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Fibre Products

A Guide to the Design and Application of BBR FRP Strengthening Systems

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BBR Systems Ltd
Bahnstrasse 23,
Postfach
CH-8603 Schwerzenbach
Switzerland

Tel: +41 1 806 80 60
Fax: +41 1 806 80 50
info@bbrsystems.ch
www.bbrsystems.ch

Contents

1. Introduction to the design and application of FRP Materials

This document offers a guide to the design and application of BBR FRP materials used in the strengthening of concrete and timber structures. It addresses strengthening by the application of carbon fibre reinforced polymers (CFRP), aramid fibre reinforced polymers (AFRP) and glass fibre reinforced polymers (GFRP) to the external parts of structural elements, both by bonding to the external surface and/or bonding within slots cut in the surface layers of the substrate.

BBR Systems Ltd has produced this manual for use by its BBR subsidiaries and licensees worldwide. The information contained herein has been researched from a number of references and is considered current as at the date given at the bottom of this page. As the use of FRPs is the subject of a large number of on-going research programmes around the world, conditions pertaining to their usage may vary from time to time. BBR Systems Ltd does not warrant the correctness of the material provided in this manual and shall not be liable for any special, incidental, consequential, indirect or any damages whatsoever, which arise out of any breach of warranty, breach of contract, tort, strict liability or any other cause of action.

The successful application and use of this manual is the sole responsibility of the user and is dependent on the application of sound judgement by a qualified Engineer who has a thorough understanding of structural mechanics and material behaviour, especially as it relates to reinforced concrete. The user of the manual must ensure that the design procedure adopted is relevant for use on the intended application and must select appropriate values suitable for the specific application. Reference to an appropriate set of Design Recommendations is essential (either the German General Guidelines, The UK Concrete Society Design Guidance TR55, the *fib* bulletin 14 or the draft ACI 440 Recommendations would be appropriate documents for this purpose). Any design carried out must comply with the relevant Codes of Practice for the country concerned.

The manual is not to be relied on as the sole basis for design. Procedures contained in the manual, if adopted, imply that the user acknowledges and agrees to the terms of usage outlined above and further implies that the user understands the manual has been prepared to supplement the user's knowledge on this specialised subject.

Any implied or expressed warranties covering this manual, including any warranties of fitness for particular purpose and warranties with respect to effect or result of the application of the manual to specific strengthening work and any warranties with respect to the completeness or effectiveness of the repair or strengthening for which the manual was used is expressly excluded.

It is envisaged that Chapters 6, 7 & 8 will be upgraded regularly as the divergence of opinion which exists between current guidelines comes closer together. The material contained therein should be taken as introductory at this stage.

BBR Systems Ltd

R.W. Irwin
Director of MRR Technology

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2. BBR FRP Strengthening Systems

The basic fibres used in FRP composites are imbedded in a matrix of epoxy resin and are applied as reinforcements to an existing structural member. The fibres are supplied either as a fabric, known as **sheet form** or as a precured laminate, known as a **laminate form.** When supplied in sheet form, the embedment into the epoxy matrix takes place on site by hand lamination. When supplied as pre-cured laminates, the laminates are adhered directly to the substrate.

BBR offers three types of fibre; carbon, e-glass and aramid. Each has its unique place in the field of structural strengthening, as is explained below.

BBR Sheet must be used in conjunction with approved epoxy resins. Likewise, BBR Laminates must be used in conjunction with approved epoxy adhesive pastes. BBR Systems can supply resins and adhesives, but users are able to source their own resin products, provided they meet with the prior approval of BBR Systems and have been rigorously tested for performance in conjunction with the appropriate BBR Fibre Product.

2.1 BBR Glass and Aramid Fibre Systems

These are supplied in sheet form only. In unidirectional BBR sheets, where the fibres lie mainly in a single direction, the fibres can be considered to be straight, although during hand lamination, they tend to become slightly wave-like in form. Reduction factors are used in designs to allow for irregularities in hand laminating techniques. In bi-directional BBR sheets, the fibres are woven and hence take on a pronounced wave-like form. Again, the appropriate reduction factor used in the design, takes care of this aspect.

2.1.1 BBR Glass Fibre Sheets (GFS) available are:

GFS E73 175/175:	E-glass, E modulus = 73,000 MPa, 175 gm/m^2 of fibre in two orthogonal directions.
GFS E73 400/40:	E-glass, E modulus = 73,000 MPa, 400 gm/m^2 of fibre in the main direction.
GFS E73 800/80:	E-glass, E modulus = 73,000 MPa, 800 gm/m^2 of fibre in the main direction.
GFS AR65 175/175:	AR-glass, E modulus = 65,000 MPa, 175 gm/m^2 of fibre in two orthogonal directions.
GFS AR65 400/40:	AR-glass, E modulus = 65,000 MPa, 400 gm/m^2 of fibre in the main direction.
GFS AR65 800/40:	AR-glass, E modulus = 65,000 MPa, 800 gm/m^2 of fibre in the main direction.

2.1.2 BBR Aramid Fibre Sheet (AFS) available is:

AFS A120 290/0: Kevlar, E modulus 120,000 MPa, 290 gm/m^2 of fibre in a single direction.

2.2 BBR Carbon Fibre Systems

These exist in either **sheet** or pre-cured **laminate** form. Carbon fibres with high modulii of elasticity are used in their production. This modulus of elasticity is the decisive parameter when comparing the various types of carbon sheet and carbon laminate.

2.2.1 BBR Carbon Fibre Sheets (CFS) available are:

CFS 240 150/30:	E-modulus 240,000 MPa, 150 gm/m2 of fibre in the main direction.
CFS 240 200/30:	E-modulus 240,000 MPa, 200 gm/m2 of fibre in the main direction.
CFS 240 300/30:	E-modulus 240,000 MPa, 300 gm/m2 of fibre in the main direction.
CFS 240 400/40:	E-modulus 240,000 MPa, 400 gm/m2 of fibre in the main direction.
CFS 440 300/30:	E-modulus 440,000 MPa, 300 gm/m2 of fibre in the main direction.
CFS 640 400/30:	E-modulus 640,000 MPa, 400 gm/m2 of fibre in the main direction.

2.2.2 BBR Carbon Fibre Laminates (CFL) are available in two grades as follows:

Grade 205

CFL 205 50/1.4:	E-modulus 205,000 MPa, 50mm x 1.4mm strip.
CFL 205 80/1.4:	E-modulus 205,000 MPa, 80mm x 1.4mm strip.
CFL 205 100/1.4:	E-modulus 205,000 MPa, 100mm x 1.4mm strip.
CFL 205 120/1.4:	E-modulus 205,000 MPa, 120mm x 1.4mm strip.

Grade 165

CFL 165 10/1.4:	E-modulus 165,000 MPa, 10mm x 1.4mm strip
CFL 165 50/1.4:	E-modulus 165,000 MPa, 50mm x 1.4mm strip
CFL 165 80/1.4:	E-modulus 165,000 MPa, 80mm x 1.4mm strip
CFL 165 100/1.4:	E-modulus 165,000 MPa, 100mm x 1.4mm strip
CFL 165 120/1.4:	E-modulus 165,000 MPa, 120mm x 1.4mm strip

BBR supplies FRP sheet and laminates in rolls. In special cases, part rolls can be supplied, but this adds to the unit cost.

For details on rolls sizes and weights for shipping purposes, see Technical Specification Sheets for individual product (Section 4).

3. Selection of the BBR FRP Strengthening System

There is no fixed rule as to whether sheet or laminate should be used. Usually economy dictates the choice of one system or the other, but sometimes it is a design choice. Carbon (laminate or sheet) appears to be more economic for use in flexural or shear strengthening. Certainly, carbon has better fatigue properties than glass, so where the strengthening is used to carry often occurring fluctuating live loads, carbon should be chosen. Glass, because of its lower E-modulus, is more suitable for use in confinement of concrete, although it can, in certain circumstances, be used for flexural enhancement. Because of its low modulus, glass is seldom used for shear enhancement.

Laminates can only be applied to plane surfaces, therefore carbon, aramid or glass sheet are used on curved surfaces. Carbon sheet, on the other hand, is difficult to cut and handle in thin strips and therefore laminates are preferred, when narrow bands of FRP reinforcement are required.

Bi-directional glass fabrics are used for increasing the shear strength of masonry walls. Lighter fabrics are used where the substrate strengths are low, such as in old and historic masonry or brick buildings.

