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Structural reinforcement with FRP

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by BASF

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to find innovative, sustainable solutions for your structural requirements.
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enables us to support your business as its grows - today and tomorrow.

from Master Builders Solutions
The Master Builders Solutions brand brings together
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the construction industry. The know-how and experience of
BASF's global community of product and technology experts
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provides us with the experience
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The Master Builders Solutions product offering
includes additives for concrete and mortar, additives
for cement, chemical solutions for underground
projects, waterproofing and sealing products, products for repairing
and protecting concrete, and performance
grouts and solutions for performance flooring.
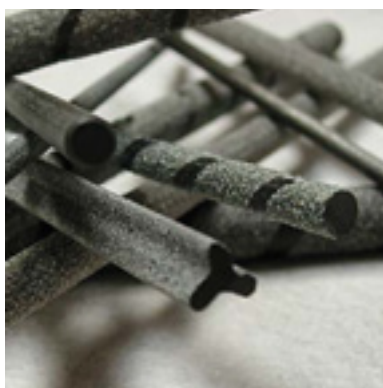
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Technical file

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1. Introduction

With decades of experience in construction projects and research, BASF CC Italia Spa offers **an integrated approach** to each specific structural problem, and offers the designer a wide range of FRP products, repair mortars, calculation manuals, full technical documentation as well as project consultancy from third party experts in the technology. The objective is to educate the technician and enable him to resolve the structural challenges he faces in his work to best effect. This documentation provides technical suggestions as well as critical consideration of the real potential and pitfalls of the technology. The information in this document is the outcome of vast practical experience.

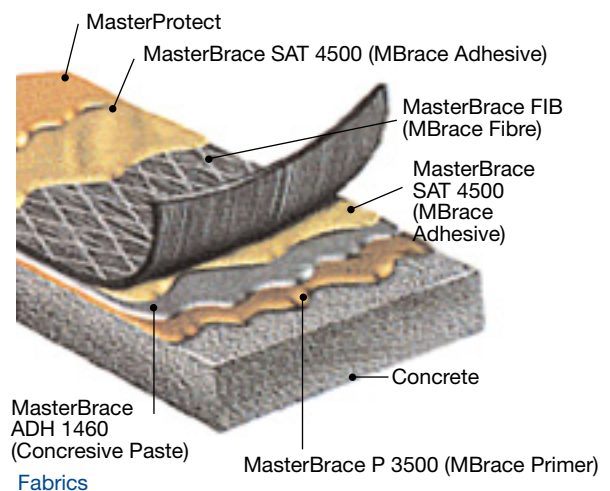**Four types or FRP products are generally used in construction:**

- **bars**: specifically aimed at applications requiring long life and improved fire protection. The matrix is designed to offer a high glass transition temperature Tg and thus excellent resistance to high temperatures. The fibres are a mix of high strength and high modulus of elasticity carbon fibre. The resulting system can be used in combination with Emaco mortar restoration, thus completely doing away with the need for conventional resins.

- **carbon fibre/resin plates in an epoxy paste**: the system is designed for applications requiring quick reinforcement installation. The resins are especially suited for levelling and glueing, have a good pot-life and are easy to mix, thus reducing the time required for the job.

- **unidirectional fabrics** and an epoxy impregnation resin of adequate viscosity for proper impregnation of MasterBrace FIB (MBrace Fibre) fabrics. The system adheres perfectly to the substrate, so long as the latter is properly prepared. This system optimises the amount of fibre on teh structure and is very well suited for multi-directional reinforcement applications.

- **carbon fibre net** applicable with epoxy resin or cement mortar. By nature, FRP (Fiber Reinforced Polymer) products are anisotropic and elastic with linear extension to failure. In contrast with steel, they are NOT ductile, isotropic or plastic. This means that FRP has only modest resistance to compression; if a fibre is cut or perforated at any point its contribution to the system's strength is lost over its entire length; no tension is transferred between fibres laid orthogonally to each other; FRP products cannot be welded, layers must be coupled by means of resin; FRP products, with the exception of fabrics before being impregnated, cannot be folded on site since they are fragile and may fracture over time due to creep in the polymer impregnating the fibres.

MasterProtect
MasterBrace SAT 4500 (MBrace Adhesive)
MasterBrace FIB (MBrace Fibre)
MasterBrace SAT 4500 (MBrace Adhesive)
Concrete
MasterBrace ADH 1460 (Concresive Paste)
MasterBrace P 3500 (MBrace Primer)

Plates

Bars

Fabrics

MasterBrace (MBrace/MBar) systems are used to reinforce structures in three major applications:

■ **glueing fabrics, net or laminates** to the tension surface of beams and columns in undegraded concrete;

■ **glueing fabrics, net or laminates** to the tension surface of beams and columns, following repair of the degraded concrete;

■ **insertion of bars** into the tension surface of beams or columns, following formation of pockets in the undegraded concrete or restoration of the reinforcement covering.

Given that reinforcement is not required solely for undegraded beams, but on the contrary is far more frequently required for degraded structures, it is essential that the MasterBrace (MBrace/MBar) reinforcement be coupled with restoring mortar specified for good adhesion to the substrate, dimensional stability, high interface failure energy and modulus of elasticity which is compatible with that of the existing structure. The MasterBrace (MBrace/MBar) system is thus supplemented by a range of cement products for structural restoration, with the name MasterEmaco.

MasterBrace (MBrace/MBar) products are quality controlled
The MasterBrace (MBrace/MBar) system falls under Type A Applications in Table 3.2 of CNR DT 200/2004, because:

■ it provides clear technical data sheets which provide all the necessary parameters, referring to the finished product ready for installation

■ the above-mentioned mechanical properties are controlled and certified for each production batch

■ it is involved in national and international research into the area

■ it has a vast range of comparative tests which attest its regulatory compliance and the reliability of its calculation methods.

1.1 Traction testing of MasterBrace fabrics
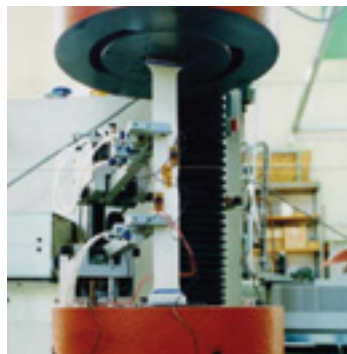
1.2 Traction testing of MasterBrace SAT 4500 adhesive (MBrace Adhesive)

The MasterBrace (MBrace/MBar) system, pursuant to standard CNR DT 200/2004, has a material safety coefficient of gm = 1.1 (bending and traction) and 1.2 (loss of adhesion), rather than 1.2 and 1.5 respectively. This means that the reinforcement can handle a higher level of tension and thus the amount of material required to complete a reinforcement job is less than that of other products which do not meet the above specifications.

Collapse mode	Partial coefficient	Type A application	Type B application
Fracture	γ_f	1.10	1.20
Delamination	$\gamma_{f,d}$	1.20	1.50

Partial coefficients γm for materials and products

2. Recurring FRP product terminology

For proper information about the technology, it is essential that one be clear about terms relating to FRP product. We review them in detail.

MasterBrace FIB FABRICS (MBRACE FIBRE)

■ **Reference direction:** the direction in which the fibres are laid in the fabric.

■ **Dry fibre:** the individual fibre produced in the mill, protected by it protective layer, and wound onto bobbins for subsequent processing: weaving, pultrusion, lamination, etc.

■ **Weave / fabric:** the designer must be provided with the traction resistance of the finished fabric, in relation to the width x thickness of the dry fibre. Knowing the mechanical specifications of the individual fibre (or filament) is not only pointless, it can be counterproductive, both because weaving reduces its mechanical properties, and because the dimensional effect is enhanced in such products. BASF data sheets include all value of use to the designer.

■ **Unidirectional fabric:** a fibrous fabric in which all fibres are laid in the same direction. BASF fabrics are all unidirectional.

■ **Bidirectional fabric:** a fibrous fabric in which some fibres are laid in one direction and others in a different direction.

■ **Four-axis fabric:** a fibrous fabric in which the fibres are laid in four different directions.

■ **Reference weight:** the amount, in gsm, of fibre per reference direction.

■ **Equivalent thickness of dry fabric:** the equivalent thickness of dry fibre laid in the reference direction. Unidirectional fabrics have only one reference direction; for bidirectional fabrics two reference thickness must be specified, one for each direction of laying, and so on. The reference thickness is the ratio between the weight and density of fibre used in the direction in question.

■ **Minimum overlap length:** the minimum length of overlap between fibres which fully transfers tension between them, in other words, the minimum overlap beyond which failure of the sample under traction lies outside the overlap itself.

