantees the complete impregnation of the glass fibres and an extremely high degree of curing.



Cross-section of a ComBAR® bar

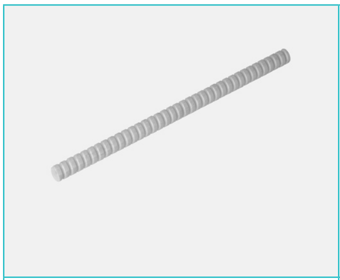
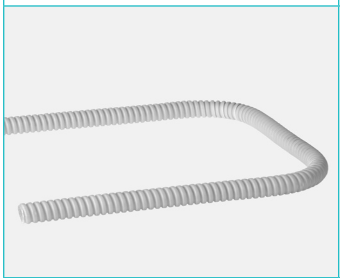


Longitudinal section of a ComBAR® bar

The unique geometry of the ribs and the fact that the ribs are ground into the hardened bar guarantee bond properties which are analogous to those of steel rebar.
The characteristic material properties of ComBAR® result from the uni-directional orientation of the fibres: high axial tensile strength, relatively low tensile and compressive strength perpendicular to the fibres. The analogy to the natural construction material timber best describes the non-isotropic material properties.

ComBAR® has been certified in Canada as per CSA S807 – 10

All types at a glance

	straight bars [1] ϕ 8 mm ϕ 13 mm ϕ 16 mm ϕ 20 mm ϕ 25 mm ϕ 32 mm other diameters on request	standard lengths 0.2 to 11.8 m	▶ As load bearing reinforcement for tensile forces in concrete.
	bars with anchorage heads ϕ 13 mm ϕ 16 mm ϕ 20 mm other diameters on request	bar lengths (standard) 0.25 to 4.0 m longer bars on request	▶ As end anchorage ▶ As shear reinforcement in slabs and beams (in conjunction with bent bars).
	bent bars/stirrups ϕ 12 mm ϕ 16 mm ϕ 20 mm	bar lengths 0.5 to 6.5 m	▶ As ties / transverse reinforcement for confinement in beams. ▶ As edge reinforcement in slabs, corbels, etc. ▶ As shear reinforcement.

[1] load-bearing core diameters in mm

There are many ways to fasten ComBAR® and they should be done according to the contract specifications. For applications where the reinforcement is to contain no metallic elements at all, plastic spacers (lattice tubes), plastic cable ties and plastic clips (polypropylene) for the connection of ComBAR® bars can be used. Alternatively, ComBAR® bars can be tied using conventional plastic zip ties.

Product description

ComBAR® was conceptualized as internal reinforcement in concrete members. The mechanical properties and bond properties are comparable to those of steel rebar. The material properties were determined for predominantly static loads in central European and North American climates. They are certified for a design service life of 100 years.

ComBAR® bars are linearly elastic up to failure. For all bar diameters it occurs at stresses well above 1,000 MPa. As a result of the comparatively low modulus of elasticity of ComBAR® (≥ 60 GPa), the failure of ComBAR® reinforced concrete members is preceded by large deflections. When the load is removed the deflection returns to near zero.

ComBAR® bars with end heads can be installed where geometric constraints require reduced development lengths. Double headed bars are ideally suited as shear and punching shear reinforcement in beams and slabs.

ComBAR® bars can not be permanently deformed or bent. If a straight bar is bent it returns to its original shape as soon as the applied force is removed. Bars with small diameters can be bent elastically (circular tunnel cross-sections). Customised bent bars and stirrups are prefabricated at the shop.

ComBAR® bent bars have been durability-tested for a service life up to 100 years.

Material characteristics Fields of application

• high corrosion resistance	=>	open and underground parking garages, bridge caps, barrier walls, curbs, sidewalks, approach slabs, wing walls, slim facade elements, shore line stabilization, hydraulic engineering
• high chemical resistance	=>	industrial floors, industrial containers, sewage-treatment plants, agricultural facilities
• electrically non-conductive	=>	transformers, reactors / inductors, machinery with high field-strengths, non ballasted rail slabs (signals and switches of railways)
• non-magnetic	=>	sensitive electronic equipment, structural biology, nano technology, quantum physics, MRIs, non ballasted rail slabs
• ease of machining	=>	shaft walls in tunnelling, formwork anchors, temporary structures
• very low thermal conductivity	=>	energy conservation in housing construction

Comparison reinforcement materials

property	steel rebar	stainless steel rebar	Fiberline ComBAR®
ultimate tensile strength (MPa)	> 500[1)]	655	> 1,000
ultimate elongation (‰)	> 25[1)]	50	> 16.7
elastic modulus E (GPa)	200	190	> 60
bond strength (MPa)	13.7	13.7	12.2[2)]
min. required concrete cover (mm)	40 (exposed) 30 (unexposed)	< 30	d_b + 10 mm
density (g/cm3)	7.85	7.92	2.2
thermal conductivity (W/mK)	60	16	< 0.5
coefficient of thermal expansion (1/K)	0.8 to 1.2 x 10^{-5}	1.73 x 10^{-5}	0.6 x 10^{-5} (axial) 2.2 x 10^{-5} (radial)
specific resistance (μΩcm)	1 – 2 x 10^{-5}	7.2 x 10^{-5}	> 10^{12}
magnetism	yes	slightly	no

[1)] for grade 400R steel rebar
[2)] values for 16 mm ComBAR® bars (certification of compliance with ISIS specifications/CSA S807, University of Toronto)
Sources for material values of steel and stainless steel on request.

Product data sheet of straight bars

Bar sizes, dimensions, weights, ultimate tensile strength

ComBAR® bar	designated diameter (ACI/CSA)	core diameter (mm)	exterior diameter (mm)	cross-sectional area[1] (mm²)	specific weight (kg/m)
ø 8	M8	8	9	50.3	0.13
ø 13	M13	13	14.5	132	0.34
ø 16	M15	16	18	201	0.53
ø 20	M20	20	22	314	0.80
ø 25	M25	25	27	491	1.22
ø 32	M32	32	34	804	1.93

[1] Determination of load-bearing cross-sectional area:
The load bearing cross-sectional area of ComBAR® bars is the area of the core. The ribs are not included, as they do not contribute to the tensile capacity of the bars. To determine the load-bearing core cross-sectional area of the perfectly round ComBAR® bars the exterior diameter is measured using callipers. Twice the depth of the ribs, measured with callipers, is subtracted from this value to determine the core diameter.

Material properties of straight bars

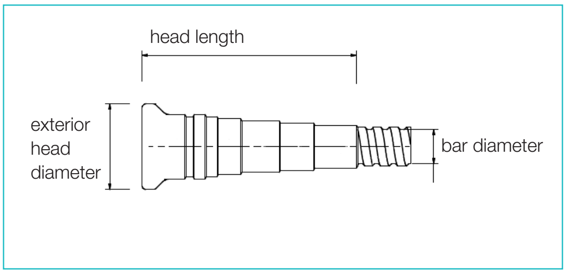
properties	terms	values	comments
ultimate tensile strength	f_u	> 1,000 MPa	all bar diameters
1,000 hour tensile strength [1]	F_{k1000h}	950 MPa	5th percentile
logarithmic temporal slope [1]	R_{10}	< 15 %	5th percentile
modulus of elasticity	E_f	> 63.5 GPa	8, 12, 16, 25 mm [2]
ultimate elongation	ε_{Fu}	1.67%	ø 16mm bar [2]
bond strength	τ_F	12.2 MPa	ø 16mm bar
bar surface profile factor (bond)	k5	≤ 1.0	(CSA S806 9.3)
bond coefficient	k_b	0.6 [3]	(CHBDC 16.8.2.3)
bar surface factor	k_4	≤ 0.8	(CHBDC 16.8.4.1)
transverse shear strength [4]	t	≥ 180 MPa	acc. CSA / ACI
min. concrete cover	min. c	d + 10 mm/d + 5 mm (pre-cast)	min. cover for load transfer
fibre content	–	> 75% (vol.)	no secondary fibres or fillers
void ratio	–	< 1%	–

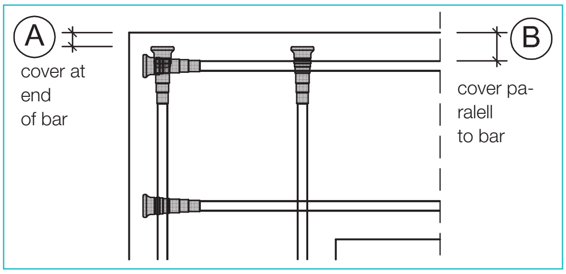
[1] values for determination of design value of tensile strength according to durability concept of fib defining time-to-failure lines (see page 15)
[2] values for 16mm ComBAR® bars (certification of compliance with ISIS specifications/CSA S807, University of Toronto); certifications for 8, 12, 16, 25 mm bars completed
[3] value determined for ComBAR® bars of all diameters
[4] values in tests according to CSA / ACI not for design of dowels. Ongoing test series show substantially higher values.