The following table sets out typical uses for the various products:

Composite Type	Fibre direction	Fibre arrangement	Typical application
BBR Carbon Fibre Sheet (CFS)	Uni-directional	Straight	Increase in flexural and shear capacity; confinement
BBR Aramid Fibre Sheet (AFS)	Uni-directional	Straight	Special applications
BBR Glass Fibre Sheet (GFS)	Bi-directional	Woven	Increase in confinement and ductility
BBR Carbon Fibre Laminate (CFL)	Uni-directional	Straight (partially pre-tensioned)	Increase in flexural capacity

3.1 Demand on the Substrate

The substrate to which the FRP is to be adhered, must have sufficient strength to transfer the loads from the FRP to the structure. Testing of the tensile strength of the substrate by pull-off tests is imperative. The following table sets out the minimum substrate strengths required for each of the FRP materials to be used efficiently:

Product	**Minimum Tensile Strength** (MPa)
BBR Carbon Fibre Sheet (CFS)	> 1.0
BBR Aramid Fibre Sheet (AFS)	> 1.0
BBR Glass Fibre Sheet (GFS)	> 0.2
BBR Carbon Fibre Laminate (CFL)	> 1.5

Fig 3.1: Proceq Dyna Pull-off Tester used for determining substrate tensile strength

3.2 Types of Fibres used in BBR FRP Systems

BBR FRP materials comprise either single type fibres or a fibre combination (hybrids). The range of mechanical properties as well as some advantages and disadvantages of the various fibre types are as follows:

Type of Fibre	Modulus of Elasticity (GPa)	Tensile Strength (MPa)
Carbon	240 - 640	2,500 – 4,000
Aramid	124	3,000 – 4,000
Glass	65 - 70	1,700 – 3,000
Steel	190 - 210	250 - 600

E-glass: Uncoated E-glass corrodes in alkaline environments, thus there is a risk in using E-glass together with freshly cured concrete, unless the E-glass is completely submerged in epoxy. However, there is no problem when E-glass is applied directly to old concrete, which is the majority of cases.

AR-glass: Alkali resistant glass is suited for use as confinement reinforcement in combination with an epoxy resin matrix and a water vapour permeable matrix, used in certain types of building elements.

Aramid: Aramid is a very tough material and thus provides benefits when used as a strengthening material for special applications, such as strengthening of rectangular columns. Due to its high cost, Aramids can be economically replaced by glass or carbon fibres in most cases. For further information on BBR Aramid sheets, contact BBR Systems.

Carbon: Carbon fibre provides a number of benefits over the other materials. It has a high modulus of elasticity, a very low coefficient of thermal expansion (approximately 50 times lower than steel), excellent fatigue properties, excellent resistance to chemical attack. It will not corrode and exhibits a high resistance to freeze/thaw and de-icing salt attack.

4. Technical Data of BBR FRP Strengthening Systems

4.1 BBR FRP Sheets (Sheets made of Carbon, Aramid and Glass fibres)

- **Application**

  BBR FRP Sheets made of different types of fibres are used as bonded reinforcement for the strengthening of structural elements made of steel, concrete, stonework and wood as well as for the reinforcement of historical structures.

- **Application Uses**

  Enhancement of load carrying capacity due to changed usage
  Upgrading due to changes in the building code
  Alteration to the intended structural form
  Rectification of mistakes made during design or construction phases

- **Advantages of FRP Strengthening Systems**

  Low unit weight
  Low profile thickness
  Ease of application due to lightness
  High E modulus – carbon modulus is greater than that of steel
  Excellent fatigue behaviour
  Alkali resistance (in the case of AR-glass:- E-glass has some limitations in this respect)
  Corrosion resistant
  Covering with a variety of paints, coatings etc is possible .

- **Product names**

  Type: BBR CFS 240 (four weights)
  BBR CFS 440
  BBR CFS 640
  BBR GFS AR65 (three weights)
  BBR GFS E73 (three weights)
  BBR AFS A120

- **Product Specifications**

  The following are the details of the individual Product Specifications. Please note that BBR reserves the right to vary its specifications from time to time, according to source of Material supply.

BBR AFS A120 Sheet

Technical details of fibre	Properties
Modulus of Elasticity (MPa)	120,000
UTS (raw filament – MPa)	2,900
Weight of sheet (main/transverse fibres – gm/m^2)	290/30
Density (gm/cm^3)	1.45
Ultimate strain ε_{ult} (%)	2.50
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.20
Cross section for design purposes (per metre width – mm^2)	200
Roll dimensions	300 mm x 150 m

BBR CFS 240 Sheet

Technical details of fibre	Properties			
	150 gm/m^2	200 gm/m^2	300 gm/m^2	400gm/m^2
Modulus of Elasticity (MPa)	240,000	240,000	240,000	240,000
UTS (raw filament – MPa)	3,800	3,800	3,800	3,800
Weight of sheet (including transverse fibres – gm/m^2)	150/25 = 175	200/30 = 230	300/30=330	400/30=430
Density (gm/cm^3)	1.70	1.70	1.70	1.70
Ultimate strain ε_{ult} (%)	1.55	1.55	1.55	1.55
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.0882	0.117	0.176	0.235
Cross section for design purposes (per metre width – mm^2)	88.2	117	176	235
Roll dimensions	300 mm x 150 m	300 mm x 150 m	300 mm x 150 m	300 mm x 150 m

BBR CFS 440

Technical details of fibre	Properties
Modulus of Elasticity (MPa)	440,000
UTS (raw filament – MPa)	2,650
Weight of sheet (including transverse fibres – gm/m^2)	300/30 = 330
Density (gm/cm^3)	2.10
Ultimate strain ε_{ult} (%)	0.6
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.143
Cross section for design purposes (per metre width – mm^2	143
Roll dimensions	300 mm x 50 m

BBR CFS 640

Technical details of fibre	Properties
Modulus of Elasticity (MPa)	640,000
UTS (raw filament – MPa)	2,650
Weight of sheet (including transverse fibres – gm/m^2)	400/30 = 430
Density (gm/cm^3)	2.10
Ultimate strain ε_{ult} (%)	0.4
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.19
Cross section for design purposes (per metre width – mm^2)	190 (main direction)
Roll dimensions	300 mm x 50 m

BBR GFS E73 175/175; BBR GFS AR65 175/175

Technical details of fibre	Properties E-glass	Properties AR-glass
Modulus of Elasticity (MPa)	73,000	65,000
UTS (raw filament – MPa)	3,400	3,000
Weight of sheet (including transverse fibres – gm/m^2)	175/175 = 350	175/175 = 350
Density (gm/cm^3)	2.60	2.68
Ultimate strain ε_{ult} (%)	4.5	4.3
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.067	0.065
Cross section for design purposes (per metre width – mm^2)	67 (each direction)	65 (each direction)
Roll dimensions	680 mm x 50 m	680 mm x 50 m

BBR GFS E73 90/10: 400/40: BBR GFS AR65 90/10: 400/40

Technical details of fibre	Properties E-glass	Properties AR-glass
Modulus of Elasticity (MPa)	73,000	65,000
UTS (raw filament – MPa)	3,400	3,000
Weight of sheet (including transverse fibres – gm/m^2)	400/40 = 440	400/40 = 440
Density (gm/cm^3)	2.60	2.68
Ultimate strain ε_{ult} (%)	4.5	4.3
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.154	0.149
Cross section for design purposes (per metre width – mm^2)	154 (main direction only)	149 (main direction only)
Roll dimensions	680 mm x 50 m	680 mm x 50 m

BBR GFS E73 90/10: 800/80; BBR GFS AR 65 90/10: 800/80

Technical details of fibre	Properties E-glass	AR-glass
Modulus of Elasticity (MPa)	73,000	73,000
UTS (raw filament – MPa)	3,400	3,000
Weight of sheet (including transverse fibres – gm/m^2)	800/80 = 880	800/80 = 880
Density (gm/cm^3)	2.60	2.68
Ultimate strain ε_{ult} (%)	4.5	4.3
Thickness for design purposes [weight/(densityx10^3)] (mm)	0.308	0.299
Cross section for design purposes (per metre width – mm^2)	308 (each direction)	299 (each direction)
Roll dimensions	680 mm x 50 m	680 mm x 50 m

4.2 BBR resins for Application of FRP Sheets

BBR 120 Epoxy Resin primer

(Primer resin for BBR FRP sheet systems)

- **Application**

  BBR 120 Epoxy Resin primer is a solvent free, low viscosity resin with high capillary activity, able to penetrate into finest cracks, capillaries and pores. It is therefore suitable as a priming resin and is used as the primer for all BBR FRP Sheet systems.