Polymer matrix

Fibre
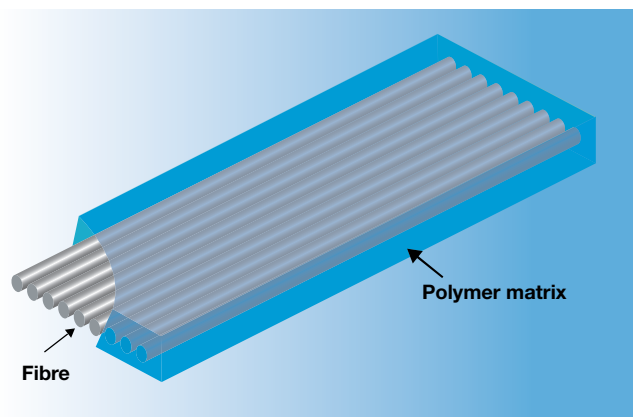
2.1 All MasterBrace fabrics are unidirectional
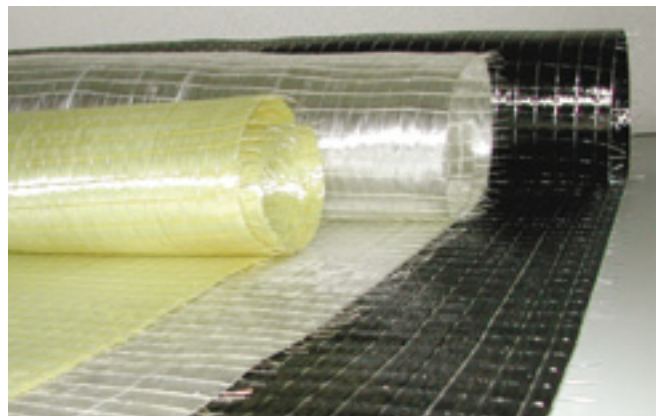
2.2 MasterBrace FIB 300/50 CFH (MBrace High Modulus) and MasterBrace FIB 300/50 CFS (MBrace High Strength) fabrics are supplied in the 50 cm width. MasterBrace CFRP fabric is supplied in the 30 cm width. They are sold in 50 m rolls, and can be cut to size with scissors

MasterBrace BAR bars (MBar Galileo, MBar Leonardo)

- **Nominal diameter:** the diameter of the bar net of coating and sanding, measured during pultrusion, before the surface is roughened. The value is certified by the manufacturer.

MasterBrace LAM plates (MBRACE LAMINATE)

- **Nominal thickness:** the thickness of the plate after hardening, net of coating and sanding (as applicable). It is obtained by direct measurement during pultrusion and before surface roughening.

2.3 MasterBrace LAM plates (MBrace Laminate) have a thickness of 1.4 mm, width 50 or 100 mm, and are wound on 50 m rolls. They can be cut to size using a hacksaw

Recurring quality control terminology

IT is useful to be able to read product certifications properly:

- **Minimum resistance to traction:** the minimum value obtained in testing. Given the wide range of results, it is not true that the minimum value is less than the characteristic value.
- **Characteristic value available to project ftk:** the 90% fractile obtained from at least 5 traction tests using samples from a single production batch. The fractile is calculated, pursuant to ACI 440, as follows: ftk=fmean-3std. dev.; this value is used in the calculation, as indicated in recommendation CNR DT 200/2004.

| MasterBrace FIB 300/50 CFH (MBrace High Modulus)					
Control	Width mm	Nominal thickness **mm**	ft MPa	E GPa	Elongation %
1	29.97	0.165	3.331	393.9	0.8
2	29.19	0.165	4.146	353.9	1.2
3	30.06	0.165	3.734	373.4	1.0
4	29	0.165	3.664	387.0.	0.9
5	29.83	0.165	3.700	435.4	0.8
Mean			**3.715**	**388.7**	**1.0**
Minimum			**3.331**		
Standard deviation			290		
Characteristic value: fm -3 sd			**2.844**		

A recent control of a production batch of MasterBrace FIB 300/50 CFH fabric (MBrace High Modulus)

As can be seen from the table, the **minimum value** *may be much higher than the* **characteristic value**

- **Dimensional effect of samples:** the experimental characterisation must be run on products used without modifying their section or form. Not doing so can result in the dimensional effect, i.e. the measured strength is greater than the actual strength. The literature confirms that a narrow sample of fabric with many layers may have a higher strength than a wider layer of the same fabric. The test strength obtained with plates of 100 mm width is less than that obtained with plates which are 50 or 30 mm wide.

2.4 Estimating the modulus of elasticity in traction

- **Modulus of elasticity: the best fit slope** of the σ–ε curve under traction in the section between 0.1 and 0.4 ftk for each direction of laying of the fibres. If the product is high quality, the σ–ε curve should be perfectly linear. If the fibres are not all perfectly aligned, the curve will be slightly curved downwards. If the fibres are not all of the same quality, the curve will be slightly curved upwards.
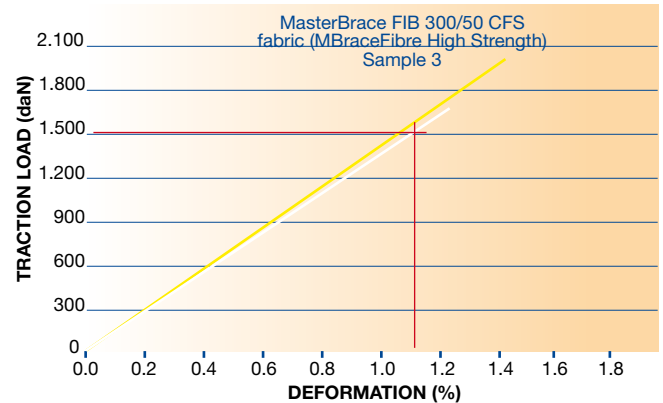
- **Glass transition temperature:** the temperature beyond which the mechanical properties of the polymer consistently decline. Testing is done in accordance with the ASTM FRTO Certificated standards. For example, the glass transition temperature of the polymer used in normal carbon fibre bars is around 150°C. MasterBrace BAR (MBar Galileo HTG) products are certified for a transition temperature of over 250°C, and are thus well suited to structures requiring protection against fire.

- **Adhesion by traction:** the pull-out test of a round or square steel bar gives the resistance against traction of the weakest interface. There are three basic interfaces: filament/matrix (internal delamination of the FRP product), polymer/restoration mortar (delamination of the reinforcement), mortar/concrete substrate (delamination of the cladding). The best possible result is obtained when the concrete substrate itself fails.

- **Manual impregnation:** carbon fibre fabrics are impregnated on site with the epoxy polymer. Manual impregnation is difficult for heavy fabrics (>600 gsm), the resin does not penetrate completely between the filaments, thus reducing the system's ability to transfer the load.

2.5 The pull-out test, manual impregnation is not correct if the fabric is heavy weight

It may happen that certain forms of weave (for example, fabrics of more than 600 gsm often have bunched together and not evenly distributed fibres) give a positive adhesion test result because the resin passes between the bundles of filaments to the interior of the assembly.

This impregnation, however, does not correspond to good practice, since, as can be seen in figure 2.6, the resin does not impregnate all fibres and the unimpregnated fibres do not contribute to the reinforcement, which is thus ineffective.

2.6 Heavy weight fabrics form bundles of filaments which the adhesive cannot penetrate (left: 1200 gsm fabric, right: 800 gsm fabric)

3. Applicable standards

Although MasterBrace products may be used for new reinforced concrete structures, the main application is repairing and reinforcing existing structural elements. In this area, FRP is a clear technical improvement over existing techniques such as:

- **plating** with steel plates of inflected structure, replacement of steel plates (heavy, subject to rapid corrosion and requiring bolting to the structure) with sheets of FRP fabric is certainly a technological step forwards, which eliminates the problem of corrosion, simplifies installation, reduces the time required to complete the job, and does not change the size of the reinforced structure;
- **cladding** columns with metal profiles to augment their compression strength, in this case too the use of FRP is much less invasive, everything is concealed and the application is faster;
- **armouring** with an armature against shear and bending. This solution is very common increases the strength of the structure by building it up with a large amount of compression resistant material (mortar or cement bentonite) and a metal cage: bars and brackets, to increase the resistance against bending and shear.

All the types of reinforcement with FRP mentioned above have been tried and tested experimentally and in practice from the Nineties to the present day. At the level of design, however, the issue is far more complex. In the first place, designers in different countries certainly have very different approaches. In Italy there is a large amount of legislation governing the construction industries. Since Law 1086 in 1971, not only has the legislator aimed to regularise the roles and responsibilities of the various authorities involved in constructions and define the mechanical aspects, but has also regulated the rules of design. This approach, which on the one hand safeguards the role of the designer, on the other prevents innovation, and gives priority to conventional methods over new concepts. In many other countries the situation is completely different: the designer is given complete freedom to select the design method, while the legislator, or even individual owner, is required to define the loads and structural objectives. In this panorama, which varies widely from country to country, there is a common line, and numerous expert committees have published recommendations or guidelines which are used in many countries. Standards which have the weight of the law do NOT exist; we will have to wait for the process which issues such standards to consolidate the technology itself. In 2004, an expert committee instituted by the Italian CNR published a recommendation about the matter which is currently being revised; although it is a useful tool, it is incomplete and often either too or insufficiently cautious in its approach. After these lengthy but necessary general considerations, we will consider the details of the standard to offer the designer a tool and method of actual use. The following is largely based on **CNR DT 200/2004** with a few contrasting considerations which we will highlight in the course of the review. With the explanatory circular to consolidated law 2008 dated 2/2/09 n. 617, FRP materials have been approved by law for the restoration and reinforcement of existing masonry work and reinforced concrete structures.
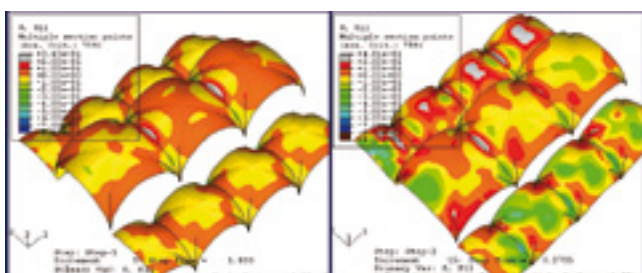
The appropriate design rules are given in CNR DT 200/2004. For use in seismic applications, FRP materials are authorised for the following objectives:
■ increasing the shear resistance of columns and walls by applying belts of fabric whose fibres are oriented in the direction of the brackets;
■ increasing the strength of beams and columns by applying belts of fabric whose fibres are oriented in the direction of the longitudinal bars and suitably anchored;
■ increasing the ductility of the ends of columns and beams by strapping them with continuous fibres laid out along their perimeters;
■ improving the efficiency of overlapping joints by strapping with continuous fibres laid out along the perimeter;
■ external circling of masonry structures, so long as the straight line sections of the circling are not too long and corners are chamfered;
■ reinforced injection into masonry structures;
■ reinforcement of vaulted structures, so long as suspended thrust is avoided;
■ making wooden floor or ceiling slabs more rigid with cross plating.