The Quality of all components of the ComBAR® reinforcement system is continuously tested as part of the Quality Control program of Fiberline Composites

Bar end heads

ComBAR® bar end heads are used to reduce the embedment length of straight bars in geometrically constrained reinforcement situations or as shear reinforcement in diaphragm walls and drilled piles (double headed bolts). ComBAR® bar end heads are made of polymeric concrete. They are cast onto the ends of straight ComBAR® bars. Their long-term behaviour / durability is governed by the behaviour of the bar. Long-term pull-out tests have been performed on bar end heads cast into highly alkaline concrete cubes. The heads were subjected to constant loads until failure occurred. The concrete cubes were heated to 60°C and saturated with water over the duration of the tests. The time-to-failure line for the headed bars was established using the results of a large number of tests at different load levels. The characteristic value of the anchorage strength of the headed ends was determined for applications with a maximum effective temperature of 40°C (for projects in Canada and Europe). Refer to pages 15 and 16 for further details on the durability concept.
The shape of ComBAR® end heads has been designed to minimize the tensile splitting action. As a result, heads can be installed close to the concrete surface and still develop the full design force. The minimum concrete cover parallel to the head bar is 50 mm (B). The end of the head may touch the formwork (A).

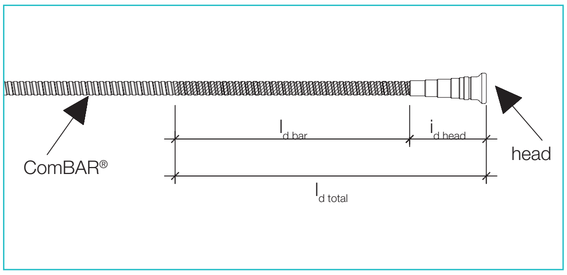




Dimensions, characteristic values anchorage forces of headed ends

bar diameter (mm)	head length (mm)	ext. head diam. (mm)	$F_{head,k}$ short term (kN)	$F_{head,k}$ long-term (100 yrs.) (kN)
13	60	31	54	27
16	100	40	100	59
20	100	50	180	90

The total developed force of a ComBAR® bar with a headed end is the sum of the force anchored by the head and the additional force developed along the bar. Analogously, the total development length is the sum of the length of the head and the additional development length along the bar.



$$F_d = F_{d\,head} + F\,d_{bar}$$

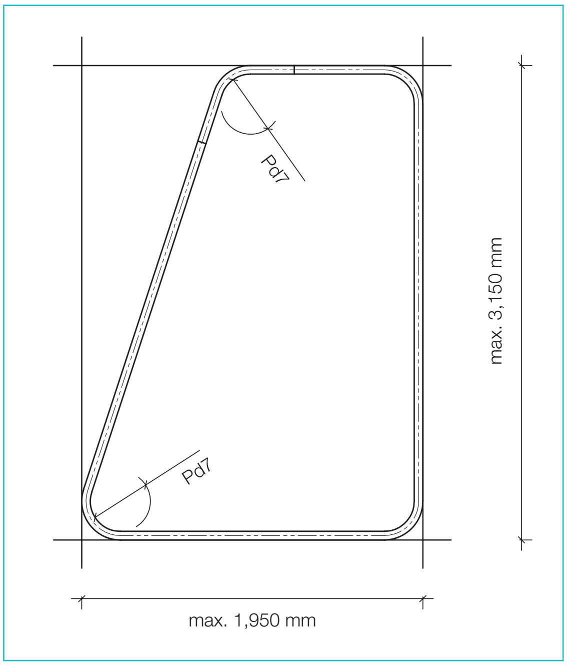
$$l_{d\,total} = l_{d\,head} + l_{d\,bar}$$

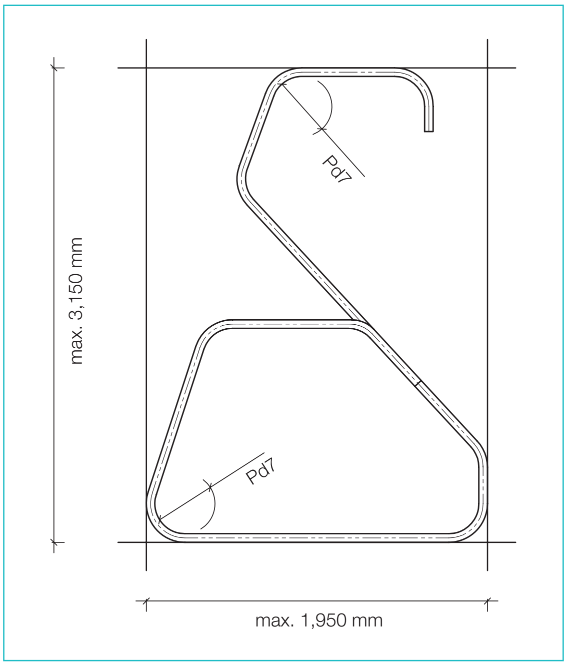
The load is transferred along the entire length of the head. At least one cross bar is to be installed at the end of the head to allow for the complete anchorage of the head. Ideally this bar is located at the middle of the head.

Bent bars and stirrups

ComBAR® bent bars and stirrups are produced by bending a specially made polypropylene conduit pipe filled with glass fibres and a vinyl ester epoxy resin into the desired shape. These raw bars are then thermally cured. This procedure allows for a high fibre content and a nearly parallel alignment of the fibres in the bent portion of the bars, resulting in high strength and a modulus of elasticity similar to that of straight ComBAR® bars.

ComBAR® bent bars can be produced in all bending shapes (2D) known for bent steel rebar. Spirals, 3D bars and bending in two directions are also possible. The smallest pin diameter is seven times the nominal bar diameter. Bent ComBAR® bars are hardened in a form with maximum dimensions 1.95 by 3.15 m.





Bar sizes, dimensions, weights of bent bars

nominal diameter (mm)	core diameter (mm)	exterior diameter (mm)	core cross sectional area (mm²)	specific weight (kg/m)	min. pin diameter 7 d_b (mm)	min. / max. bar length (m)
12	11.6	15.5	106	0.30	84	0.5 m / 6.5 m
16	15.6	19.8	191	0.49	112	
20	19.1	23.8	287	0.71	140	

Material properties bent bars

property		term	values		comments
			12mm	16*, 20mm	
ultimate tensile strength	straight portion	$f_{u\ (straight)}$	1000 MPa	900 MPa	
	bent portion	$f_{u\ (bent)}$	700 MPa	550 MPa	
characteristic value tensile strength (long-term)		$f_{fk\ (bent\ bar)}$	≥ 250 MPa		tested for 100 years
modulus of elasticity		$E_{f,bent}$	≥ 50 GPa		
bond strength	straight portion	$f_{f,bond\ (straight)}$	8 MPa	10 MPa	
	bent portion	$f_{f,bond\ (bent)}$	10 MPa	12 MPa	
fibre content		–	72.8 % (weight)		no secondary fibres or fillers

* Independent long-term testing of material properties of 16 mm bars in progress (Germany and Canada)
All material properties not shown in the table above are the same as those of straight ComBAR® bars.

Dowels

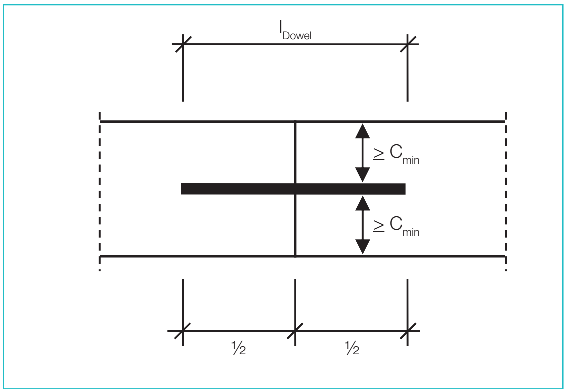
ComBAR® bars with and without ribs can be used as shear dowels to connect adjoining concrete elements (highway slabs, precast elements, etc.).
Tests were performed on ComBAR® dowels cast into concrete elements to determine their shear load capacity. It was shown that the load bearing capacity of the dowels is controlled by their interlaminar shear strength. Once this is exceeded cracks form in the dowel along parallel to its axis. These result in a reduction of the effective width of the dowel. The concrete along the front edge is overloaded leading to concrete failure below the dowel.
The (long-term) design values for ComBAR® dowels were determined in durability tests performed at 60°C in highly alkaline concrete with a compressive strength of 35 MPa. This testing concept is analogous to the durability concept specified in the European general construction certifications of ComBAR® and adapted by the International Federation for Structural Concrete (fib).