- **Material description**

  Solvent free, low viscosity liquid, colourless 2 component epoxy resin with formulated amine hardener.

- **Characteristics**

  BBR 120 Epoxy Resin primer exhibits good substrate wetting properties and has an extended pot life. When cured it is inert to sewage, alkalis, weak acids, salt solutions, as well as petroleum products. In addition, the cured resin can operate in constant as well as changing temperatures in the range of –30°C to +80°C in dry conditions and up to +50°C in wet conditions.

- **Packaging** | **Content**

  Pre-packaged Containers | 6 litre, 10 litre or 200 litres

- **Surface Preparation**

  Concrete substrates must be dry, free from cement laitance, dust and loose material, oil and grease. All surfaces must be clean to ensure good adhesion with the FRP material and to avoid possible separation. If required, the substrate should be cleaned by sandblasting or scabbling. It should be noted that the surface preparation conditions are more severe for the situation where FRPs are being used for flexure or shear, than those where it is used for confinement.

- **Usage**

BBR 120 Epoxy Resin primer is delivered in pre-packaged containers. The hardener (Component B), is mixed into the resin (Component A). The mixing of the two components must be carried out with a slow speed drill equipped with a mixing paddle, which runs at a controlled speed of 500 – 600 revolutions per minute. The components must be mixed thoroughly while carefully scraping the sides and the bottom of the container while mixing, to ensure that the hardener is evenly distributed throughout the resin. After blending, the mix must be homogeneous, i.e. without streaks. The ideal temperature of both components at the moment of mixing should be in the range of 15°-20°C. Higher temperatures considerably reduce the working time. In hot climates, it may be necessary to keep the resin components in cooled environments to ensure the required working life is achievable. Conversely, in cold climates, it is necessary to pre-heat the resins components before mixing to the 15 – 20^{o}C range. The resin is able to be applied by airless spray, roller or brush

- **Technical Properties**

(the standard values refer to 20^{0}C and 50% relative humidity)

Viscosity		350 mPas
Density		1.07 kg/litre
Mix Ratio		2:1 (resin to hardener, by weight)
Thermal expansion		70 x 10^{-6} m/m ^{0}K
Glass transition temperature (T_g)		57^{0} C
Minimum-working-temperature (ambient)		+ 8^{0} C
Working time at	+ 10^{0} C	1 ½ hours
	+ 20^{0} C	1 hour
	+ 30^{0} C	¼ hour
Touch dry time		2 hours.
Recoat time		7 days.
Reduction in volume		3.5 %
Linear shrinkage		0.3 %
Compressive strength	7 days	85 MPa
Tensile strength	7 days	35 MPa
Tensile strength (flexure)	7 days	45 MPa
Elongation at break		4 %
E-Modulus	28 days	2'800 MPa
Usage as primer (depends on porosity of substrate)		Approx:. 50 - 100 gm./m^{2}
Toxicity class, Comp A and B	Comp A & B	4
Transportation class	Comp B	8/53c
Storage		Cool/dry place; protected from frost
Shelf life		12 months

- **Cleaning of Equipment**

  When work stops for longer than 15 minutes, all tools, mixing vessels and equipment should be thoroughly and carefully cleaned with a suitable epoxy cleaner (MEK or similar).

- **Handling precautions**

  Once cured, the BBR 120 Epoxy resin is inert. However, prior to mixing, the hardener (component B) is caustic. It is important that neither the resin (component A) nor the hardener come into contact with the skin. For this reason it is imperative that protective clothing and rubber gloves be worn when handling the product. If contact with the skin does occur, it is necessary to wash the affected area without delay, using soapy water. Should the resin come in contact with the eyes, they must immediately be washed with copious supplies of clean water and medical attention must be sought immediately.

  A short list of remedies is given below:

  - Avoid contact with the eyes, skin and avoid breathing the resin vapour.
  - Wear protective clothing and gloves when mixing or using.
  - If poisoning occurs, contact a doctor immediately.
  - If swallowed, do **not** induce vomiting – drink glasses of water
  - If skin contact occurs, remove the contaminated clothing and wash skin thoroughly.
  - If splashed in the eyes, hold the eyes open, flood with water for at least 15 minutes and seek medical help urgently.

BBR 125 Epoxy Resin
(Saturating resin for BBR FRP Sheet systems)

- **Application**

  BBR 125 Epoxy Resin is used as the saturating resin for all BBR FRP Sheet systems. For sheets up to 400 gm/m2, hand lamination can be achieved without the use of a saturator machine to pre-saturate the sheet. Hand impregnation can be achieved by rolling the BBR 125 resin into the previously placed sheet. Alternatively, the resin may be rolled into the sheet while it is laid on a flat surface. It is then transported to the work face and applied. For sheet weights in excess of 400 gm/m2, proper saturation is best achieved by passing the sheet through an epoxy bath, which features rollers which control the amount of resin applied to the sheet.

- **Material description**

  Solvent free, colourless 2 component epoxy resin with formulated amine hardener.

- **Characteristics**

  The resin exhibits good substrate and fabric wetting properties and has an extended pot life. When cured it is inert to sewage, alkalis, weak acids, salt solutions, as well as petroleum products. In addition, the cured resin can operate in constant as well as changing temperatures in the range of –30°C to +80°C in dry conditions and up to +50°C in wet conditions.

- **Packaging** **Content**

  Pre-packaged Containers 6 litre, 10 litre or 200 litres

- **Usage**

BBR 125 Epoxy Resin is delivered in pre-packaged containers. The hardener (Component B), is mixed into the resin (Component A). The mixing of the two components must be carried out with a slow speed drill equipped with a mixing paddle, which runs at a controlled speed of 500 – 600 revolutions per minute. The components must be mixed thoroughly while carefully scraping the sides and the bottom of the container while mixing, to ensure that the hardener is evenly distributed throughout the resin. After blending, the mix must be homogeneous, i.e. without streaks. The ideal temperature of both components at the moment of mixing should be in the range of 15°-20°C. Higher temperatures considerably reduce the working time. In hot climates, it may be necessary to keep the resin components in cooled environments to ensure the required working life is achievable. Conversely, in cold climates, it is necessary to pre-heat the resins components before mixing to the 15 – 20°C range.

- **Technical Properties**

(The standard values refer to 20 °C and 50% relative humidity)

Viscosity		650 mPas
Density		1.11 kg/litre
Mix ratio		7:3 (resin to hardener by weight) 2:1 (resin to hardener by volume)
Thermal expansion		70x 10^{-6} m/m ^{0}K
Glass transition temperature (T_g)		50°C
Minimum working temperature		+ 8^{0} C
Workability time at	+10 °C	1 ½ hrs
	+20 °C	½ hr.
	+30 °C	¼ hr
Touch dry after		2 hrs
Recoat time		0 - 12 hrs
Cure time to full strength		7 days
Reduction in volume		4 %
Linear shrinkage		0.3 %
Resistance to pendulum impact (Koenig)		100-200 sec
Bending Tensile Strength	7 days	33 MPa
Tensile Strength	7 days	24 MPa
Compressive strength	7 days	65MPa
Elongation at break		10 %
E-modulus$_{(tangent)}$		1,550 MPa

Usage as saturant for BBR Sheet		Varies according to sheet type and weight
Toxicity class	Comp A&B	4
Transportation class	Component B	8/53c
Storage		cool and dry place; protected from frost
Shelf life		12 months

BBR 125 Epoxy Resin must be protected from moisture for 6-8 hours after the application. If contact with moisture occurs during this period, the outer surface will become white and sticky, while the resin below the outer surface cures as normal. This whitening and the resultant affects will reduce the effective adhesion of any following layers. It is very important to take this into consideration. The resin is able to be applied by airless spray, roller or brush.

- **Cleaning of Equipment**

When work stops for longer than 15 minutes, all tools, mixing vessels and equipment must be thoroughly and carefully cleaned with a suitable epoxy cleaner (MEK or similar).

- **Handling precautions**

Once cured, the BBR 125 Epoxy resin is inert. However, prior to mixing, the hardener (component B) is caustic. It is important that neither the resin (component A) nor the hardener come into contact with the skin. For this reason it is imperative that protective clothing and rubber gloves be worn when handling the product. If contact with the skin does occur, it is necessary to wash the affected area without delay, using soapy water. Should the resin come in contact with the eyes, they must immediately be washed with copious supplies of clean water and medical attention must be sought immediately.