4. Advantages and disadvantages of FRP in repairs / reinforcement work

The success of FRP materials is essentially due to three properties: the material's greater durability than conventional steels, its light weight, and the potential for optimising its mechanical properties for the application in question. In the last case we must emphasise that, although there is an infinite possible variety of combinations of filaments, number of layers and orientation, only certain families of FRP products are currently used in construction.
There is a considerable difference between carbon, glass and aramid fibres, especially in relation to:
■ mechanical strength and modulus of elasticity under traction;
■ durability when exposed to the environment;
■ relaxation or creep.

First of all, we must recall that the fibres cited above DO NOT indicate a single product; just as with steel, there are many qualities of carbon and glass fibres. Even modest changes in the production temperature when manufacturing carbon fibres, for instance, can result in very different strengths and moduli of elasticity. The average strength of carbon fibre varies from 1900 MPa to 4900 MPa, while its modulus of elasticity varies from 640 GPa to 230 GPa.
Carbon filaments, therefore, are more rigid and stronger than steels used in construction.
They are suited for all reinforcement against bending and shear, especially under conditions of fatigue or high permanent tension.

At the same time, the composition of the protective finish applied to the filaments immediately after production increase their weavability or impregnability, and so on.

The mean strength of glass fibres varies from 2500 to 3500 MPa, while the modulus of elasticity under traction varies from 60 to 80 GPa. Glass filaments may thus be stronger than steel, but have a low modulus of elasticity. These materials, as will be detailed below, are suited to strapping, containment of cracks and in all applications in which they are subject to a modest amount of permanent tension. As for their durability, it is well known that the most common glass fibre filaments, coded as E-Glass, dissolve in alkaline conditions. Concrete is thus potentially very aggressive to glass filaments when their protective finish and impregnating polymer is removed.

To partially solve this problem, the AR-Glass formulation was invented, with improved resistance to alkaline conditions.

Aramid fibre filaments have strength and elasticity specifications which fall between those reviewed above. IT is also well known that carbon fibre filaments conduct electricity, while glass fibre and aramid filaments are electrically insulating. IT is also known that aramid filaments sublime at around 400°C.

Depending on the aggressiveness of the environment in which the structure to be reinforced is located and the permanent tension on the fibres, all available international recommendations introduce coefficients to reduce the manufacturer's declared strength characteristics, to obtain a "final project strength" for use in calculation: the environmental reductive coefficient varies from 0.95 to 0.7, depending on the aggressiveness of the environment, while the reductive coefficient for permanent loads varies from 0.55 (carbon fibre) to 0.3 (glass) to account for relaxation and creep, see Table 2.

As for the fibres, there is a vast world of polymers and resins. There are many different formulations with accordingly different mechanical properties.

There is not specific standard classifying polymers for construction applications, nor can an optimal formulation be identified - i.e. one capable of resolving all problems associated with construction engineering: durability, resistance to heat, propagation of flame, high adhesion, high shear resistance, good impregnability., etc.

Achieving one objective often results in losing a contrasting requisite.

BAF has selected three polymer formulations to optimise, for each family of FRP products, certain specific characteristics.
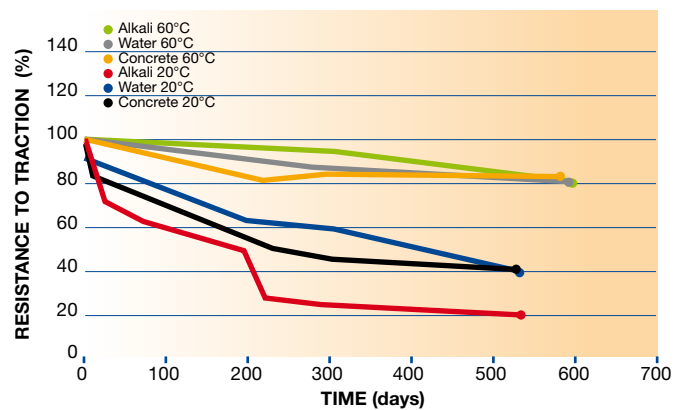
4.1 Typical data for E glass fibre bars + polyester resin immersed in the cement matrix; after around 1-2 years, there is a strong change in strength in the alkaline environment
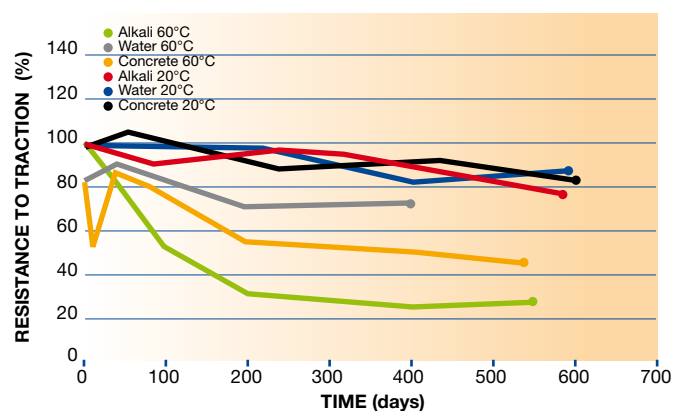
4.2 Typical data for AR glass fibre bars + polyester resin immersed in the cement matrix; after around 1-2 years, there is a strong change in strength in the alkaline environment only if the environment is alkaline

5. Guidelines for effective repairs / reinforcement work

It often happens that important aspects are neglected in the design and realisation of a reinforcement job using FRP. This text offers some practical information based experience, which can be summarised in the following 3 points.

A) Peeling or delamination of ends:

in plating masonry or concrete, do not apply products whose reference thickness is greater than 2 mm (for instance, two plates on top of each other, see figure).

The risk is the prevalence of failure due to delamination, a fragile mechanism which can be seen at loads lower than the project is rated for. This effect can be contained in three ways: by extending the reinforcement to the supports, using small thicknesses (at most 6 layers of fabric), and using U-straps running across the fabric (see figure).

B) Spinta a vuoto:

Avoid points of spinta a vuoto. This phenomenon, which is well know to designers of reinforced concrete structures, occurs as shown in the following figure. When the reinforcement is subjected to traction, it detaches due to the low resistance to traction of the adhesive itself.

FRP FABRIC   **SPINTA A VUOTO**

C) Preparing the surface:

when the existing substrate is degraded, non-coherent, not flat, plating with FRP must be preceded by deep scarification and use of a repair mortar with volumetric stability, high adhesion to the substrate, compatible modulus of elasticity and high interface failure energy. The MasterEmaco (Emaco Formula) line, especially the fibre reinforced products such as
MasterEmaco S 498 FR (Emaco Formula Tixofiber), MasterEmaco T 1400 FR (Emaco Fast Fibre), MasterEmaco A 680 FR (Emaco A660 FR) and MasterEmaco S 444 FR (Emaco SFR), have given excellent results in testing and practice. When the concrete substrate is of good quality, on the other hand, it must be sandblasted to reveal the inert substrate (see figure), i.e., simply cleaning the surface is NOT enough.

D) Optimising the fibrous reinforcement:

it is important to optimise the fibrous reinforcement for the application in question. For reinforcement against bending and shear loads, or shear of beams and columns, and for containment of columns, it is best to use a unidirectional fabric since the loads to be absorbed are themselves unidirectional. For reinforcement against loads in multiple directions, once can use multiple layers of unidirectional fabrics, in which each layer has a given direction, or multiple layers of bidirectional or four-axis fabric, so long as there is sufficient overlap in each direction. The overlap should be at least 20 cm, and must be certified by the manufacturer of the reinforcement system with traction testing. Note also that the impregnation of multidirectional fabrics is difficult, since the fibres are laid in different orientations.

6. Basic design rules

6.1 Reinforcement against bending forces

The Italian recommendations and tests run by BASF demonstrate that the calculation model to be
adopted in the design must be based on the following assumptions:

■ sections remain flat during deformation;

■ concrete has a parabolic/falling relation, as shown in Fig. 1a), where the maximum compression tension
   is $f_{cd}=0.83 \times 0.85 \times R_{ck}/1.5$ at a 0.0035 deformation;

■ steel is elastic/plastic, see Fig. 1b);

■ MasterBrace is considered a certified system as given in Table 3.2 of document CNR DT 200/2004, i.e.
   with strict production batch quality control and technical data sheets pursuant to CNR DT 200/2004.
   The constitutional relation is given in Fig. 1c);

■ MasterBrace absorbs only axial forces in the direction of the fibre, the bending effect is negligible if the
   overall thickness of the reinforcement is very small relative to that of the beam itself.