Design values ComBAR® dowels (without ribs)

diameter [mm]	cross sectional area [mm²]	value shear strength [kN]	length [mm]	min. concrete cover* [mm]
14.5	165	3,4	200	116
18.0	254	5.1		144
22.0	380	7.6	2 x 110 = 220	176
34.0	908	18.2	2 x 175 = 350	272

* values apply to reinforced elements only; min. cover for elements without reinforcement: 200 mm

Installation detail
The concrete cover in concrete elements without reinforcement should be no less than 200 mm (smallest value in laboratory tests).



Certifications and test reports

International certifications

organisation, country	title	issue date
DIBt, Berlin, Germany	General construction authority permit ComBAR® glass fibre reinforced polymer rebar; nominal diameter: ø 16 mm (extension to 8, 12, 16 and 25 mm bars applied for)	Dec. 2008
DIBt	General construction authority permit ComBAR® Thermoanchor	Nov. 2009 extended Dec. 2011
KOMO, KIWA, The Netherlands	ComBAR® glass fibre reinforcement in concrete ø 8, 12, 16 mm	Feb. 2009 extended Dec. 2011
University of Toronto, Canada	Compliance of 8, 12, 16, 25 mm straight ComBAR® bars, 12 and 20 mm bent ComBAR® bars with CSA S807-10	Oct. 2007 - Mar. 2011
Syracuse University, USA	Evaluation and Certification of GFRP bars ComBAR®; Tests with Respect to the Requirements of the ACI 440. R3-04 Report (12, 16 and 32 mm)	July 2006 extended Aug. 2012

Test reports and expert opinions

ComBAR® bars have been extensively tested by independent experts around the world and at the laboratory of Schöck Bauteile GmbH. in conjunction with the certifications in Germany, in the Netherlands , Canada and the US. These tests were monitored by independent experts.

Selected English language reports and expert opinions on tests of the material and mechanical properties of ComBAR® are listed below. These documents are available online at www.fiberline.com. English summaries or translations of German language test reports will be provided upon request.

material property	title of report	author
human health and safety	Continuous Filament Glass Fibre and Human Health	European Glass Fibre Producers Association, APFE
chemical properties	Expert Report GFRP – Reinforcing Bars "ComBAR®"	University of Erlangen Dep. of Polymer Technology
behaviour in concrete	Expert opinion regarding the application for a general construction authority permit for the GFRP reinforcement ComBAR®	Technical University Munich, Engineering Office Schiessl, Gehlen, Sodeikat, Munich
environmental impact	Categorisation of GFRP bars ComBAR® into the group Z0	Chemical Lab Dr. Vogt, Karlsruhe, Germany
tensile strength	Report on mechanical testing of GFRP rebars (8, 12, 16mm)	Arab Center for Engineering Studies, Doha, Qatar
fire performance	ComBAR® bond fire performance	Danish Technological Institute, Taastrup, Denmark
temperature dependence	Determination of temperature-dependent tensile strengths of ComBAR® reinforcement bars	Materials Testing Institute Braunschweig, Germany
durability	Durability and creep-rupture tests performed on straight GRFP bars with standard coating d=16mm	Schöck Bauteile GmbH (certification tests)
bent bars	Shear design for concrete elements reinforced with fibrepolymer-composite reinforcement	RWTH Aachen, Institute for Concrete Construction
other properties	on request	

Tests of behaviour in concrete

Test series in Canada and North America (excerpt)

application	title of project / description	lead investigator, year	notes
ComBAR® in infrastructure projects to increase their durability	GFRP reinforced concrete structures	Prof. Shamim Sheikh University of Toronto 2010 – 2012	NSERC CRD grant; industry partner: Facca Inc.
ComBAR® in bridge deck cantilever with steel guard rails – static tests	Bridge deck-guard rail anchorage strength and serviceability using newly developed GFRP bent bars and headed studs	Prof. Khaled Sennah Ryerson University 2010	for North Channel Bridge project
Glass fibre bars as connectors of precast elements	Development of sustainable concrete bridge deck slab systems using corrosion resistant FRP bars	Prof. Khaled Sennah Ryerson University 2011	OCE coll. research project
ComBAR® in concrete bridge trusses subjected to earthquake loads	investigation of the behaviour of joints of slender concrete trusses using comBAR® headed and bent bars	Prof. Mamdouh El-Badry University of Calgary 2010 – 2011	for bridge project City of Calgary
ComBAR® in PL-3 barrier walls (testing to achieve MTO standard) – crash test and static tests	Crashworthiness of GFRP-reinforced PL-3 concrete bridge barriers (crash test and static tests)	Prof. Khaled Sennah Ryerson University, Dr. Gene Buth Texas Transportation Institute 2010 - 2011	in cooperation with MTO
ComBAR® in concrete structures subjected to earthquake loads	Experimental Investigation on the Seismic Performance of Beam-Column Joints Reinforced with GFRP Bars	Prof. E. F. El-Salakawy University of Manitoba ongoing	
ComBAR® durability	Multiscale Analysis of GFRP Reinforcements for Concrete Under Special Stress and Environmental Conditions	Prof. M. Polak University of Waterloo 2012 - 2014	including extensive testing of ComBAR® bent bars

crash test of PL-3 barrier wall reinforced with ComBAR® (Nov. 2010)

Storage, transport and machining

Storage and transportation

In general, high intensity long-term exposure to UV-rays can lead to the discoloration of polymers. After a prolonged (> 6 months) exposure the surface of the material becomes brittle. Unless special protective measures are undertaken, this results in the lasting deterioration of the polymers. As a result, Fiberline ComBAR® should be covered and stored in a dry environment, especially when stored for longer time periods. Tests on ComBAR® bars that were stored outdoors for up to eight weeks without being protected, showed that climatic exposure in central Europe and Canada leads to a discoloration without causing a reduction of the bond or the tensile strength. To avoid damage to the ribs, the material should not be dragged across rough surfaces. It should not be subjected to abrasive or impact forces.

When hoisted by crane, the deflection of ComBAR® bars is similar to that of steel bars of equal diameter. It is important that the appropriate cross beam/lifting equipment is used at all times.

Cutting

Cutting Fiberline ComBAR® is significantly easier than cutting steel rebar. Either a hacksaw, band saw, or a grinder, using a diamond or a tough metal disc, is recommended. Both are fine enough to achieve a clean cut. ComBAR® bars should not be trimmed with bolt cutters or shears, as the glass fibres fray when the material is sheared off. If desired, grates at the bar ends can be removed with a file or a rasp.

Bending

ComBAR® bars are linearly elastic up to failure. They can not be bent permanently (plastically). If a straight bar is bent it returns to its original shape as soon as the applied force is removed.

Small diameter ComBAR® bars can be bent into a radius as long as they are fixed in position while the concrete hardens. The stress induced in the bar by the bending process is to be added to the stress induced by the subsequently applied loads. The total stress must not exceed the permissible value.

ComBAR® customised stirrups and bent bars are pre-fabricated at the factory. As bent bars are produced in a different process than straight bars, their material properties are different (refer to page 9).

Connection technology

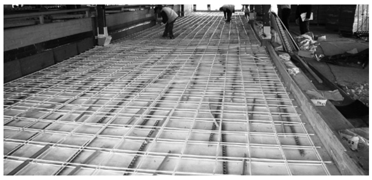
Reinforcement cages made of ComBAR® bars can be assembled with ordinary or stainless steel tying wire. Damage to the bars caused by properly installed tying wire is insignificant. In cases where reinforcement cages are to be entirely free of steel, plastic / nylone zip ties, such as those used by electricians, can be used. A tightening wrench facilitates pulling and trimming of the ties.