A short list of remedies is given below:

- Avoid contact with the eyes, skin and avoid breathing the resin vapour.
- Wear protective clothing and gloves when mixing or using.
- If poisoning occurs, contact a doctor immediately.
- If swallowed, do **not** induce vomiting – drink glasses of water
- If skin contact occurs, remove the contaminated clothing and wash skin thoroughly.
- If splashed in the eyes, hold the eyes open, flood with water for at least 15 minutes and seek medical help urgently.

4.3 BBR Carbon Fibre Laminates (CFL)

- **Application**

The BBR CFL Laminates are used to enhance the load carrying capacity of structural elements made of reinforced concrete.

- **Application Uses**

Enhancement of load carrying capacity due to changed usage
Repairs to damaged structures
Upgrading due to changes in the building code
Alteration to the intended structural form
Rectification of mistakes made during design or construction phases

- **Advantages of FRP Strengthening Systems**

Low unit weight - low profile thickness
Ease of application due to lightness
High E modulus – carbon modulus is greater than that of steel
Excellent fatigue behaviour
Alkali resistance - Corrosion resistant
Ability to be covered with a variety of paints, coatings etc.

- **Product names**

Type: BBR CFL Laminate 165 (thickness 1.4 mm; various widths)
BBR CFL Laminate 205 (thickness 1.4 mm; various widths)

- **Technical Data**

BBR CFL 205

Details		Mechanical Properties		
Type	**Size** (w x t) (mm)	**E-modulus** (dry fibre) (MPa)	**Ultimate strain** ε_{ult} (%)	**UTS** (MPa)
CFL 205	50/1.4	205,000	1.30	2,400-2,600
CFL 205	80/1.4	205,000	1.30	2,400-2,600
CFL 205	100/1.4	205,000	1.30	2,400-2,600
CFL 205	120/1.4	205,000	1.30	2,400-2,600

BBR CFL 165

Details		Mechanical Properties		
Type	Size (w x t) (mm)	E-modulus (dry fibre) (MPa)	Ultimate strain ε_{ult} (%)	UTS (MPa)
CFL 165	50/1.4	165,000	1.40	2,800-3,000
CFL 165	80/1.4	165,000	1.40	2,800-3,000
CFL 165	100/1.4	165,000	1.40	2,800-3,000
CFL 165	120/1.4	165,000	1.40	2,800-3,000
CFL 165	10/1.4	165,000	1.40	2,800-3,000

4.4 Adhesives for BBR CFL

BBR 150 Epoxy Paste

(2-component epoxy resin adhesive)

- **Application**

  The BBR 150 Epoxy Paste can be used for the structural, non-elastic bonding of structural elements made of concrete, steel or timber. It is specially designed for the application of BBR CFL laminates.

- **Description of product**

  Solvent-free 2-component epoxy resin based adhesive

- **Features**

  The BBR 150 paste is thixotropic and can be applied to vertical and overhead surfaces. When fully cured, it provides high mechanical strength. It is resistant to alkaline solutions, diluted acids, saline solutions, mineral oils and aliphatics, and is weather resistant..

  BBR 150 Epoxy Paste is resistant to constant as well as changing temperatures within the range of minus 30°C to +80°C in dry conditions and to +50°C in wet conditions

  .

- Safety Precautions

  When fully cured, BBR 150 Epoxy Paste is physiologically harmless. It is essential that no skin contact with the resin (Component A) or the hardener (Component B) takes place. The hardener is caustic. It is recommended that applicators wear rubber gloves during handling and application. If skin contact occurs, rinse immediately with soap and plenty of water. If eye contact occurs, rinse at once with plenty of water (using an eye rinsing kit) and seek medical advice immediately.

- **Technical Data**

(The standard values given below are based on +20°C and 50% relative humidity of air.)

Colour	Component A Component B	White (resin) Dark grey (hardener)
Mix ratio	By weight By volume	3:1 3:1
Viscosity		Thixotropic
Density		1.5 kg/litre
Temperature expansion coefficient		45×10^{-6} m/m °K
Minimum cure temperature		+8°C
Working time	+10°C +20°C +30°C	160 minutes 80 minutes 40 minutes
Bond strength	Concrete CFRP	3.9 MPa (concrete failure) 12.9 MPa
Tensile strength (flexure)		22 MPa
Tensile strength		15.8 MPa
Compressive strength		57.4 MPa
Shear strength		8 MPa
Static modulus of elasticity	CRFP - CFRP	7.9 GPa
Maximum layer thickness		15 mm per layer
Consumption		1.5 kg/m² per mm of layer thickness
Transport class		See material safety data sheet
Toxicity class		See material safety data sheet
Storage		In tightly closed containers, in a cool dry place
Minimum shelf life		12 months

- **Packaging** **contents**

Units of 6 kg

- **Substrate**

Concrete substrates must be dry, free from cement laitance, dust and loose material, oil and grease. All surfaces must be clean to ensure good adhesion with the FRP material and to avoid possible separation. If required, the substrate should be cleaned by sandblasting or scabbling. Where substrates have a very high porosity, they should first be treated with BBR 120 primer resin. If the bonding adhesive is required to be placed soon after treatment with primer resin, the surface may be covered with a light sprinkling of quartz sand of size 0.8–1.2 mm at a coverage rate of 3 kg/m^2.

- **Usage**

BBR 150 Epoxy Paste is delivered in pre-packaged containers. The hardener (Component B), is mixed into the resin (Component A). The mixing ratio of both components is 3:1 by weight (paste:hardener) as well as by volume. The mixing of the two components must be carried out with a slow speed drill equipped with a mixing paddle, which runs at a controlled speed of 500 – 600 revolutions per minute. The components must be mixed thoroughly while carefully scraping the sides and the bottom of the container while mixing, to ensure that the hardener is evenly distributed throughout the resin. After blending, the mix must be homogeneous, i.e. without streaks. The ideal temperature of both components at the moment of mixing should be in the range of 15°-20°C. Higher temperatures considerably reduce the working time. In hot climates, it may be necessary to keep the resin components in cooled environments to ensure the required working life is achievable. Conversely, in cold climates, it is necessary to pre-heat the resins components before mixing to the 15 – 20^{o}C range.

BBR 150 Epoxy paste must be protected from moisture for 6-8 hours after the application. If contact with moisture occurs during this period, the outer surface will become white and sticky, while the resin below the outer surface cures as normal. This whitening and the resultant affects will reduce the effective adhesion of any following layers. It is very important to take this into consideration. The resin is able to be applied by airless spray, roller or brush.

- **Cleaning of Equipment**

If work stops for longer than 15 minutes, all tools, mixing vessels and equipment should be thoroughly and carefully cleaned with a suitable epoxy cleaner (MEK or similar).

5. Application of BBR FRP Strengthening Systems

5.1 BBR Sheets Systems CFS, AFS and GFS (Carbon, Aramid and Glass)

5.1.1 Substrate

A substrate capable of transferring the loads from the FRP to the concrete is a prerequisite for strengthening with FRP sheet systems. Concrete with a pull-off tensile bond strength 0.2 -1.5 MPa (depending on material – see section 3.1) is required. The cement laitance must be removed to expose the base substrate. The optimal average surface roughness (amplitude) should lie between 0.5 - 1.0 mm for flexure and shear applications and 0.1 – 0.5 mm for confinement applications. Suitable roughening methods are sandblasting or scabbling. Grinding methods should generally be avoided because they tend to fill the pores of the concrete, thus blocking the penetration of the bonding resin. Surface contaminants such as dirt, oil and grease must be removed. After preparation is complete and before applying the primer and adhesive, the surface must be cleaned with oil-free compressed air or by vacuuming.

5.1.2 Flatness of substrate

The flatness of the concrete surface must be checked with a steel straight edge. Over a 300 mm length the out-of-plane measurement must not exceed 1 mm. Greater unevenness requires the use of a system approved levelling mortar (ie, BBR 175 Epoxy Resin levelling mortar) at least 1 day prior to the application of the laminate. If a cement based levelling mortar such as BBR 175 is used, then a moisture content of the levelling mortar layer less than 4% is required, prior to the application of the BBR 120 Epoxy Primer. BBR recommends the use of an epoxy based levelling mortar to avoid the introduction of moisture to the substrate.