The following relations link the deformations of the fibre,
the concrete and the steel, see Fig. 2:

$$\varepsilon_s' = \frac{\varepsilon_c(x-d_1)}{x} \qquad \varepsilon_s = \frac{\varepsilon_c(d-x)}{x} \qquad \varepsilon_f = \frac{\varepsilon_c(d+d_1-x)}{x}$$

Four analyses must therefore be run in the design or verification calculations:

a) assess the initial tension of the conglomerate and steel when the reinforcement is installed, and
deformation ε_{fo}. In order for the overlapping of effects to be valid, the initial external bending load must
generate a compression tension on the concrete of $<0.45f_{ck}$ and a traction tension on the rebar of $< 0.8f_{yk}$.
If this does NOT occur, the beam must be supported or pinned;

b) determine the final resisting moment M_{Ru} in consideration of the safety factors to be applied to the
characteristic resistance to traction. If M_{Ru} is greater than the external loads, go to the next step;

c) determine the service resisting moment M_{Rs} and check that the concrete possess an overall
compression tension of $<0.45f_{ck}$ and the steel an overall tension of $< 0.8 f_{yk}$; If M_{Rs} is greater than the
external loads, go to the next step.

d) In this last step, check that the beam's deflection is compatible with the type of structure under
consideration and that the width of cracks under the service load are within the usual limits or covered by
the fibrous reinforcement. In effect, the inertia of the reinforced beam is not modified substantially, while
the external loads supported by it increased.
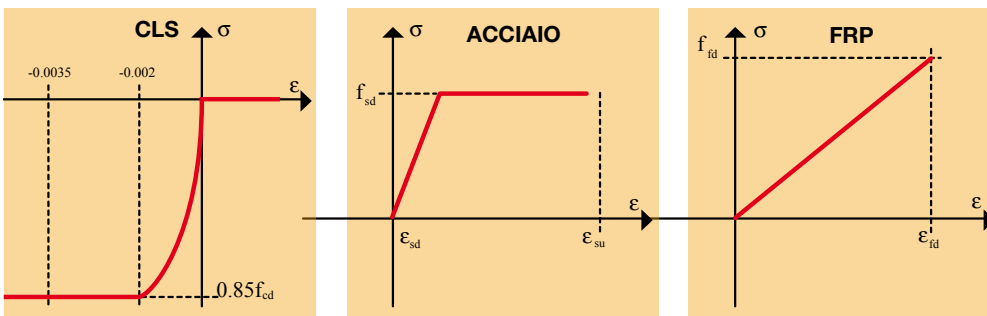
6.1.1 Constituting
relations for agglomerate
(A), steel (B) and
MasterBrace (C)
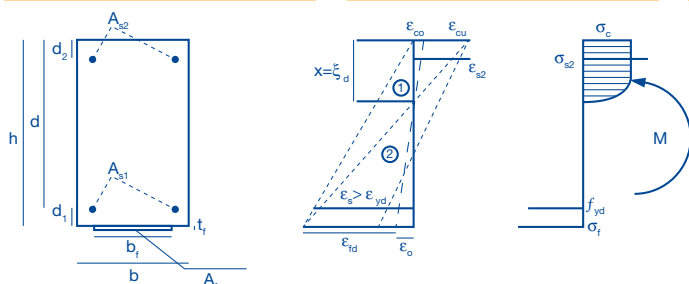
6.1.2 Functional diagram for the
resisting section

Recommendation CNR DT 200/2004 assumes perfect adherence of the fibre to the substrate and maintenance of flatness. Perfect adherence is maintained up to a certain value of tension, after which the system may delaminate from the substrate: the FRP reinforcement detaches either at its end (end delamination) or next to any flexing crack (intermediate delamination). When the reinforcement delaminates, the beam collapses because part of its strength is lost. Steel and FRP fibre contribute to the absorption of the traction force; the first has a very wide plastic range, while the second is elastically fragile, is not plastic or isotropic, and reacts to traction only in the direction of its filaments.

Although many studies have considered the glueing of sheets and fabrics to new reinforced concrete beams (see diagram in Fig. 6.3 A) and CNR DT 200/2004 also considers this type of structural element, the major application of this technology lies in reinforcing old, most likely degraded beams, with corroded rebar, low quality concrete, etc., in other words all those
real life situations in which repair and reinforcement are required.
Testing was therefore run on the three types of reinforcement shown in Fig. 6.3 B, 6.3 C, 6.3 D:
- glueing of fabric or plates to the tensioned zone of beams whose reinforcement covering has first been replaced;
- insertion of bars or plates into the reinforcement covering during its substitution;
- insertion of bars or plates in pockets of around 3x3cm, made (evidently in good quality concrete) with dual cutters.

The reasons for the preliminary restoration of the reinforcement covering are well known, but the appearance of two contact surfaces (original concrete/restoration mortar and restoration mortar/reinforcement) complicates the problem: there are two sliding surfaces, and without good adhesion at the interfaces the job is pointless.
Unfortunately this aspect is considered in detail by CNR DT 200/2004, and there are few integrated reinforcement systems: restoration mortar + FRP. So far, no specific indications have been provided for technologies involving insertion of the reinforcement into the restoration medium.

A Type P: Sand blast + CFRP plating

B Type C+P: Hydrodemolition + repair mortar + CFRP plating

C Type INT: Hydrodemolition + repair mortar + CFRP rods inside

**D** Type NSM: grooves + epoxy putty + CFRP rods
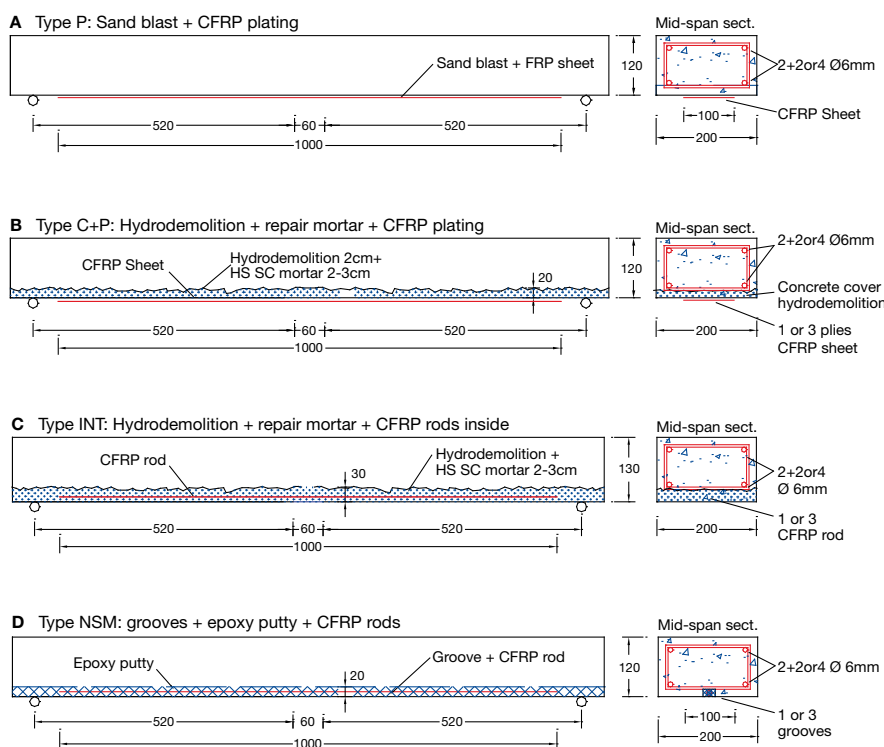
6.1.3 Principle methods of reinforcement against bending

Another very important aspect, which is often overlooked, is that of guaranteeing an elastic response to frequent or permanent combinations of loads (combinations of service loads).
IT is clear that the increase of strength obtained with fibre combines with the yield of the steel rebar cage and the appearance of an extended system of cracks, see 6.4.
Further to verifying the resisting moment, therefore, one must identify the maximum moment of the elastic response and the amplitude of the cracks under the maximum service load.
CNR DT 200/2004 does not cover this aspect fully, but as will be seen in the section related to experimental testing, its identification enables adequate safety coefficients to be obtained.
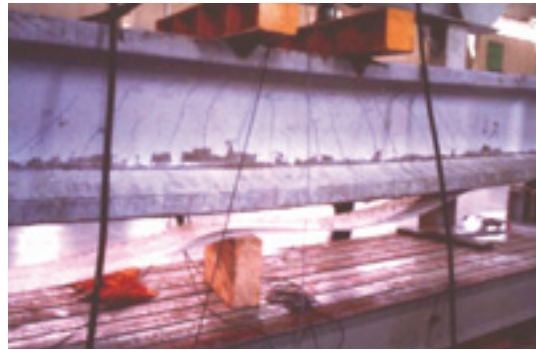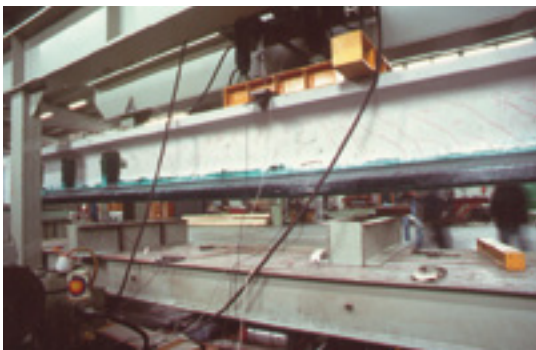
6.1.5 Bending failure test
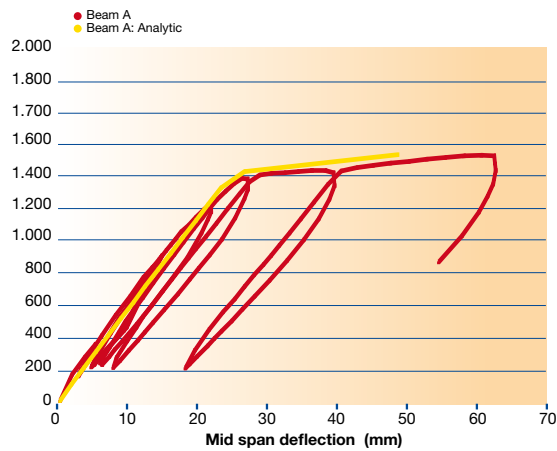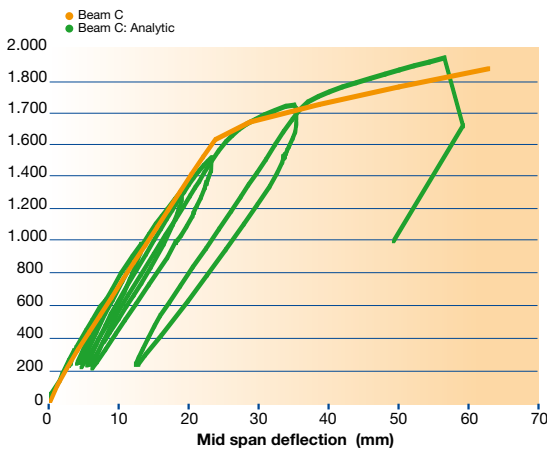
6.1.4 The increase in resistance is obtained at the cost of yield of the internal rebar cage and the appearance of extended cracking