Plastic clips have been developed to connect ComBAR® bars at ninety degree angles to form meshes. The clips are attached to the bars using a rubber hammer or a similar tool. On a solid surface the clips can be attached by stepping on them.

Bar couplers, that are glued onto the ComBAR® bars in the factory, are an alternative means of connecting ComBAR® and steel bars. When the ComBAR® bars are connected with the steel bars, it is important that they are handled and turned at the connector, not at the bar. The glued couplers should not be exposed to temperatures above 100° C. Special care needs to be taken when welding in the vicinity of the couplers to be sure that sparks do not fly onto the ComBAR® bars.

Wire rope grips can be used to connect ComBAR® bars to steel reinforcing bars. The ComBAR® bar should be placed in the curved form piece of the grip. Two short pieces of smaller diameter steel rebar should be placed in the grip, between the ComBAR® and the steel bar, to minimize the damage to the ComBAR® bar caused by the clamping force. When diameter 32 mm bars are connected, the torque applied to the nuts should not exceed 80 Nm. Special grips with wire rope clamp straps have been developed for the connection of ComBAR® bars with steel bars having a diameter greater than 32 mm.

Applications

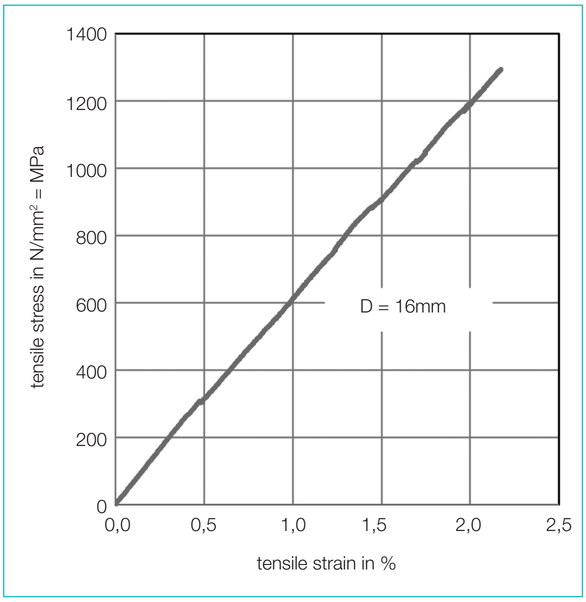
application	description	project
industrial facilities and slabs	non-metallic reinforcement: ▶ no induction currents in the rebar ▶ un-disturbed operation of transportation systems	
parking structures and garages	non-corrosive reinforcement: ▶ no crack-sealing coating required ▶ thin slabs possible	
bridge decks, barrier walls, approach slabs, sidewalks, wing walls, curbs	non-corrosive reinforcement: ▶ no damages due to de-icing salts ▶ higher integrity and extended service life time of structure	
railways	non-metallic reinforcement: ▶ no disturbance of signal systems ▶ no induction currents in the reinforcement near switches (induction coils)	
marine structures	non-corrosive reinforcement: ▶ no damages due to sea water ▶ extended service life time	
thin pre-cast elements and facade panels	non-corrosive reinforcement: ▶ minimum concrete cover sufficient ▶ minimal thickness	
research facilities	non-metallic reinforcement: ▶ no interference with electromagnetically sensitive equipment	
transformer and reactor / inductor stations	non-conducting reinforcement: ▶ no induction currents in rebar ▶ no losses due to stray currents	
civil engineering and infrastructure	easily machined reinforcement: ▶ direct penetration by the tunnelling machine ▶ substantial reduction in construction costs	

Tensile strength and modulus of elasticity (straight bars)

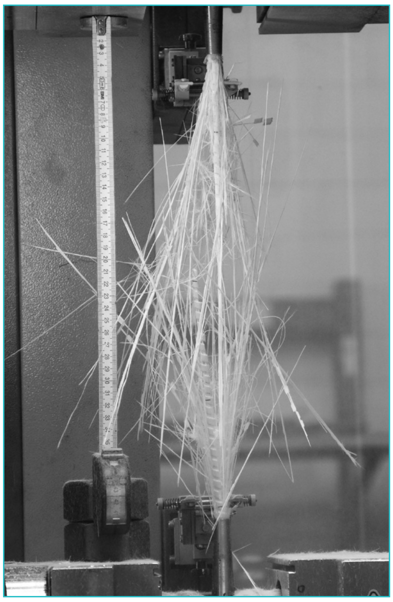
In contrast to steel, ComBAR® behaves in a linear elastic manner up to failure. Yielding is not observed. The modulus of elasticity of straight bars is well above 60 GPA (64 GPA for ø 16 mm bars). The mean value of the short term tensile strength measured in tensile tests on bare ComBAR® bars lies between 1,000 MPa (32 mm bars) and well above 1,500 MPa (8 mm). The true value is much higher, as the fibres themselves have a tensile strength of more than 3,000 MPa. With the volumetric fibre content of approximately 75% ComBAR® bars must have a short term tensile strength of approx. 2,200 MPa. The measured values are much lower, as the bars fail prematurely at the clamped ends and due to internal stresses being induced in the bars during the tests (eccentricity, application of force along the bar circumference only, etc.). As the long term strength of FRPs can not be derived from their short term strength, the meaning of the short term values for structural designs is minimal, anyhow. (Refer to pages 15 and 16.)

To determine the tensile strength and the stress-strain relationship both ends of ComBAR® bars are glued into shafts. The load is applied at approximately 1 kN/sec. in a hydraulic press. The modulus of elasticity is determined using highly sensitive strain gages.

The diagram below shows the tensile test for each diameter.



exemplary stress-strain diagram ComBAR®



shredded bar

Failure is brittle. It occurs in the free span of the test specimen, when the tensile strength of the material is exceeded. The fibres burr in the fracture zone in a brush-like fashion. The outermost bar ends, where the specimen is fixed in the hydraulic press, including the ribs of the bars, are undamaged.

In contrast to the brittle failure of the test specimen, a ComBAR®-reinforced structural element shows distinct signs of the impending failure (large deflections and cracks) well in advance of reaching the ultimate strength.

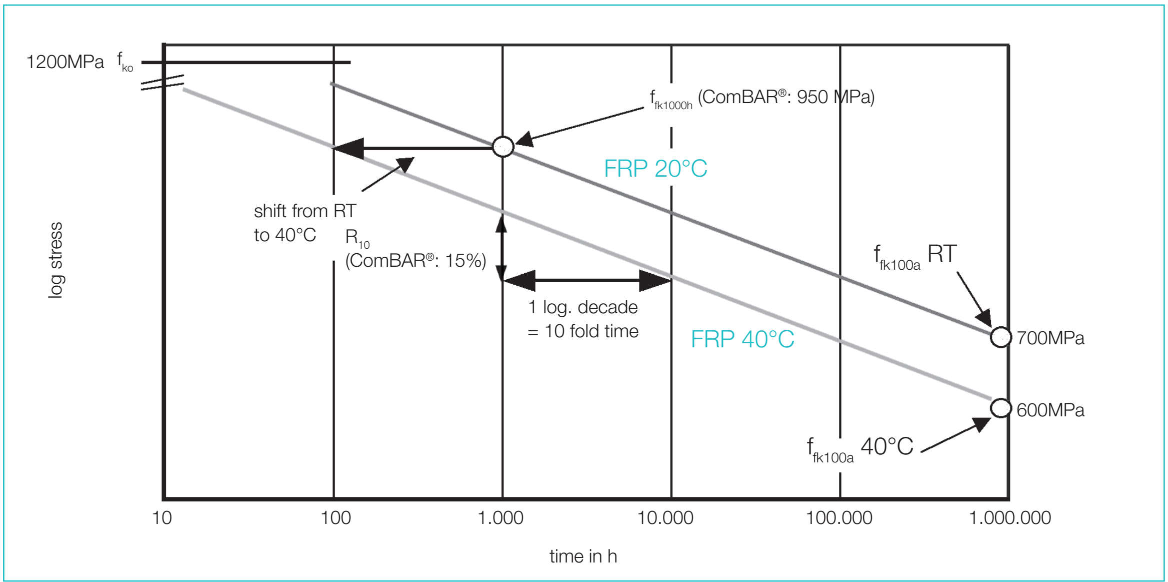
Durability, characteristic value of the tensile strength

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 ($\varepsilon \leq 0.3$ %) in an alkaline solution for specified periods of time. After the aging process the bars are unloaded and dried. Their residual tensile strength is tested in conventional tensile tests.