5.1.3 Improving the pull-off bond stress

Where pull-off bond stresses do not meet the minimum requirement, it is sometimes possible to improve the pull-off bond by impregnating the concrete with a very low viscosity resin such as BBR 120 Epoxy Resin Primer. Improvement by this method will only occur when the substrate is porous.

5.1.4 Preparation / Quality Control

The concrete surface must be cleaned of dust particles and checked visually.

When using the standard BBR Resin, the substrate moisture content of the concrete should be determined. The moisture content must lie below 4%. Directly before the application, the dew point, air temperature and surrounding environment temperature, as well as the relative humidity must be determined. If the dew point interval The difference between the substrate temperature and the dew point) amounts to less than 3° C, then the substrate must be heated or the relative humidity lowered. The substrate temperature must be at least 3^{o}C higher than the dew point temperature.

During the bonding of the sheet, the minimum temperature should not be less than 5° and a maximum of 35° C. Special adhesives for applications at temperatures down to –15° C are available on request.

5.1.5 Priming

The entire dust-free substrate must be primed in the area where the FRP is to be applied. BBR 120 Epoxy Resin Primer is used. This may be applied with a brush, a roller or an airless spray.

5.1.6 Saturating and application of the Sheet

The importance of the complete saturation of the FRP sheet is emphasised here. For sheets up to 400 gm/m^2, hand lamination (dry lay-up) can be achieved without the use of a saturator machine to pre-saturate the sheet. Hand impregnation can be achieved by rolling the BBR 125 resin into the previously placed cloth. Alternatively, the resin may be rolled into the sheet while it is laid on a flat surface. It is then transported to the work face and applied. For sheet weights in excess of 400 gm/m^2, proper saturation is best achieved by passing the sheet through an epoxy bath, which features rollers which control the amount of resin applied to the sheet.

5.1.6.1 Hand saturation (dry lay-up)

A liberal coating of BBR 120 Epoxy primer is applied to the substrate and the sheet is pressed and rolled on to the primed substrate. Additional resin is applied by means of a roller until the weave of the sheet is fully saturated. If a second layer of sheet is required, this may be added at a time when the resin in the first layer achieves a stage of cure whereby it will support the second layer without sagging. This period varies according to the ambient temperature, whether the application is overhead or vertical and the weight of the sheet..

5.1.6.2 Machine saturation (wet lay-up)

The exact method of using the machine saturator will depend on the type of machine used. In principle, resin is contained in a trough through which the dry sheet is passed. Usually, a set of friction rollers pulls the sheet through the bath, whereby the amount of resin is controlled by the gap between the rollers.

The saturated cloth is then carefully folded and stored for transportation to the work face. It is applied using rollers and usually no further resin is required to be added.

In general, the primer is placed by a brush , airless spray or roller, regardless of how the sheet is saturated.

It is possible to check visually as to whether the sheet has been impregnated completely with resin.

5.1.7 Resin usage

The table below gives guidelines as to usage of the BBR Resins when a saturator is used to pre-saturate the fabric. **It should be noted that the usage will approximately double if the sheet is saturated manually in place.**

Product	BBR 120 Epoxy Resin Primer	BBR 125 Epoxy Saturating Resin
BBR E73 GFS 175/175	~ 50 - 100 gm/m^2	0.30-0.40 litre/m^2
BBR E73 GFS 400/40	~ 50 - 100 gm/m^2	0.30-0.45 litre/m^2
BBR E73 GFS 800/80	~ 50 - 100 gm/m^2	0.75-0.85 litre/m^2
BBR AFS A120 290/30	~ 50 - 100 gm/m^2	0.25-0.35 litre/m^2
BBR CFS 240 150/30	~ 50 - 100 gm/m^2	0.12-0.25 litre/m^2
BBR CFS 240 200/30	~ 50 - 100 gm/m^2	0.15-0.25 litre/m^2
BBR CFS 240 300/30	~ 50 - 100 gm/m^2	0.25-0.35 litre.m^2
BBR CFS 440 300/30	~ 50 - 100 gm/m^2	0.25-0.35 litre/m^2
BBR CFS 640 400/30	~ 50 - 100 gm/m^2	0.25-0.35 litre/m^2

Fig 5.1: Impregnation of BBR GFS Sheet using a saturator

Fig 5.2: Application of saturated BBR GFS to column

5.1.8 Overlapping / Splicing of BBR FRP Sheet

The following minimum laps should be observed when using BBR FRP Sheet

Product	Lap/splice distance in the direction of the main fibres	Lap/splice distance at right angles to the main fibres.
BBR E73 GFS 175/175	100 mm	50 mm
BBR E73 GFS 400/40	125 mm	70mm
BBR E73 GFS 800/80	150 mm	100mm
BBR AFS A120 290/0	120 mm	N/A
BBR CFS 240 150	150 mm	N/A
BBR CFS 240 200	100 mm	N/A
BBR CFS 240 300	125 mm	N/A
BBR CFS 440 300	125 mm	N/A
BBR CFS 640 400	150 mm	N/A

5.1.9 Quality Controls

During the site laminating work and until the saturating resin is touch dry, disruptions to the work process must be avoided in the region of influence of the FRP. After the primer has hardened, the FRP Sheet must be tested for the existence of drummy areas. In addition, the flatness of the FRP laminate must be checked. Any deviations should be no greater than 1 mm on a test length of 300 mm. Concave areas, where the Sheet is curved into the concrete, are not acceptable.

5.1.10 Fire Protection

As FRP systems are only able to support heat up to 50–60° C, special care needs to be taken for fire protection when required by codes or circumstances.

5.2 BBR Carbon Fibre Laminate Systems CFL

5.2.1 Substrate

A substrate capable of transferring the loads from the FRP to the concrete, is a prerequisite for strengthening with laminates. Concrete with a pull-off tensile bond strength according to the information given in section 3.1 is required. The cement laitance must be removed to expose the base substrate. The optimal average surface roughness (amplitude) should lie between 0.5 - 1.0 mm. Suitable roughening methods are sandblasting or scabbling. Grinding methods should be generally be avoided because they tend to fill the pores of the concrete, thus blocking the penetration of the bonding resin. When using BBR 120 Epoxy Resin Primer, the penetration of moisture must be avoided. Surface contaminants such as dirt, oil and grease must be removed. Once preparation is complete and before applying the adhesive, the surface must be cleaned by oil-free compressed air or by vacuuming.

5.2.2 Flatness of substrate

The flatness of the concrete surface must be checked with a steel straight edge. Over a 2 metre length the out-of-plane measurement must not exceed 5 mm. Greater unevenness requires the use of a system approved levelling mortar (BBR 175 Epoxy Resin) at least 1 day prior to the application of the laminate. If a cement based levelling mortar is used, then a moisture content of the levelling mortar layer less than 4% is necessary. BBR recommends the use of an epoxy based levelling mortar such as BBR 175, to avoid the introduction of moisture to the substrate.

5.2.3 Improving the pull-off bond stress

Where pull-off bond stresses do not meet the minimum requirement of >1.5 MPa, it is sometimes possible to improve the pull-off bond by impregnating the concrete with a very low viscosity resin such as BBR 120 Epoxy Resin Primer. Improvement by this method will only occur when the substrate is porous.

5.2.4 Preparation / Quality Control

The concrete surface must be cleaned of dust particles and checked visually for defects.

When using the standard BBR Resin primer, the substrate moisture content of the concrete should be determined. It must lie below 4%. Directly before the application, the dew point, air temperature and surrounding environment temperature, as well as the relative humidity, must all be determined. If the dew point interval (difference in temperatire between substrate and dew point) amounts to less than 3°C, then the substrate must be heated or the relative humidity lowered.

During the bonding of the laminate, the minimum temperature must not drop below 5° or exceed 35° C. Special adhesives for applications at temperatures down to –15° C are available on request.

5.2.5 Cleaning / Preparation of the BBR CFL Laminates

The contact surface should be rubbed with a clean white rag moistened with solvent. As well as general impurities, carbonic dust deposits must be removed. The cleaning must be repeated until no traces of black carbonic dust is left on the white rag.

5.2.6 Application of the Adhesive

The cleaned and completely dry CFL laminates are coated with BBR 150 adhesive using a spatula. The adhesive is applied to the laminate in a curved transverse profile, with more adhesive in the centre of the laminate than at the edges. The laminates are then pressed on to the dust free substrate.