CNR DT 200/2004 provides that the producer of the reinforcement system must certify and report 3 parameters in the data sheet:

1. the characteristic resistance to traction ffk

2. the nominal thickness of the reinforcement tf

3. the fracture energy of the weakest interface G

These are related as follows:

$$f_{fd} = \min(h_a \frac{f_{fk}}{g_m}, f_{fdd}) \qquad f_{ffd,2} = \frac{3}{g_{fd} \cdot \sqrt{g_c}} \sqrt{\frac{2 E_f \Gamma_{Fk}}{t_f}} \qquad \Gamma_{Fk} = a\, k_b \sqrt{f_{ck}\, f_{ctm}}$$

If no specific data are available on the interface failure energy, the Italian standard sets ☐=0.03. In relation to this aspect, the standard does not clarify which tests should be run for characterisation; furthermore, some researchers have observed a large variation in the value of α related to the quality of the surface preparation and the type of mortar used for the repairs. 6.8, for example, shows how the maximum load reduces relative to the potentially obtainable load, simply as a result of failing to sandblast the substrate properly. Without proper surface preparation, delamination can occur unexpectedly at very much lower loads than the theoretical values.
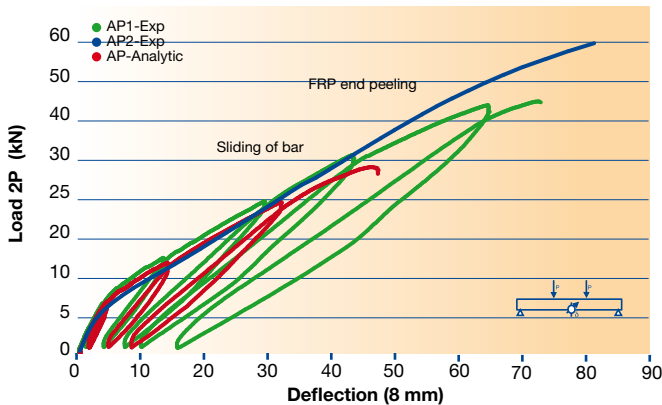
6.1.6 The difference in the load/deflection response between a sample plated after proper sandblasting and a sample plated after washing

6.1.7 Sandblasting is essential in plating interventions

6.1.8 In restoration of the reinforcement cover, high pressure scarification assures adequate adhesion of the interface

To summarise, the bending response of a beam is related to the following parameters:

■ **type of existing agglomerate:** a porous concrete with reduced mechanical capacity cannot provide the same interface adhesion as a prefabricated and/or precompressed concrete; note also that the surface of the latter is much harder to prepare than the former;

■ **amount of internal reinforcement:** if a beam is designed to fail on the rebar side, it will have a very modest amount of reinforcement, whereas structures exist which are designed to fail in the compressed area with a very large amount of internal reinforcement;

■ **type of load:** the reinforcement in the tensioned area is often applied to an already loaded beam. This problem is very topical in the area of roadworks, since all the permanent load and a good part of the transient load are already present when the reinforcement is applied; the result is that the restoration mortar cures and the reinforcement is glued on in a dynamic situation (open to traffic) and only take effect for increases in the load;

■ **type of environment:** in very humid conditions, the glueing resins are hard to polymerise, while in saline water conditions the mechanical interface of porous concrete may degrade more quickly and the steel may continue to corrode if the reinforcement covering is still cracked;

■ **type of repair mortar:** cement mortars with varying rheological qualities are commercially available: mortars which expand in the air - the MasterEmaco A 400 line (Emaco Formula line) -, fibre-reinforced mortars with polymer fibres of modest ductility, mortars with a very high resistance to traction which are also very fragile, normal cement mortars whichretract, etc.

■ **type of preparation and maximum number of defects:** the preparation of the surface is a critical parameter which is often neglected; concrete n site, especially if subjected to traffic, will have even large cracks; the percentage of cavities and their size, the spacing of cracks and their size, and points of discontinuity are all variables which negatively effect the final performance of the repair and reinforcement;

■ **type of reinforcement:** material resistant to traction applied in the area can be distinguished by various mechanical parameters, the most important of which are: the modulus of elasticity (in the range up to 50% of traction resistance), the characteristic resistance to traction, and the equivalent thickness.

6.2 Reinforcement against shear forces

The mechanism of shear is often modelled with the Moersch truss. According to this model, the shear strain is contrasted with a truss of ideal inclined pins and horizontal and vertical ties. The former is formed by the concrete, while the second by the traction resistant reinforcement (longitudinal bars and brackets). Within this scheme, one can reinforce the beam against shear by adding traverse straps of carbon fibre fabric; the most common solution is discontinuous U strapping, where the straps are applied after rounding off the corners of the beam's wing and anchored to the infrados of the screed.

CNR DT 200/2004 recommends that the design resistance to shear of the reinforced element be assessed as follows:

$$V_{Rd} = \min\left(V_{Rd,ct} + V_{Rd,s} + V_{Rd,f}, V_{Rd,max}\right)$$

$V_{Rd,ct}$ = contribution to shear of the concrete, calculated in compliance with established regulations;

$V_{Rd,s}$ = contribution to shear of the brackets, calculated in compliance with established regulations;

$V_{Rd,f}$ = contribution to shear of the FRP reinforcement, calculated as shown below;

$V_{Rd,max}$ = resistance of the compressed rod of concrete.

If the reinforcing straps can be applied in U's or wrapped around a square or rectangular section, the contribution of the FRP reinforcement in the last limit state, $V_{Rd,f}$ can be assessed as follows:

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} \cdot 0.9 \cdot d \cdot f_{fcd} \cdot 2 \cdot t_f \cdot \left(\cot\theta + \cot\beta\right) \cdot \frac{w_f}{p_f}$$

f_{fcd} = effective resistance of the calculation, assessed at points 2.1 and 2.2 below;

t_f = thickness of the fabric straps;

w_f = width of the fabric straps;

p_f = pitch of the fabric straps;

θ = angle of inclination of the shear cracks relative to the axis of the element (45°);

β = angle of inclination of the fibres relative to the axis of the element.

The reference diagrams are given in figure 6.11. The concept is that of integrating a traction resistant element with the concrete in the tensioned area. If adhesion is perfect, the reinforcement will conserve the flat sections and failure of the beam will be due either to failure under compression of the concrete or failure due to traction of the fibre, see the diagram in 6.10

6.2.1 MasterBrace U strapping to reinforce against shear

6.2.2 FRP shear reinforcement diagrams
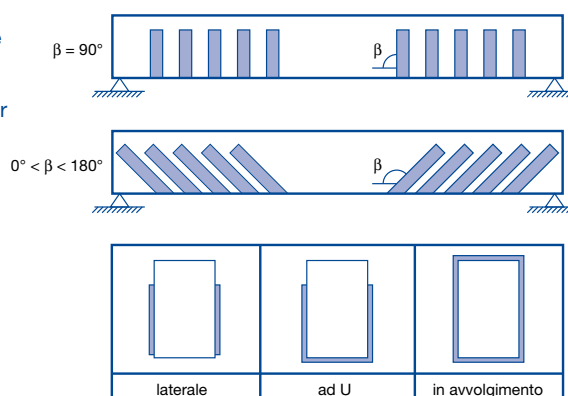
6.3 Boundary reinforcement

In all construction materials, to every stress applied in a given direction corresponds a deformation even in the orthogonal directions (the Poisson effect).

For example, a column in compressed concrete, while it shortens, or is compressed, dilates transversely to around 15% of its reduction in height. Once the elastic limit is exceeded, the proportionality between longitudinal and transverse deformations is lost, the Poisson coefficient increases but the behaviour is not described by any clear law. If we apply fibre fabric strapping in the horizontal direction, we obtain a passive confinement of the pillar. Under modest loads, this confinement is subject to modest transverse dilations, whereas at high loads the strapping's effect increases greatly in relation to the increase in the Poisson coefficient. This effect terminates when the transverse dilation exceeds the maximum traction failure deformation of the fibre, or when the overlaps of fabric fail due to shear failure of the interface. Experimental tests identify the following structural benefits:

■ increased resistance to compression;

■ significant increase in ductility.