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. Newest generation glass fibre bars, such as ComBAR®, are able to sustain far higher stresses. Their bond properties are virtually analogous to those of steel reinforcement. Unlike steel, however, the strength of FRPs decreases with time. In addition, the continuously sustainable tensile stress of FRPs is a function of the prevalent environmental conditions (mean temperature, amplitude of temperature changes, moisture / humidity level).

To allow for an economic utilisation of these bars a new safety concept had to be developed. This concept is needed to derive design values of the tensile strength for any specific environment and any specified design service lifespan. The central objective of the concept is to guarantee the same level of safety in any design of FRP reinforced concrete members while at the same time allowing for efficient and economic structures.

In this time-to-failure (creep rupture) approach the characteristic value of the tensile strength for a specific project is determined on the basis of the 1,000 hour strength $f_{fk1000h}$ (at room temp.; 5th percentile) of the chosen FRP material. $f_{fk1000h}$ is determined in tensile tests on bars cast into prisms of highly alkaline (ph ≥ 13.7) concrete. The prisms are saturated with water and kept at a constant temperature over the entire duration of each test. $f_{fk1000h}$ is the stress in the bar which results in its failure after a load application over 1,000 hours.



Relationship of sustained stress vs. time to failure (ComBAR®)

The characteristic value of the tensile strength $f_{fk,t}$ for a specific set of environmental conditions and a specified design life (t) is obtained by multiplying this value by the environmental factor η_{env}.

$$f_{fk,t} = f_{fk1000h} * \eta_{env}$$

The environmental factor is defined as

$$\eta_{env} = [(100 - R_{10})/100]^n \qquad \text{(ComBAR®: } 0.85^n\text{)}$$

Durability, characteristic value of the tensile strength

where

R_{10}	logarithmic temporal slope	specified in a series of durability tests for each FRP material While standard GFRPs have R_{10} values of 25%/dec and CFRP has 5%, R_{10} for ComBAR® is 15%/dec.
n	environmental exponent	$n = n_{mo} + n_T + n_{SL}$
n_{mo}	moisture exponent	
n_T	effective temperature exponent	
n_{SL}	service life exponent	

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

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

design service life (years)	n_{SL} or resistance against accidental load nSL= 0.0
100	3.0
50	2.7
20	2.3
10	2.0
5	1.7
1	1.0
0.1	0.0

The long-term strength of FRPs depends on both the maximum temperature and on the frequency and amplitude of the temperature changes whereto the bars are exposed. These are considered by defining the effective temperature and then selecting the corresponding effective temperature exponent n_T. The most feasible approach to determining the effective temperature is to add a margin of safety to the mean annual temperature of the location of the concrete structure. This temperature margin depends on the intensity of the exposure to the sun or another external heat source and on the thickness of the member.

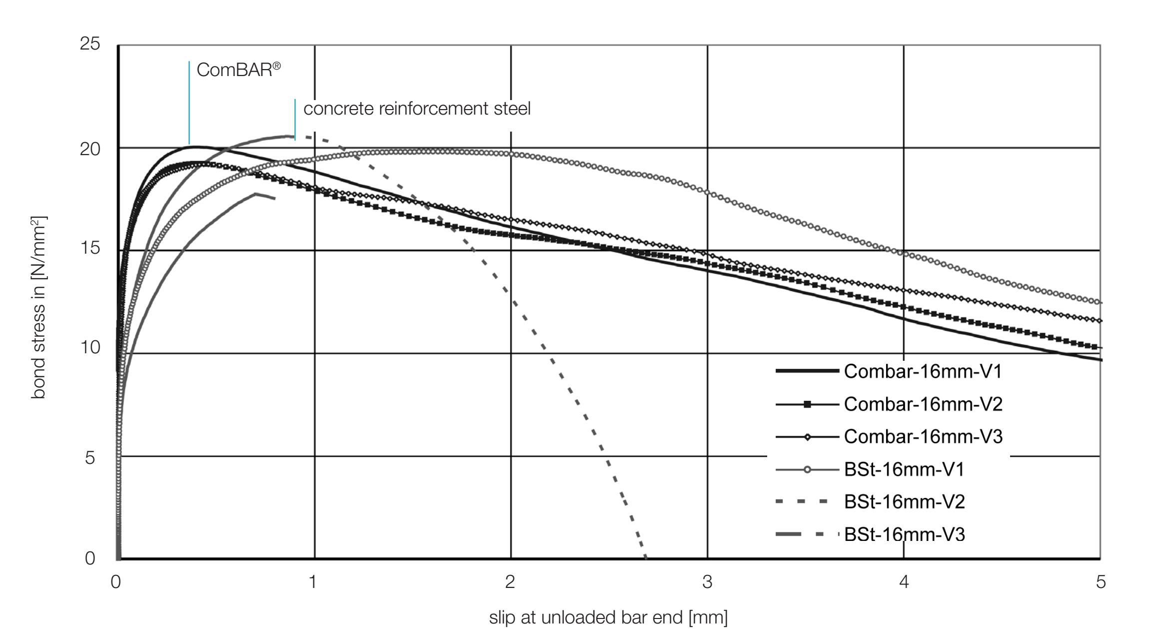
location	environment	member thickness	temperature margin
dry	constant room temperature (23 °C)	no influence	± 0°C
outdoor	direct exposure to sun, mostly dry	h ≥ 200mm	+ 10°C
		100 < h < 200mm	+ 15°C
		h ≤ 100mm	+ 20°C
	no direct exposure to sun, mostly dry	no influence	+ 10°C
wet / moist	fully submerged in water	no influence	+ 5°C
	frequently wet (tidal influence, splash water)	see outdoor	see outdoor
	embedded in soil	no influence	effective temp. = 10°C

All values for typical Canadian environments

Characteristic values (CSA S806) / specified values (CSA S6 - CHBDC) of the tensile strength of ComBAR® bars for common Canadian environmental conditions and for typical design service live spans are listed in Table 1 (page 27) of this technical information.

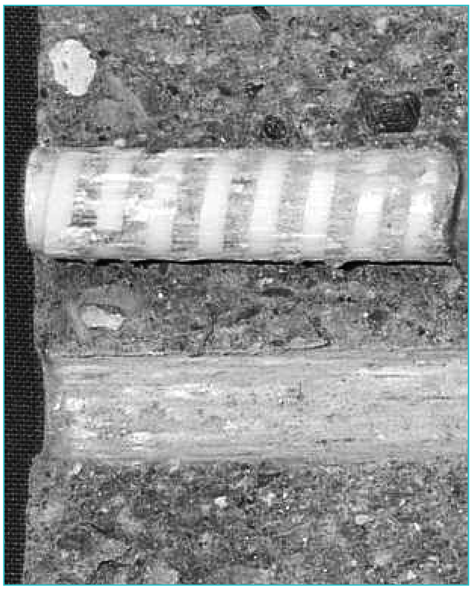
Bond behaviour (short-term)

Centric pull-out tests were performed on a 150 mm concrete cube, according to the RILEM RC 6 recommendations. The displacement at the unloaded end of the bar was plotted as a function of the load. The compressive strength of the concrete was > 40 N/mm².



The results of the test series are:

- The failure mode is, as with steel rebar, extraction of the concrete corbels from the concrete block. The ribs of the rebar are largely undamaged.
- As is the case for reinforcing steel, higher bond stresses are observed in higher grade concrete.
- No significant differences were observed regarding the slip of the unloaded bar end of ComBAR® and steel bars. The maximum bond stress was recorded at a slip between 0.4 mm and 0.6 mm.
- Even though the bond stress of ComBAR® bars is greater at the same amount of slip, the tensile splitting forces are lower than those of steel rebar.
- Further bond tests have shown that, in normal grade concrete the bond behaviour of ComBAR® is controlled by the strength of the concrete corbels, in high strength concrete (> 60 MPa compr. strength) by the strength of the ComBAR® ribs.



The special surface profile of ComBAR® bars ensures optimal bond between concrete and the rebar.