5.2.7 Fixing of the Laminates to the Concrete

The CFL laminates are pushed with light finger pressure on to the concrete surface. The adhesive is thixotropic and will hold the laminate in place without the need for additional support. Following this initial pressure, a hard rubber roller is used to press the laminate into the adhesive in a manner which causes the adhesive to be expelled at both edges of the laminate. This guarantees that the adhesive is applied thoroughly eliminating voids. The expelled adhesive can be removed with a suitably shaped spatula. The adhesive layer thickness should average 2mm (with minimum 1mm and maximum 3mm). Edges of the laminate can be cleaned of excess adhesive using solvent, provided the adhesive has not hardened. The spacing between CFL laminates should be greater than 5mm.

5.2.8 Quality Control

During the adhesive application and for the first 1 – 2 days of curing of the BBR adhesive, it is preferable that vibrations in the zone of influence of the application area be minimised. After the phase of hardening of the adhesive, the laminates should be tested by means of tapping to locate potential drummy areas. The flatness of the laminate surface after curing must also be checked. Any deviation should not be more than 1 mm over a 300 mm gauge length. Alternatively, on a gauge length of 2 m, any deviation should not exceed 5 mm.

Placing laminates on a concave surface is not acceptable as they will delaminate when under tensile stress. Thus concave areas should be filled prior placing of the laminate, with a suitable repair material, preferably BBR Epoxy Resin 175 Levelling Mortar

Fig 5.3: Application of the CFRP laminate

5.2.9 Fire Protection measures

As 2 component, adhesives are normally only able to function up to temperatures of maximum 50 – 60° C, special protection measures need to be taken in the situation where fire protection is specified.

6. Design for Flexural Strengthening

6.1 Design Approach

The design of externally bonded FRP reinforcement (FRP EBR) for flexural members is based on limit state principles and relies upon the composite action between a reinforced or prestressed concrete element and the EBR. In general, strength, ductility and serviceability requirements must all be investigated. The design procedure is analogous to that for reinforced concrete beam and slab sections, with no axial load. The FRP strengthening materials are treated as additional reinforcement with different material properties. The only difference is the initial strains that are present in the concrete and reinforcement, due to the dead load at the time of applying the FRP.

Current design recommendations generally set acceptable levels of safety against the occurrence of both serviceability limit states (excessive deflections, cracking) and ultimate limit states (failure, stress rupture, fatigue). Possible failure modes and subsequent strains and stresses in each material (concrete, steel and FRP) should be assessed at ULS and the avoidance of a brittle concrete failure ensured. In respect of the design of FRP systems for the seismic retrofit of a structure, attention is drawn to recommendations given in 8.1 of R6.2.

The design procedure must consist of a verification of both limit states. In some cases, it may be expected that the SLS will govern the design.

For buildings (and other applicable structures), fire should also be included as a limit state as it will influence the properties of both the FRP and the adhesive used to attach it to the concrete.

Accidental loss of support from the FRP due to vandalism, impact etc, should be considered.

The safety concepts at ULS, adopted by most guidelines, are related to the different failure modes that may occur. Brittle failure modes, such as shear and torsion, should be avoided. In addition, and for the same reason, it should be guaranteed that the internal steel is sufficiently yielding at ULS so that the strengthened member will fail in a ductile manner, despite the brittle nature of concrete crushing, FRP rupture or bond failure. Hence the governing failure mode of a flexural member will be either steel yielding/concrete crushing (before FRP rupture or de-bonding) or steel yielding/FRP failure (either FRP rupture of bond failure) before concrete crushing. In all cases, verification that the shear (torsion) capacity of the strengthened member is larger than the acting shear (or torsion) forces is necessary. If needed, flexural strengthening must be combined with shear strengthening.

The design approach to strengthened sections is normally based upon a trial and error approach, which can be easily carried out by means of a simple spreadsheet. The initial type, size and length of the FRP reinforcements are selected at random. Then the flexural safety of the strengthened section is checked by analysing its limit states. If the safety check fails, or if the selected FRP strengthening elements are not economical, a new size or type of element is selected and the process is run again. Usually a few iterations are sufficient to arrive at a safe and economical solution.

Custom designed software exists for the design of FRP strengthening using CFRP laminates. One particularly good programme is available in the public domain on www.frp.at. It is written for either the ACI code (US), the British, French and German codes, as well as Eurocode 2. The properties of the FRP used in this programme are those relating to the products manufactured by the owner of the software. However, these properties are sufficiently close to those of the BBR CFL range that they may be used in the programme as a check on any calculation made by the long-hand method.

The following assumptions are considered valid for the concept of design of FRP EBR:

- There is a perfect bond between the FRP and the bonded substrate. This is, in fact, achieved without difficulty in practice, and failure, if it occurs, is always in the substrate.
- Plane section remain plane (Bernoulli's principle).
- The stress-strain responses for concrete and steel reinforcement follow the idealised curves presented in current codes and standards.
- FRP has a linear elastic response.
- The tensile strength of the concrete is ignored.
- Loads which are in place at the time of application of the FRP cause the element being reinforced to act within its elastic limit.
- The existing conditions have been properly evaluated (this includes steel areas and properties, concrete strength, existing moments and shear forces, steel and concrete strains, etc).

For the ultimate and serviceability limit states, the design loading is obtained by multiplying the characteristic dead and imposed loads by appropriate load factors and strength reduction factors. Designers must incorporate factors from design codes acceptable to the location of the works. Table 6.1 sets out load factors, partial factors of safety and material reduction factors for some codes.

In addition, it is normal to use strength reduction factors when calculating ultimate strength. Some codes (EC2 and BS 8110, for example) use separate material strength reduction factors for reinforcing steel and concrete, while others (ACI 318, NZS 3101 and Austroads Bridge Design Code, for example) use global strength reduction factors for these two materials.

Code	Load Factors		Material Strength Reduction Factors				Strength Reduction Factors
	Dead loads	Live Loads	Concrete	Steel Reinforcement	FRP Reinforcement		
	g_G	g_Q	g_C	g_S	Strength	E-modulus	f
BS 8110	1.4	1.6	1.5	1.15	varies	1.1	-
ACI 318	1.4	1.7	-	-	0.85	1.0	0.7 – 0.9
NZS 3101 & NZS 4203	1.2	1.6	-	-	-	-	0.85
Eurocode 2	1.35	1.5	1.5	1.15	varies	1.0	-
Austroads	1.2	2.0	-	-	-	-	0.6 – 0.8

Table 6.1: Load Factors, Material Partial Safety Factors & Strength Reduction Factors used by different Design Codes and FRP Design Guidelines

The methods of incorporating strength reduction material factors for the FRP varies according to the FRP Design Guideline used.

The **UK Concrete Society TR 55** [R6.1] recommends 3 separate factors, which relate to the method of manufacture, the type of FRP material and the degradation of the E-modulus over time.

The **German General Guidelines** [R6.3] presently recommend reduction factors by limiting the allowable strain at ULS to between 0.4 and 0.7 of the ultimate strain and at SLS.

The draft **ACI 440** [R6.2], as well as using a global strength reduction factor recommends a strength reduction factor for the FRP of 0.85 and an additional environmental strength reduction factor (see below).

The ***fib* Bulletin 14** uses FRP material safety factors and also places limitations on the FRP strain at ULS and SLS.

At the time of this revision (July 2002), there are no Codes of Practice that include for the use of FRP as a reinforcement material. The designer therefore must take into account suitable limitations on the use of FRP, either by separate material reduction factors as per the UK and *fib* Guidelines, additional strength reduction factors used in conjunction with the global reduction factor, as for ACI 440, or a fixed upper limit of allowable strain, as per the German General Guideline and ACI 440.

All guidelines limit the stress/strain in the FRP to avoid de-bonding, which can occur in several mechanisms. In addition, due to the general decrease in ductility of a member strengthened with FRP, care must be taken to ensure ductility is preserved, by ensuring the internal steel will sufficiently yield at failure. This is done by limiting the depth of the compression zone at ULS.

6.2 Design values for material properties

6.2.1 Introduction

As mentioned above, at the time of writing there are no Codes of Practice that set down the requirements for the design and execution of concrete strengthening using FRP. However, there are at least eight national guidelines that have been produced by recognised authorities and these can be accepted as state-of-the-art guidelines for the present. Nevertheless it must be recognised that the use of FRP as a strengthening medium, is a relatively new art and that research is being undertaken in many centres worldwide. The results of this research will undoubtedly cause the recommendations to be varied as experience is gained.