The area subtended by the axial load and axial shortening diagram is greatly increased from the non-confined to the confined case. The first result is important for repairs and reinforcement, while the second is very useful for increasing the structure's seismic safety. The effectiveness of the confinement strapping depends on the geometry of the solid. The effect is maximised on circular sections, in the case of elongated rectangles the confinement is concentrated on the corners and is of greatly reduced effectiveness.
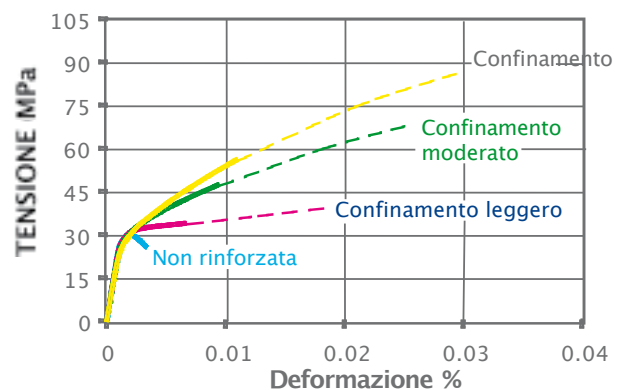

6.3.1 Confinement of a reinforced concrete column
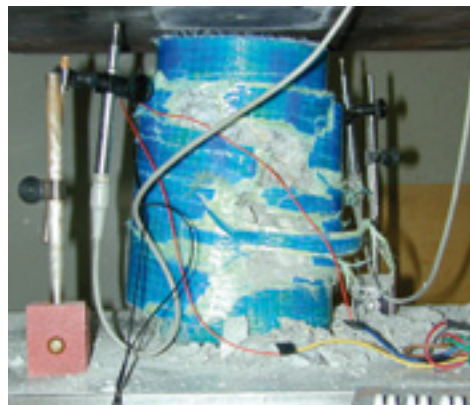
6.3.2 Compression failure testing of reinforced concrete columns
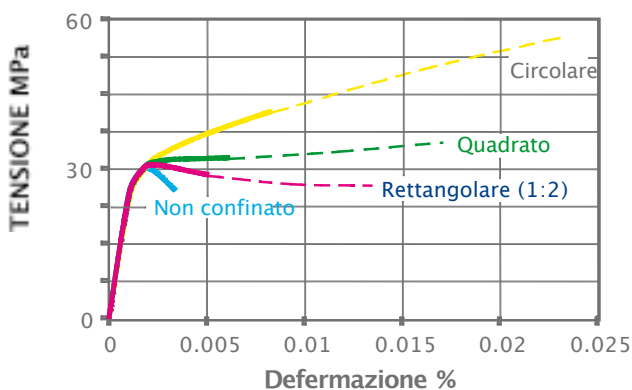
6.3.3 Variation of the degree of reinforcement with the form of the strapped element

6.3.4 Variation of the increase in strength with the amount of reinforcement

CNR DT 200/2004 provides a number of formulations for calculating the strength of a confined column. For circular section elements, the calculation of the confined concrete's strength, fccd, can be determined as follows:

$$f_{ccd} = f_{cd}\left[1 + 2.6\left(\frac{f_{l,eff}}{f_{cd}}\right)^{2/3}\right]$$

where: f_{cd} = calculated strength of unconfined concrete as given in established regulations;

$f_{l,eff}$ = if the effective lateral confinement pressure, evaluated as below.

where:

$$f_{l,eff} = \frac{1}{2} \cdot \rho_f \cdot E_f \cdot \varepsilon_{fd,rid} \cdot k_v \cdot k_a$$

$$\rho_f = \frac{4 \cdot t_f \cdot b_f}{D \cdot p_f}$$

D = diameter of the transverse section;
t_f = total thickness of MasterBrace fabric employed;
E_f = modulus of elasticity of the material in the direction of the fibres;
b_f = width of fabric;
p_f = pitch of the fabric straps;
$\varepsilon_{fd,rid}$ = limit deformation of the FRP, as follows:
where the environmental coefficient ηa is the confinement safety factor γ_f with a value of 1.1, for a certified system, and the characteristic failure

deformation

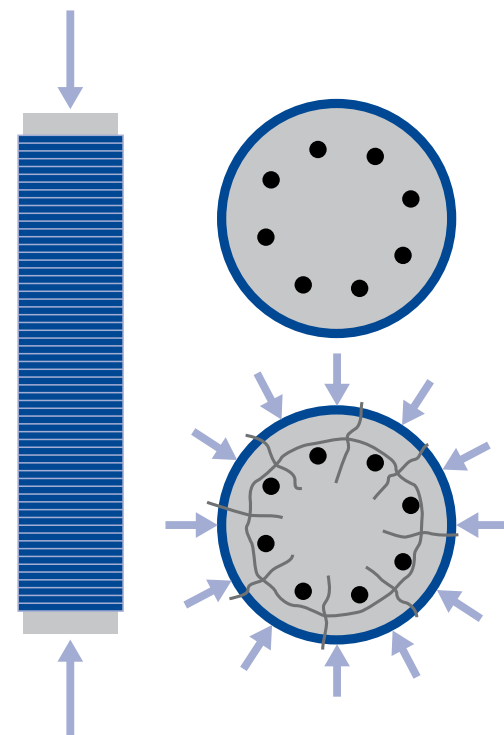$$\min\left[\frac{\eta_a \cdot \varepsilon_{a}}{\gamma_f}, 0.004\right]$$

ε_{fk} is certified by the manufacturer.
k_v = coefficient of vertical efficiency in case of non-continuous strapping;
k_a = orientation coefficient, in the case of helical strapping.
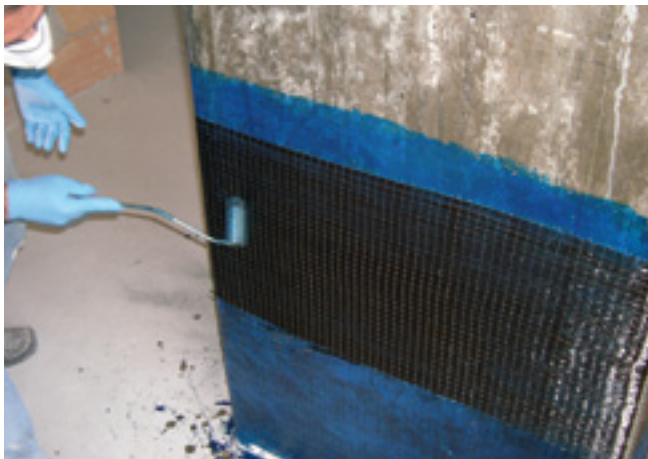
6.3.3 Reinforcement diagrams for confinement with FRP fabric

7. MasterBrace (MBrace/MBar) composite fibrous system: sample applications

MasterBrace (MBrace/MBar) fibrous composites can be used where a pure traction force or traction resulting from bending or shear are to be absorbed. BASF has run innumerable tests and experiments in each of the following areas. The classic cases include:
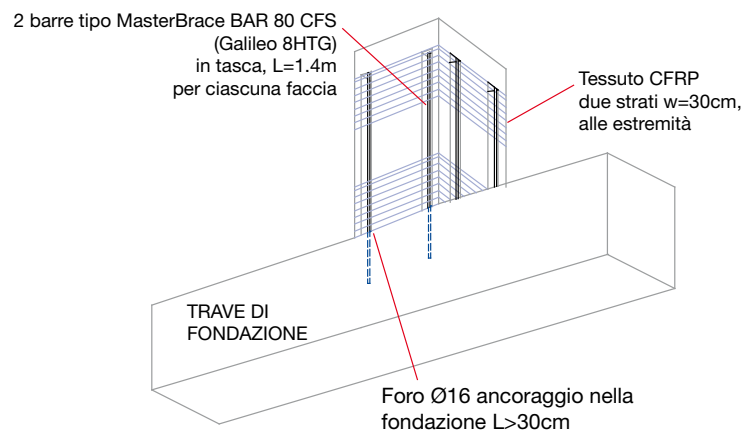
- Gates
- Column/beam joints
- Reinforcement of degraded bridge beams
- Reinforcement of floor/ceiling slabs
- Reinforcement of trusses
- Reinforcement of reinforced concrete beams
- Reinforcement of wooden structures
- Reinforcement of masonry structures

7.1 Gates

The top beam is subject to a vertical load, while the RH column is subject to horizontal loading by the wind. Traction is generated in the beam's intrados, externally close to the beam/column joint and at the base of the columns.
What possible measures can be taken?
One can strap over the beam/column joint with MasterBrace (MBrace) fabric, reinforce the beam's intrados with plates or bars, and add MasterBrace BAR (MBar) bars in pockets at the feet of the columns, see the diagrams below. Once the reinforcement against bending has been installed, one can apply horizontal strapping to prevent delamination.