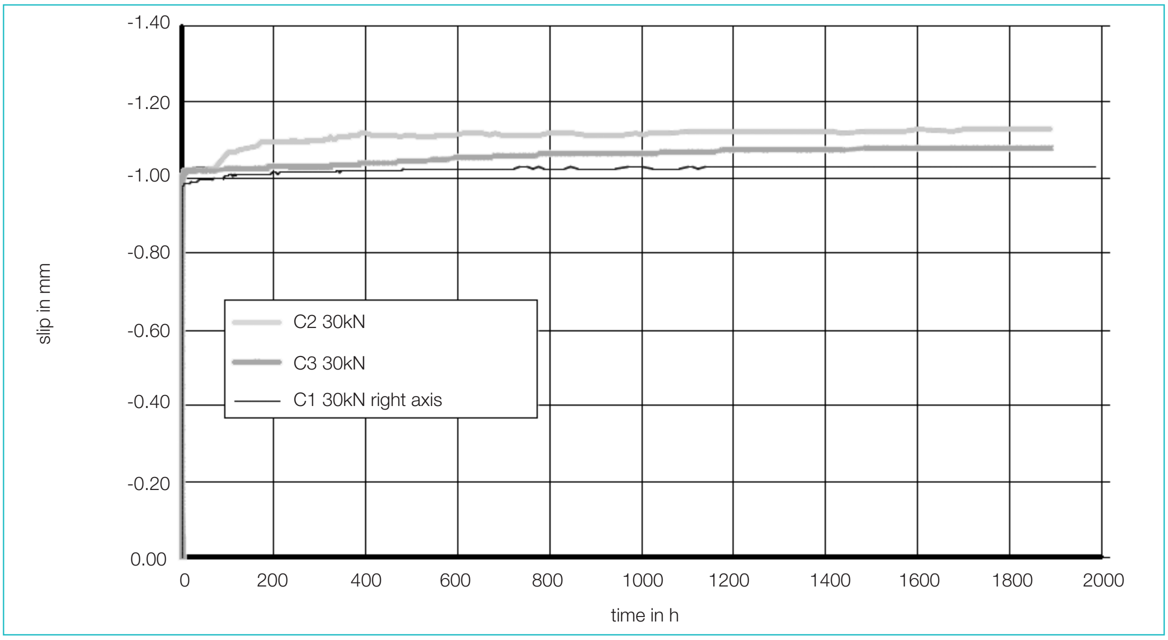
Bond behaviour (long-term)

To determine the long-term bond behaviour and bond-creep behaviour of ø 16mm ComBAR® bars two series of bond test were run according to the RILEM recommendation RC6. The aim was to derive the bond behaviour of ComBAR® bars over a service life of 100 years on the basis of accelerated long-term tests under extreme conditions.

Bond-creep after pre-loading

To evaluate the bond-creep behaviour of ComBAR® bars in cracked, that is in pre-loaded, concrete members ComBAR® bars were cast centrically into 150 mm concrete cubes. The embedment length was five bar diameters $l_{b,net}$ = 5 df (80 mm). The cubes were cured in water at room temperature. In a first step the bars were loaded until the total slip at the loaded end was between 1 and 3 mm.

Subsequently a somewhat smaller permanent load was applied to the bars. For the entire duration of this second test phase the concrete cubes were heated to 60°C and were kept completely saturated with water. At a constant bond stress of 11.2 MPa the additional slip at the loaded bar end was less than 0.6 mm after 2,000 hours. A bond stress of 7.5 MPa resulted in a slip of less than 0.2 mm.



Bond-creep after pre-loading at f_b = 7.5 MPa; 60°C, constantly saturated concrete

Bond-creep without pre-loading

Without pre-loading ComBAR® bars were able to sustain loads of up to 55 kN, under otherwise identical conditions..

Conclusions

- The long-term bond strength (100 year service life) is well above the required value of 8.0 MPa (CSA S806 / S807).
- At the required value of 8.0 MPa the total slip at the loaded end of the bar will be less than 0.3 mm.
- The bond coefficient k_b (CHBDC) can be taken to be 0.6, the bar surface factor k_4 = 0.8, and the bar surface profile factor (CSA S806) k_5 = 1.0.
- The bond properties of bars with other diameters are equivalent to those of the 16 mm bar.

Crack width

To determine the crack widths, tensile tests were carried out on cylindrical strain elements

(ComBAR® ø = 16 mm; concrete cover c_v = 65 mm; reinforcement ratio ρ = 1.1 %, concrete strength (cube) $f_{c,cube}$ = 30 N/mm²).

The strain elements did not contain any additional reinforcement. They were loaded up to a stress of 900 MPa. Cracks appeared in the specimen at a spacing of approximately 300 mm once the tensile strength of the concrete was reached. As the load was increased, the width of the cracks increased. After the maximum load had been reached, the specimen was unloaded. The cracks closed nearly entirely. A detailed analysis of the specimen showed that the concrete corbels had sheared off in the vicinity of the cracks. Between the ribs of the bars the concrete corbels were intact. The bars did not show any signs of damage.

Results

- Entirely intact concrete corbels are seen in the middle sections of the fragments of the test specimen. In the vicinity of the cracks the concrete corbels have been sheared off.
- The bar, as well as its ribs, remain undamaged.


first crack (150 N/mm²)


second crack (300 N/mm²)


575 N/mm²


900 N/mm² (max. stress)


strain body after unloading

Conclusions

- The crack behaviour of ComBAR® is analogous to that of steel rebar.
- The distances between neighbouring cracks were generally smaller in reinforced concrete members with ComBAR® than they were in members with the same reinforcement ratio in steel.

Charts are available upon request.

Crack width

The following approach can be taken to derive the approximately required cross sectional area of ComBAR® crack reinforcement from the required amount of steel rebar.

The crack width is proportional to the diameter of the rebar, independent of the reinforcing material which is used. If more bars of a smaller diameter are installed at a closer spacing crack widths will be smaller.

As is the case for steel rebar, the total slip of ComBAR® bars (pull-out test) is proportional to the square of the stress in the bar. If the stress is reduced by half, the slip decreases to 25 %.

It can be conservatively assumed that the crack spacing is the same in a member reinforced with ComBAR® as it is in a comparable steel reinforced section.

Based on these facts and assumptions the relationship between the required amount of ComBAR® bars and the required amount of steel rebar is:

$$\frac{W_{k,\,ComBAR}}{W_{k,\,steel}} = 1.0 = \frac{200{,}000\ N/mm^2}{60{,}000\ N/mm^2} \cdot \left[\frac{P_{ComBAR}}{P_{steel}}\right] \cdot \left[\frac{f_{ComBAR}}{f_{steel}}\right]^2$$

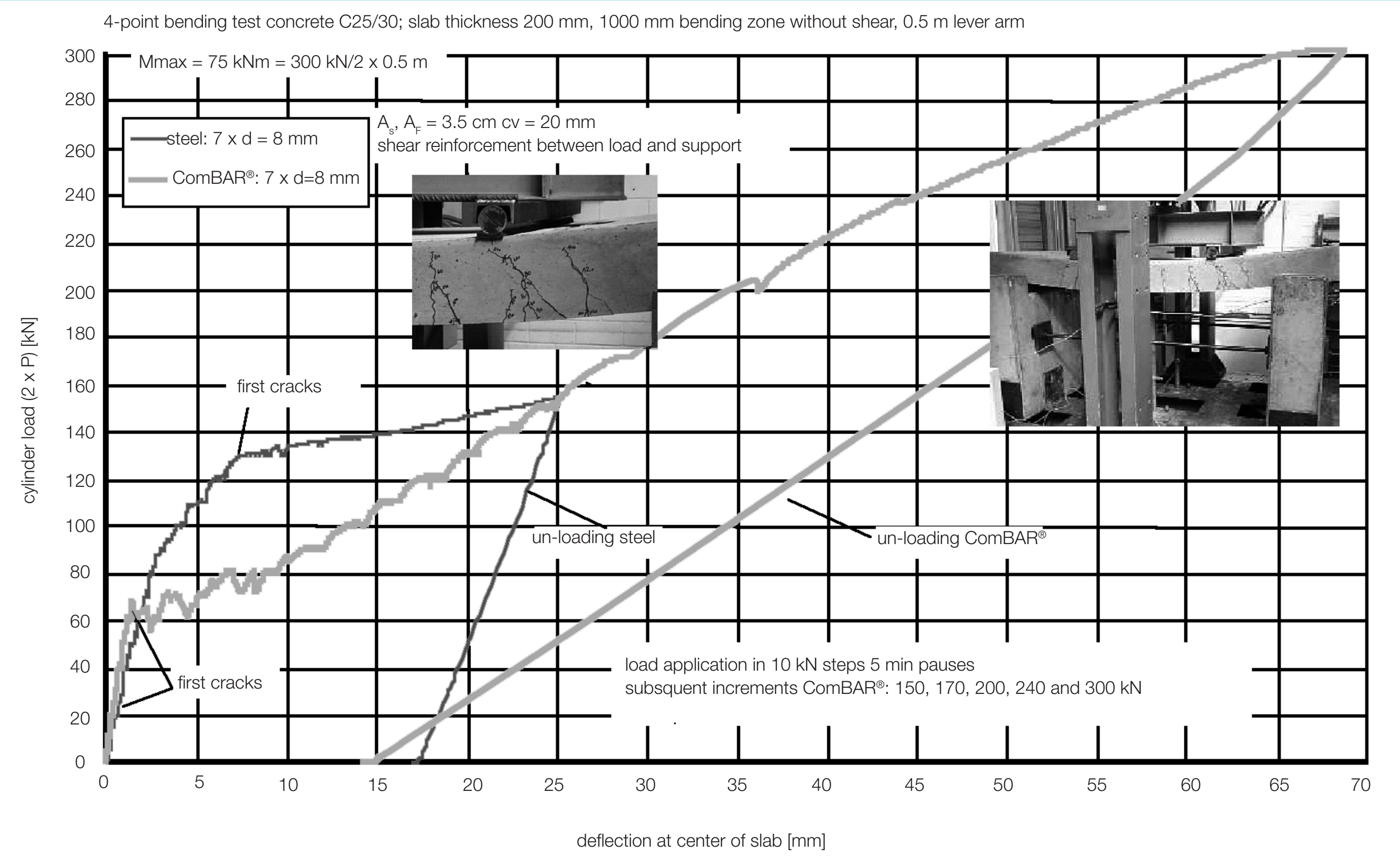
For equal bar diameters this implies:

$$req.\ A_{ComBAR} = \sqrt{\frac{200{,}000}{60{,}000}} \cdot A_{steel} = 1.83\ A_{steel}$$

Deflection

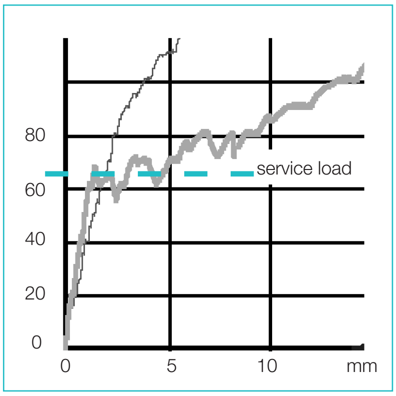
Due to the significantly lower modulus of elasticity of ComBAR® ($E_F \geq$ 60GPa), special attention needs to be devoted to checking the serviceability limit state requirements. The experience with glass fibre reinforced concrete members is still relatively limited. As a result, controlling the deflection by limiting the member stiffness, as it is customary with steel reinforced concrete members, is not yet possible.

In a lab test two concrete slabs of identical dimensions (2,500 x 1,000 x 200 mm) were tested in a four point bending test (bending zone without shear: 1,000 mm). Slab 1 was reinforced with 7 ø 8 mm steel rebars (grade 500), slab 2 with 7 ø 8 mm ComBAR®. The position and distribution of the bars were identical.



4-point bending test: comparison ComBAR® - steel

The maximum load sustained by the ComBAR® reinforced slab was more than twice as high as the load sustained by the steel reinforced slab. The maximum deflection was about three times as high.
Shortly after the first cracks formed the deflection of both slabs was nearly identical. After the service load was reached in the reinforcing bar (according to German codes approx. 305 MPa; 67kN cylinder load) the deflection of the ComBAR® reinforced slab was about 2.5 times greater. At 90% of this stress (60kN cylinder load) the difference of the deflections was between 1.5 and 2.0.



Excerpt 4-point bending test

Conclusions

- In any design of GFRP reinforced concrete members special attention needs to be paid to checking the deflection requirements.
- To achieve the same maximum deflection in a ComBAR® reinforced member as in the geometrically identical steel reinforced members approx. 2.5 times the reinforcement cross-section will be required.

Thermal behaviour

Coefficient of thermal expansion

The axial and radial coefficient of thermal expansion were determined on test specimen at temperatures ranging from 0° C to 70° C.

Coefficient of thermal expansion α	ComBAR®
axial [1/K]	0.6×10^{-5}
radial [1/K]	2.2×10^{-5}

For comparison: the coefficient of thermal expansion of concrete is between 0.5 and 1.2×10^{-5} 1/K, that of reinforcing steel is 1.0×10^{-5} 1/K, that of stainless steel 1.5×10^{-5} 1/K.

Structural elements reinforced with ComBAR® are not affected by temperature changes. Expansive cracking did not occur in lab experiments, even when ComBAR® reinforcing bars were placed close to the surface of the specimen and the moisture content was varied over time. This can be explained by the relatively low modulus of elasticity of glass fibre rebars perpendicular to the bar axis. This is controlled by the modulus of the resin, which is between 3,000 and 5,000 MPa. A temperature increase of 40°C induces a strain of 0.088 % and a compressive stress on the surrounding concrete of only approximately 4.4 MPa.

Ambient temperatures

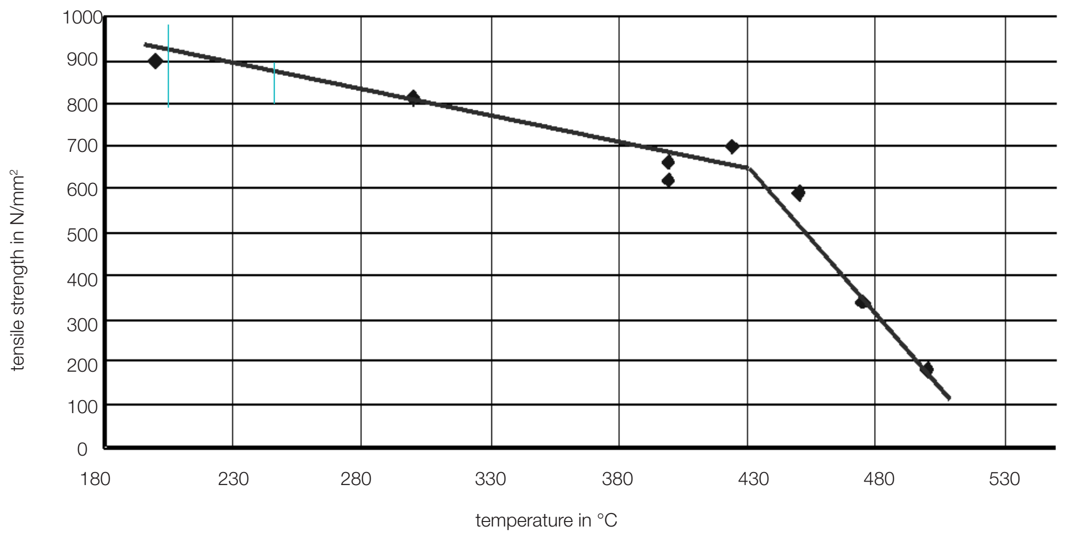
The ambient temperature of ComBAR® bars within a concrete element should not exceed 40 °C. Unless noted otherwise, all technical values specified in the product data sheets were determined at room temperature. Higher temperatures which can occur during curing of massive concrete elements do not cause any harm to the ComBAR® bars. A reduction of the load bearing capacity was not observed. If ComBAR® bars are to be permanently exposed to higher temperatures, the characteristic value of the tensile strength is to be reduced according to the durability concept outlined on pages 15 and 16.
The engineers at Fiberline are available for an in-depth consultation.