6.2.2 Design strength of FRP

The various FRP Design Recommendations treat the strength reduction of the FRP material in different ways.

6.2.2.1 UK Concrete Society TR No. 55 [R6.1]

TR 55 postulates that the partial safety factors to be applied to the characteristic mechanical properties are a function of the type of fibre and the manufacturing/site application process. Thus:

$$g_{mF} = g_{mf} \times g_{mm} \tag{6.1}$$

where g_{mf} depends on the type of fibre, as given in table 6.2 and g_{mm} depends of the manufacturing and/or site application process, as given in table 6.3.

The accuracy with which the properties obtained from test samples reflect the overall properties of the material will depend on the method of manufacture, the level of quality control and application. Table 6.3, which is taken in part from EUROCOMP Design Code [R6.4], gives a range of partial safety factors to be applied to the measured properties which reflect the various methods of manufacture and application.

Material	Partial safety factor (g_{mf})
BBR Carbon Fibre CFL & CFS	1.4
BBR Aramid Fibre AFS	1.5
BBR Glass Fibre GFS	3.5

Table 6.2 Partial safety factors for different FRP Materials recommended by TR 55 for strength at Ultimate Limit State

Type of system (and method of application or manufacture)	Partial safety factor g_{mm}
BBR Pultruded Laminates CFL	1.1
BBR Sheets CFS, AFS & GFS (wet lay up)	1.4

Table 6.3: Partial safety factors g_{mm} recommended by TR 55 for different FRP Materials based on methods of manufacture and application.

Using Tables 6.2 & 6.3, examples of the partial safety factors to be applied in various situations are as follows:

BBR carbon fibre laminate CFL, strength measured on the laminate,

$$g_{mF} = 1.4 \times 1.1 = 1.54$$

BBR carbon fibre sheet CFS, made by wet hand lay-up

$$g_{mF} = 1.4 \times 1.4 = 1.96$$

BBR glass fibre sheet GFS, made by wet hand lay-up,

$$g_{mF} = 3.5 \times 1.4 = 4.9$$

Design elastic modulus of FRP

TR 55 postulates that the modulus of elasticity of FRP may change with time, and considers it necessary to apply an additional partial safety factor. TR 55 recommends partial safety factors for modulus of elasticity are given in Table 6.4.

Material	Factor of Safety (g_{mE})
BBR Carbon Fibre CFL & CFS	1.1
BBR Aramid Fibre AFS	1.1
BBR Glass Fibre GFS	1.8

Table 6.4: TR 55 recommended partial safety factor for Modulus of Elasticity at ULS

6.2.2.2 German General Guidelines [R6.3]

The German General Guidelines approach the material strength reduction factors in a different manner. Each manufacturer must obtain an "Approval" for his particular product. This Approval, will normally limit the strain at ULS, based on testing of the particular product. For BBR products, the Approval limits the strain at ULS to fixed values with an additional reduction factor for shear in slabs. In addition, BBR recommends that the E-modulus of the FRP be reduced by a factor which takes into account the type of fabric (woven or parallel fibres), the type of material and the method of application. Table 6.5 sets out these recommendations:

Material	Design limits of strain at ULS for BBR FRP e_{fd}	Factor of Safety (g_{BBR}) to be applied to E-modulus (NB: effects are included in e_{fd})
BBR Carbon Fibre CFL	BBR CFL 205: 0.0065 BBR CFL 165: 0.0075	1.0
BBR Carbon Fibre CFS	BBR CFS 240: 0.006 BBR CFS 440: 0.004 BBR CFS 640: 0.002	1.2
BBR Aramid Fibre AFS	BBR AFS A120: 0.011	1.3
BBR Glass Fibre GFS	BBR GFS E73 0.005	1.5

Table 6.5: BBR recommended limiting strains and additional partial safety factors for use with German General Guidelines

6.2.2.3 ACI 440 Draft Guideline [R6.2]

ACI 440 limits the stress due to creep rupture (a SLS condition) to $0.55\times f_{fu}$. At ULS, an environmental exposure factor C_E reduces the ULS working strain/stress, the factor depending on the aggressivity of the environment in which the FRP is required to work. Strain at ULS is also limited to prevent debonding and peeling. A material reduction factor y_f is also applied to the properties of the FRP (dry fibre properties for sheet and laminate properties for laminate), to take into account variations in the manufacturing processes and the type of FRP material (GFRP, AFRP or CFRP).

6.2.2.4 fib Bulletin 14

fib Bulletin 14 limits the stresses in the FRP by applying FRP material safety factors. When the design is governed by the SLS or an ULS corresponding with concrete crushing or bond failure, the FRP strain at ultimate is rather limited. In this situation the FRP stress s_f at ULS is considerably lower than the tensile strength, so that the design tensile strength is not governing. To verify this or hence in those cases where the ULS is determined by the FRP tensile failure anyway, reference is made to the design tensile strength, where

$$f_{fd} = \frac{f_{fk}}{g_f}\times\frac{e_{fue}}{e_{fum}}$$

f_{fd} is the design value of the FRP tensile strength

f_{fk} is the characteristic value of the FRP tensile strength

e_{fue} is the ultimate FRP strain, and

e_{fum} is the mean value of the ultimate FRP strain.

The values for the FRP material safety factor g_f are suggested in table 6.6. Bulletin 14 points out that these factors are subject to further study, because of the lack of comprehensive study. The ratio $\frac{e_{fue}}{e_{fum}}$ normally equals 1.0 (and this is the case for BBR FRP Products).

Material Type	Application Type A	Application Type B
CFRP	1.20	1.35
AFRP	1.25	1.45
GFRP	1.30	1.50

Table 6.6: Bulletin 14 recommended material safety factors

Application Type A refers to the use of prefabricated FRP ERB systems under normal quality control conditions and wet lay-up systems where all necessary provisions are taken to obtain a high degree of quality control on both the application conditions and the application process. Application Type B refers to the use of wet lay-up systems under normal quality control conditions and application of any system where difficult site working conditions are present.

6.3 Moment Capacity

6.3.1 Introduction

Comparison of the UK, Eurocode 2 and ACI Capacity-Demand Equations are given as an illustration of how the combination of Load Factors and Material Safety Factors are used. It should be pointed out that a designer may use his local code in conjunction with any of the published guidelines, but should ensure that global strength reduction factors and individual material reduction factors are not mixed.

6.3.2 General Stress/Strain Relationships

$M_n \geq M_u$ is the standard equation which indicates that the design flexural capacity must exceed the flexural demand. Various codes use different formulae, but overall, the same principle applies, viz, the flexural capacity must be greater than the flexural demand.

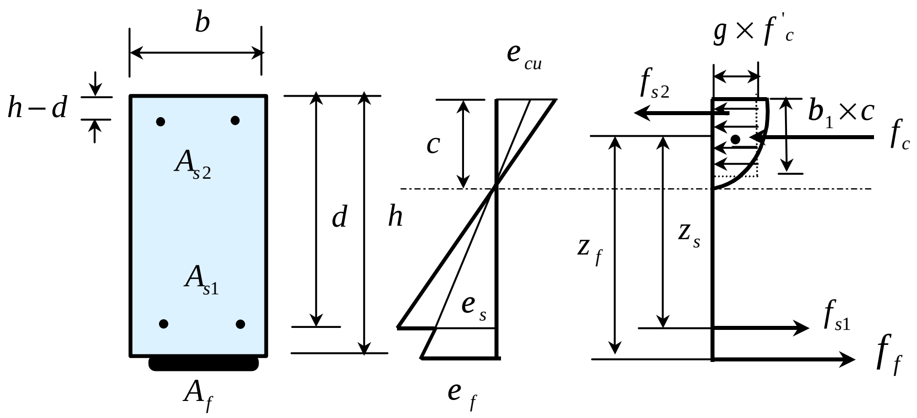


Figure 6.1: General Stress/Strain Relationships

Arising out of this, the flexural capacity is able to be calculated by the following:

$$M_n = A_{s1} f_{s1}[d - \frac{b_1 \times c}{2}] + y_f A_f f_f [h - \frac{b_1 \times c}{2}] + A_{s2} E_s e_{s2}[\frac{b_1 \times c}{2} - (h-d)] \qquad (6.2)$$

where, in this context, y_f is the combined material reduction factor, calculated according to the particular Guideline used. Values for g and b may vary from country to country but for the purposes of this illustration, the Whitney stress block is used, making $g = 0.85$ and $b_1 = 0.85$ for concrete where $f'_c \leq 30MPa$.