2 barre tipo MasterBrace BAR 80 CFS (Galileo 8HTG) in tasca, L=1.4m per ciascuna faccia

Tessuto CFRP due strati w=30cm, alle estremità

TRAVE DI FONDAZIONE

Foro Ø16 ancoraggio nella fondazione L>30cm
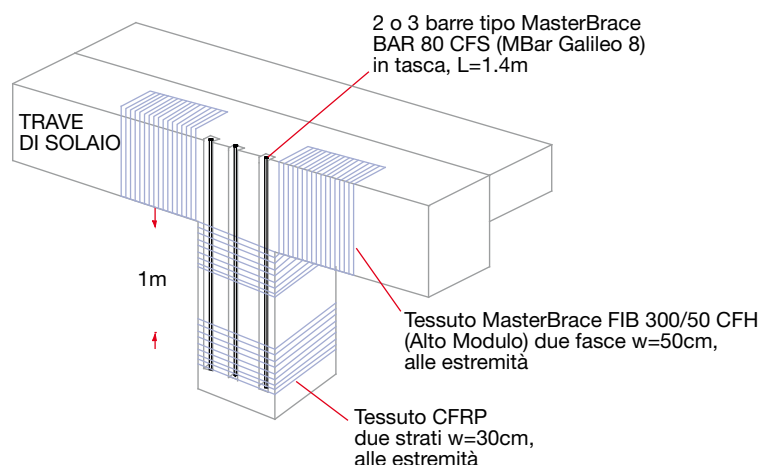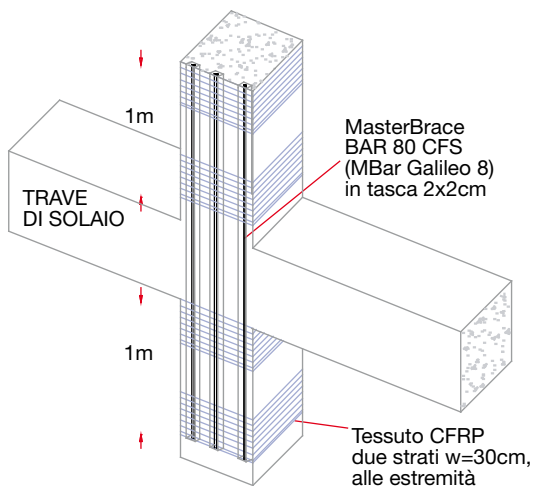
7.2 Column/crossbeam connections

The column/beam joints are generally under-dimensioned for seismic loads, and have little vertical rebar because they are calculated solely for the purely axial load. The resistance to bending can be easily increased by inserting MasterBrace BAR (MBar) in small diameter through holes.

The following diagrams show a number of ways of doing so. BASF has run a large number of tests on real samples subjected to cyclic horizontal loads to simulate seismic forces.
If the column is subjected to bending and with a minimal axial action, as is typical of earthquakes, the best increase in strength is obtained by increasing the longitudinal reinforcement.
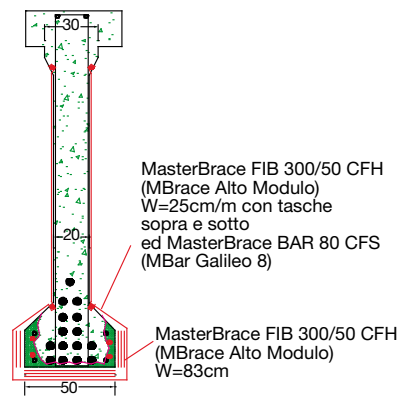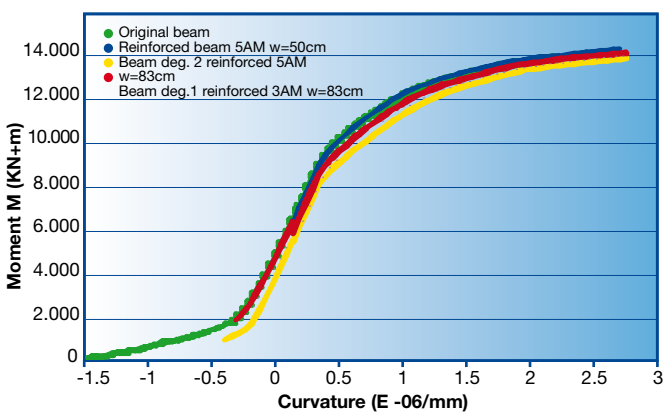This can be done in two ways:

- for columns with a modest axial compression load and a high M, the N.S.M. (Near Surface Mounted) technique is advisable, which consists in inserting carbon fibre bars in 2x2cm pockets sealed with epoxy paste;

- for columns with significant axial compression loads but a partialised section, we recommend restoring the reinforcement covering with air contrasted expansion cement mortar from the MasterEmaco line, insertion into the mortar of MasterBrace BAR and horizontal strapping with 1 strap of 2 layers of MasterBrace FIB to a height equivalent to the length of the bars.

MasterBrace
BAR 80 CFS
(MBar Galileo 8)
in tasca 2x2cm

TRAVE
DI SOLAIO

1m

1m

Tessuto CFRP
due strati w=30cm,
alle estremità

2 o 3 barre tipo MasterBrace
BAR 80 CFS (MBar Galileo 8)
in tasca, L=1.4m

TRAVE
DI SOLAIO

1m

Tessuto MasterBrace FIB 300/50 CFH
(Alto Modulo) due fasce w=50cm,
alle estremità

Tessuto CFRP
due strati w=30cm,
alle estremità

7.3 Reinforcing degraded bridge struts

This situation is very common in our country, due to the age of constructions and the aggressive conditions they are exposed to. For suspended beams, one reinforces the intrados with plates or fabric, in some cases in which the reinforcement covering is completely restored with at least 3 cm of MasterEmaco (Emaco), it is better to insert MasterBrace BAR (MBar) into the restoration mortar. Calculating bridge beams is quite complex, but nonetheless based on the general principles of conservation of flat sections and perfect adherence of the fibre and concrete up to the fibre's limit working tension per CNR DT 200. The beam reinforced with MasterBrace reacquires, in a very simple way, a failure strength which is equal to or even better than the original specification.

MasterBrace FIB 300/50 CFH
(MBrace Alto Modulo)
W=25cm/m con tasche
sopra e sotto
ed MasterBrace BAR 80 CFS
(MBar Galileo 8)

MasterBrace FIB 300/50 CFH
(MBrace Alto Modulo)
W=83cm

MasterBrace (MBrace)

Master Brace BAR (MBAR)
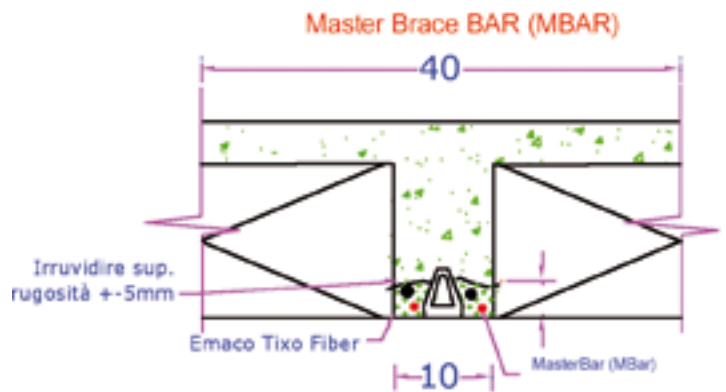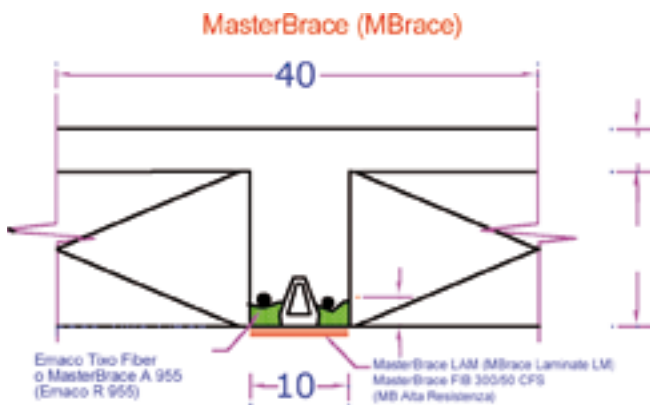
7.5 Reinforcing trusses

Trusses are very particular structural components which break up bending loads into simply tensioned elements (ties) and simply compressed elements (rods). The ties can be reinforced with MasterBrace (MBrace/MBar) with the FRP filaments oriented along the axis of the element.

The versatility of the fabric, in particular, is important, since it brilliantly overcomes the problem of anchoring the ends. Indeed, it is sufficient to wrap the fabric around the orthogonal faces, or extend it along the entire tie and close it off on itself for at least 20 cm to form a fully effective belt.

7.6 Reinforcing reinforced concrete beams

There are cases in which the building up of a beam is very complicated, or in which the combination of seismic action or distortions with vertical loads generates high bending loads in orthogonal directions. The beam is not sufficiently reinforced on its side walls. With the MasterBrace BAR (MBar) technology it is possible to limit the thickness of the reinforcement to just 3-4 cm, into which space MasterBrace BAR (MBar Galileo) bars can be inserted to considerably increase the beam's resistance to deviated bending.
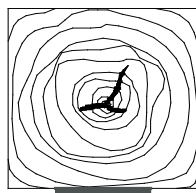

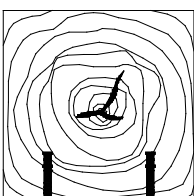## 7.7 Reinforcing wooden structures

Reinforcing wooden structures against bending loads can be done with FRP bars and plates glued to the exterior of the beam or inside pockets in its body. The following diagrams show a few possible options.
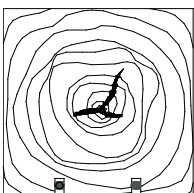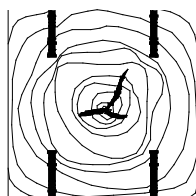