Behaviour at low temperatures

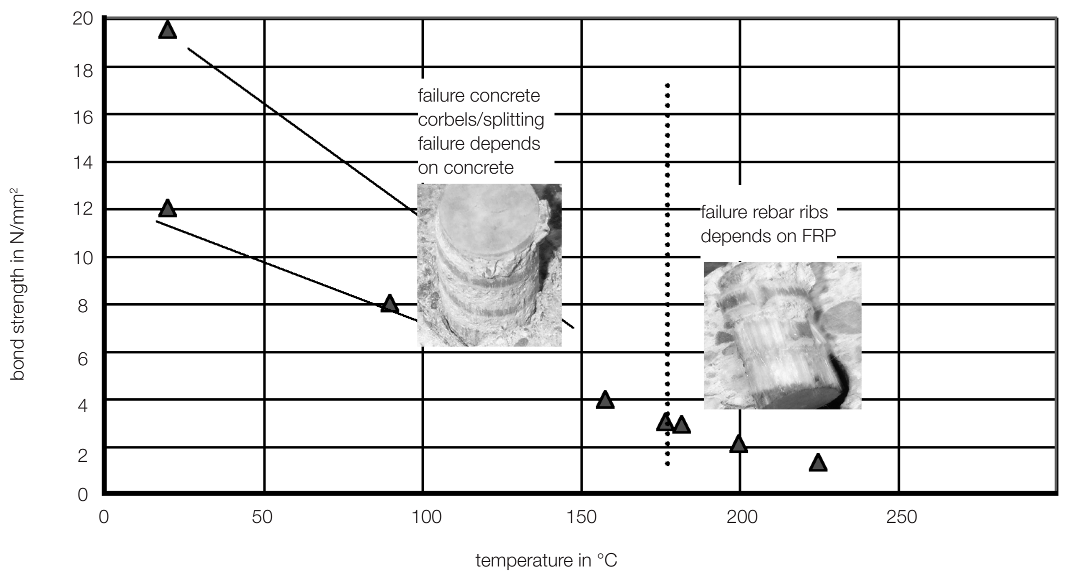
The behaviour of ComBAR® was tested at extremely low temperatures (up to –40 °C) in various test series in Canada according to ISIS specifications / CSA S807. It was shown that the material properties of ComBAR® remain nearly unchanged at extremely low temperatures.

Fire resistance

The resins used in the production of ComBAR® withstand temperatures up to about 200 °C over short time spans. The glass fibres soften/melt at about 600 °C. ComBAR® can catch on fire when exposed to an open flame. After a few seconds the bars stop burning, when no more flammable material remains on the surface of the bars. ComBAR® bars do not contain fire-resisting additives. In case an increased fire resistance of ComBAR®-reinforced structural elements is required, non-structural measures, such as an increase of the concrete cover or an encasement with fire-resistant material, are recommended. Most fire protection methods customary to conventionally reinforced concrete construction can be applied.



temperature dependence of tensile strength of ComBAR®



Pullout test MPa BS and Schöck lab et elevated temperatures: ComBAR® 16 mm

Concrete cover for a 90 Minute fire rating

The isothermal lines for concrete also apply to ComBAR® reinforced elements. The critical temperature of ComBAR® bars is 225°C. When ComBAR® bars are installed in a member with a 30 Minute fire rating the required concrete cover is 30 mm. For a 90 Minute fire rating the required concrete cover for ComBAR® bars is 65 mm. Values for other fire ratings can be interpolated or determined using the isothermal lines of the specific concrete used in the member. Wherever possible, ComBAR® reinforced members should be protected against fire by applying fire coatings or by encasing the concrete member in fire cladding. These measures result in an overall more economical structure.

Design recommendations

ComBAR® - reinforced concrete members should be designed according to the CSA S806-12 “Design and Construction of Building Structures with Fibre-Reinforced Polymers” code. Chapter 16 of the Canadian Highway Bridged Design Code (CAN/CSA-S6-06) “Fibre-Reinforced Structures” applies to the design of bridges and elements thereof. This design recommendation is structured in accordance with the CSA S806 (chapter numbers, section numbers). Chapters and sections which are not listed in these recommendations apply to ComBAR® bars without any changes or comments.
The specified design values and recommendations apply in their essence to a design according to the CHBDC.

1 General Design Requirements

1.1 Fire Performance
The critical temperature of ComBAR® bars is about 225°C. Where high fire ratings are required (90 minutes and more) the most economical design is most likely achieved by installing external fire protection measures, rather than by increasing the concrete cover on the ComBAR® bars.
Detailed information on the behaviour of ComBAR® bars exposed to high temperatures is contained on page 24 of this Technica Information.

1.2 Durability
A detailed description of the newest concept for durability tests on ComBAR® bars in concrete is contained on pages 16 and 17 of this Technical Information. The concept was adopted by the International Concrete Federation fib.

2 Factored Resistance

The resistance factor for ComBAR® bars is $\phi_F = 0.8$.

3 Properties of FRP Components and Reinforcing Materials

3.1 FRP Bars: ComBAR®
Pre-tensioned ComBAR® bars with immediate bond can be installed in pre-cast elements, for example, to produce a completely precompressed element which will remain free of cracks under service loads.
The properties of straight ComBAR® bars are summarized on pages 6 and 7 of this Technical Information.

3.1.1 Testing and Acceptance
To determine the load-bearing core cross-sectional area of the perfectly round ComBAR® bars the exterior diameter is measured using callipers. Twice the depth of the ribs, also measured with callipers, is subtracted from this value to determine the core diameter.
Extensive creep-rupture tests have been performed under load on ComBAR® bars cast into concrete. The tests are performed according to the durability testing procedure outlined on pages 16 and 17 of this Technical Information.

3.1.2 Characteristic Values for Design
The characteristic value of the long-term tensile strength of ComBAR® bars $f_{Fk,t}$ shall be determined according to the procedure outlined on pages 16 and 17 of this Technical Information. Table 1 contains typical values of the characteristic value of the tensile strength for selected environmental conditions and specified design service life times.

The resistance factor for ComBAR® bars is $\phi_F = 0.8$.

Design recommendations

4 Beams And One-Way Slabs

k_b in Equation 8-1 is 0.6 for all ComBAR® bar diameters

4.1 Vibrations

In a test series ComBAR® reinforced beams have been tested for their fatigue behaviour. The tests have shown that ComBAR® bars can sustain three million load cycles at a stress amplitude of 90% when the maximum stress in the ComBAR® bars is limited to 150MPa.
ComBAR® bars subjected to an upper stress of 250MPa and a lower stress of 150MPa sustained at least 2.5 million load cycles. These tests show that, unlike steel, higher stress amplitudes can be sustained by ComBAR® bars if the upper stress is lower.

5 Ultimate Limit States

5.1 Types of Shear Reinforcement

ComBAR® double headed bolts have been developed as shear reinforcement. The design tensile stress in these bolts should be limited to 130 MPa (corresponding strain: 0.2175 %). Conservatively, it can be assumed that the full design force of the headed bolt is anchored at the middle of the headed end. Special caution is advised in the design to make sure that the headed ends are properly embedded in the compression zone of concrete members under flexure and shear.

6 Reinforcement and Tendon Properties for Design

6.1 Design Strength for Reinforcement

The design value of the long-term tensile strength is derived by multiplying the characteristic value by the resistance factor for ComBAR® $\phi_f = 0.8$.
$f_{fd} = f_{fk,t} \times \phi_f$, ComBAR®

7 Development Length of Bars in Tension

Due to their specially developed ribs, which are cut into the hardened bar, the bond behaviour of ComBAR® bars in normal grade concrete is very similar to that of steel rebar.

The bar surface profile factor of ComBAR® bars is $k_5 \leq 1.0$.

In laboratory tests it has been shown that the tensile splitting forces along ComBAR® bars are very small. The minimum concrete cover required to allow for the full transfer of the loads from the ComBAR® bars into the surrounding concrete is d_b + 10mm.
To reduce the development length of straight bars ComBAR® bars with headed ends can be used. The force which can be anchored by a single head is given on page 8.

All ComBAR® splices are class B. The splice length is 1.3 times the development length.

Table 1:

Characteristic values long-term tensile strength ComBAR®

application	design serv. life [years]	environment	thickness (h)	effect. temp. °C	n	η_{env}	$f_{Fk,t}$ [MPa]
diaphragm wall	5	wet	1000 mm	10	2.7	0.64	612
industrial floor slab	100	indoor, const. temp.	150 mm	23	2.65	0.65	617
retaining wall	100	outdoor, direct sun	400 mm	20	3.5	0.57	537
bridge deck	100	outdoor, direct sun	150 mm	25	3.75	0.55	516
façade element	100	outdoor, direct sun	60 mm	30	4.0	0.52	495
underside of bridge	100	outdoor, direct sun	250 mm	20	3.5	0.57	537
sea wall	100	wet	500 mm	20	4.5	0.48	457
impact on barrier wall	0.1	outdoor, direct sun	> 200 mm	20	1.0	0.85	807

NOTE:
The values in Table 1 are characteristic values (as defined in CSA S806). These correspond to the „specified tensile strength" as defined in CSA S6-06 (CHBDC).
To determine design values of the tensile strength these values are to be multiplied / divided by the appropriate safety or reduction factors specified in the relevant sections of the codes.

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