Application of bars in the tension zone

Application of external plates in the tension zone
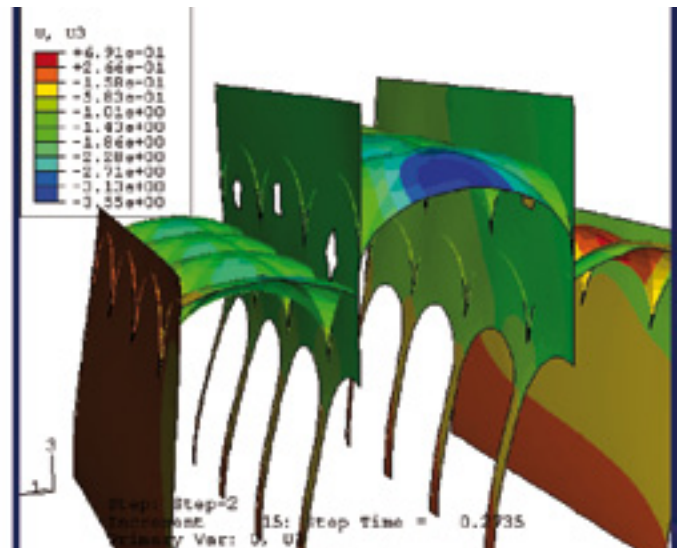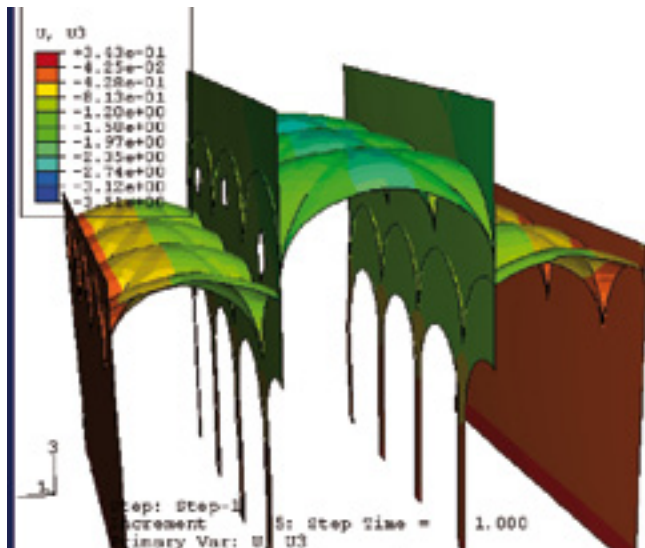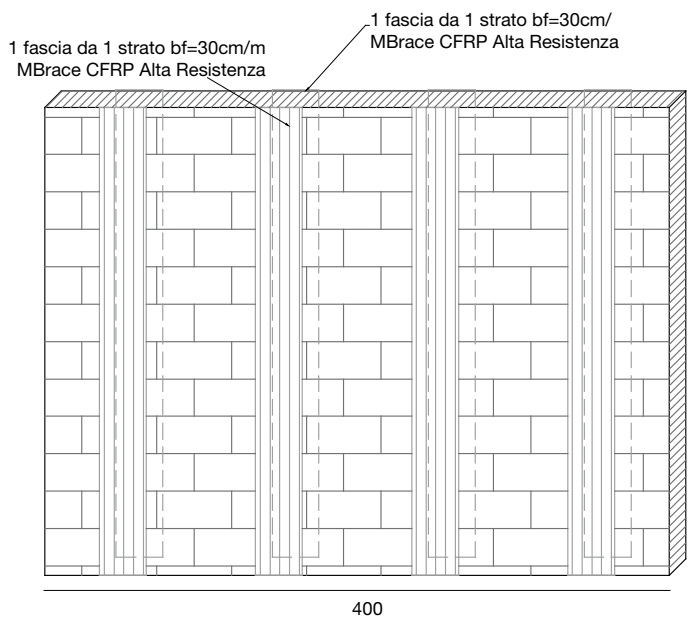
Application of internal plates in the tension zone

Application of internal plates in the tension/compression zone

7.8 Reinforcing masonry structures

The use of FRP reinforcements on masonry structure is very common in consolidating and adapting structures and must be designed and implemented appropriately.

For example, the application of the FRP reinforcement must be done on structural elements which have suitable mechanical specifications. If the masonry is damaged or not homogeneous before the reinforcement is applied, it must be consolidated first with conventional techniques (patching, injection, retipping the joints, etc.). Furthermore, when reinforcing, for example, masonry panels with FRP fabric, the adhesion of the masonry to the composite is critical, since failure by loss of adhesion is a fragile mode. Some of the many applications are illustrated in the following photographs.
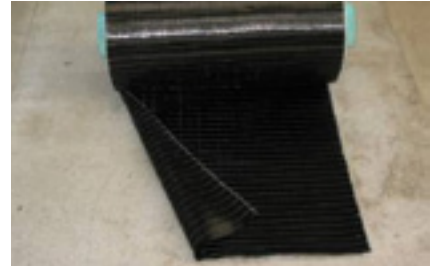

1 fascia da 1 strato bf=30cm/m MBrace CFRP Alta Resistenza

1 fascia da 1 strato bf=30cm/ MBrace CFRP Alta Resistenza

300

400

8. BASF products for structural reinforcement

BASF offers an integrated range of FRP products.
In detail:

8.1 Fabrics

BASF products include fabrics with the
following performances:

	MasterBrace FIB 300/50 CFS (MBrace high strength fibre)	MasterBrace FIB 300/50 CFH (MBrace high modulus fibre)
Type of fibre	Carbon	Carbon
Type of fabric	Unidirectional	Unidirectional
Surface density	300 gsm	300 gsm
Equivalent thickness of dry fabric	0.165 mm	0.165 mm
Mean modulus of elasticity under traction, ASTM D3039	230 GPa	390 GPa
Mean ultimate deformation under traction, ASTM D3039	1.3 %	0.8 %
Characteristic deformation under traction ftk, ASTM D3039	> 2,500 MPa	> 2,500 MPa

N.B. Characteristic resistance = mean resistance - 3 x mean square deviation

8.2 Net

BASF offers carbon and glass fibre net for reinforcing stuctures even with cement
mortar, with the following characteristics:

	MasterBrace NET 200/100 CFS (MBrace Fibrenet CF 200 B)	MasterBrace NET 220/100 GF (MBrace FiberNet GA 220)
Surface density	200 gsm	220 g/^{2}
Type of net	Balanced	Balanced
Characteristic modulus of elasticity under traction, ASTM D3039	230 GPa	65 GPa
Ultimate deformation, ASTM D3039	1.5%	2.5%
Characteristic resistance to traction ftk, ASTM D3039	> 2500 MPa	> 1300 MPa

N.B. Characteristic resistance = mean resistance - 3 x mean square deviation

8.3 Bars

BASF offers a wide range of pultruded bars. We give below the principal characteristics of the carbon fibre bars, which are particularly suited to fire resistant structures. Note their excellent resistance to high temperatures.

	MasterBrace BAR 80 CFS (MBAR Galileo HTG 8)	MasterBrace BAR 100 CFS (MBAR Galileo HTG 10)	MasterBrace BAR 100 CFH (MBAR Leonardo HTG 10)
Nominal section	50 mm²	78.5 mm²	78.5 mm²
Nominal diameter	8 mm	10 mm	10 mm
Characteristic resistance to traction ftk, ASTM D3039	1,800 MPa	1,800 MPa	2,300 MPa
Mean modulus of elasticity, ASTM D3039	165 GPa	165 GPa	200 GPa
Mean ultimate deformation, ASTM D3039	1.8%	1.8%	1.5%
Glass transition temperature, ASTM E1356 or ASTM E1640	> 190°C	> 190°C	--

N.B. Characteristic resistance = mean resistance - 3 x mean square deviation

8.4 Plates

MasterBrace Laminate is a fibrous reinforcement in the form of pultruded carbon fibre plates with better mechanical performance than that of spring steel for bending load reinforcements (plating or plaquè concrete) of concrete, wood and steel components.

IT is available in a variety of configurations, as indicated in the following table:

	MasterBrace LAM 50/1.4 CFS (MBrace Laminate LM 5/1.4)	MasterBrace LAM 100/1.4 CFS (MBrace Laminate LM 10/1.4)	MasterBrace LAM 50/1.4 CFH (MBrace Laminate HM 5/1.4)
Characteristic resistance to traction f_{tk}, ASTM D3039	2,300 MPa	2,300 MPa	2,050 MPa
Mean modulus of elasticity under traction, ASTM D3039	165 GPa	165 GPa	200 GPa
Mean ultimate deformation under traction, ASTM D3039	1.8 %	1.8 %	1.4 %
Nominal thickness	1.4 mm	1.4 mm	1.4 mm
Width	5 cm	10 cm	5 cm

N.B. Characteristic resistance = mean resistance - 3 x mean square deviation

8.5 Adhesives and accessories

The range of BASF products for reinforcement is completed by structural epoxy resins, MasterBrace CON (MBrace Connect) carbon and glass fibre connectors, bar anchors, cement and lime mortars (Linea MasterEmaco) and accessories for applying composite materials.

Master Builders Solutions by BASF for the construction industry

MasterAir
Solutions for aerated concrete

MasterBrace
Solutions for static consolidation of concrete

MasterCast
Solutions for ground/wet prefabricated casting

MasterCem
Solutions for cement production

MasterEmaco
Solutions for concrete restoration

MasterFinish
Solutions for release

MasterFlow
Solutions for precision anchoring

MasterFiber
Solutions for fibre-reinforced concrete

MasterGlenium
Solutions for high performance concrete with good workability and a low A/C ratio

MasterInject
Solutions for injection in concrete structures

MasterKure
Solutions for protecting concrete

MasterLife
Solutions for long-life concrete

MasterMatrix
Solutions for rheology control in rheodynamic concrete

MasterPel
Solutions for hydrophobic concrete

MasterPolyheed
Solutions for medium performance concrete

MasterPozzolith
Solutions for reducing water in concrete

MasterProtect
Solutions for protecting concrete

MasterRheobuild
Solutions for superfluid concrete

MasterRoc
Solutions for underground constructions

MasterSeal
Solutions for waterproofing and sealing

MasterSet
Solutions for hydration control

MasterSure
Solutions for controlling workability

MasterTop
Solutions for industrial flooring

Master X-Seed
Solutions for prefabricated concrete with accelerated hardening

Ucrete
Solutions for high durability flooring

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