Note of caution: Section 6.3.3 provides indications as to the limitations of using the equivalent rectangular stress block. These should be read and understood by the FRP designer.

Set out below are summarised details of design parameters for three published Guidelines. Readers should obtain these documents to avail themselves of the detailed information.

6.3.2.1 <u>UK Concrete Society Recommendations TR55</u>

At ULS and when the design Moment is less than the Balanced Failure Moment, the following equalities apply (Fig 6.2):

$$e_s > 0.0035 \text{ (BS 8110)} \tag{6.3}$$

$$e_f = e_{fu} \text{ or 0.8\% (CFRP), whichever is the least} \tag{6.4}$$

where $$e_{fu} = e_{fk} / g_{mF} \tag{6.5}$$

and $$g_{mF} = g_{mf} \times g_{mm} \tag{6.6}$$

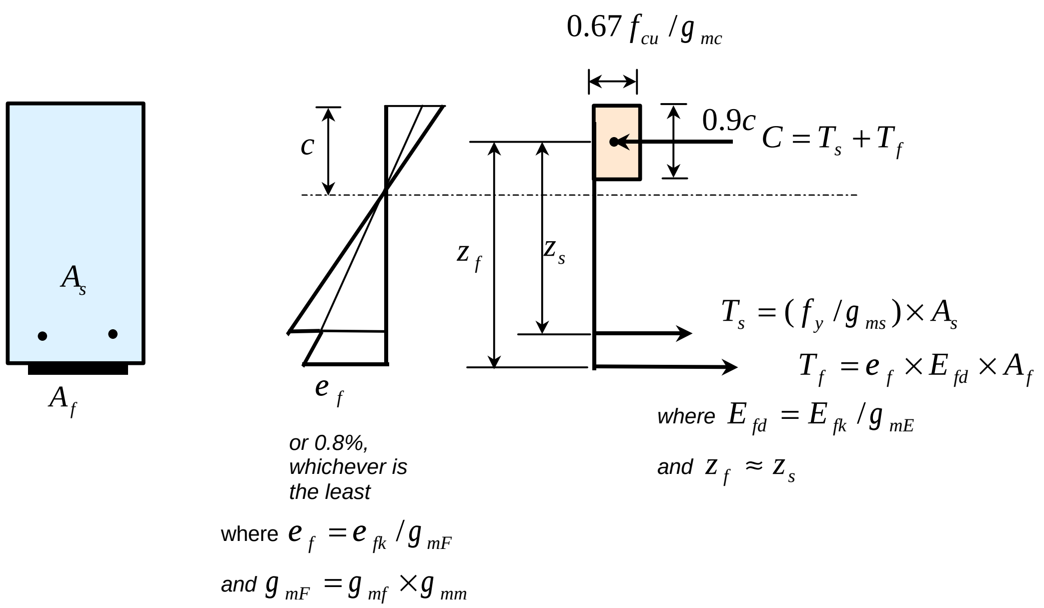


Figure 6.2: Design Moment less than Balanced Failure Moment using UK Concrete Society TR55 Guidelines and BS 8110

Then: $$C = T_f + T_s \tag{6.7}$$

where $T_s = f_y / g_{ms} \times A_s$ (6.8)

and $T_f = e_f \times E_{fd} \times A_f$ (6.9)

and $E_f = E_{fk} / g_{mE}$ (6.10)

and $z_f \approx z_s$ (6.11)

Hence the Capacity-Demand Equation is: $M_n = T_s \times z_s + T_f \times z_f \geq M_u$ (6.12)

6.3.2.2 *- ACI 440 Draft Guideline*

At ULS and when the design Moment is less than the Balanced failure Moment:

$$e_s > e_y \tag{6.13}$$

$$e_{fu} = C_E \times e^*_{fu} \tag{6.14}$$

where C_E = environmental reduction factor, which varies between 0.50 - 0.95 depending on the type of FRP and type of environmental exposure condition

and e^*_{fu} = ultimate rupture strain of the FRP, as provided by the manufacturer

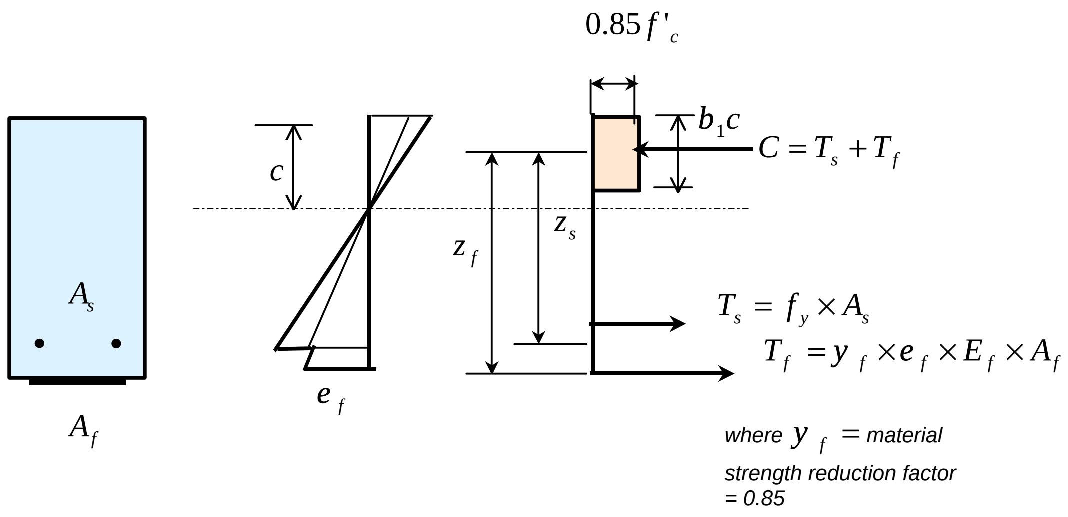


Figure 6.3: Design Moment less than Balanced Failure Moment using ACI 440 Draft Guidelines and ACI 318

Then: $C = T_f + T_s$ (6.15)

where $T_s = f_y \times A_s$ (6.16)

and $T_f = y_f \times E_f \times e_f \times A_f$ (6.17)

where y_f = material strength reduction factor = 0.85 for flexure

Hence the Capacity-Demand Equation is: $j M_n = j\,(T_s \times z_s + T_f \times z_f) \geq M_u$ (6.18)

where $j = 0.90$

6.3.2.3 - <u>German General Guidelines</u>

At ULS and when the design Moment is less than the Balanced Failure Moment, the following equalities apply Fig 6.4):

$e_c > 0.003$ (Eurocode 2)

$e_{fd} \cong 0.5 e_{fu} / g_{BBR}$ (for BBR approved materials see Table 6.5) (6.19)

where g_{BBR} = additional material reduction factor recommended by BBR (see table 6.5.

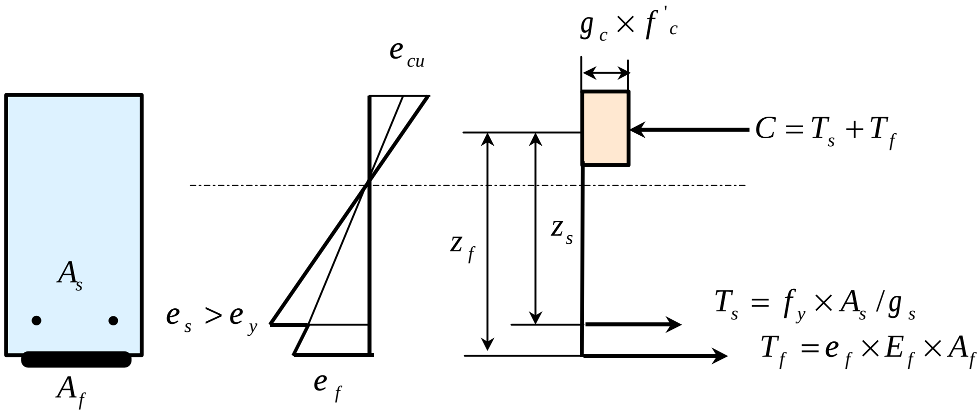


Figure 6.4: Design Moment less than Balanced Failure Moment using German General Guidelines & Eurocode 2

Then: $C = T_f + T_s$ (6.20)

where $T_s = f_y / g_s \times A_s$ (6.21)

and $T_f = e_f \times E_f \times A_f$ (6.22) and $z_f \approx z_s$ (6.23)

Hence the Capacity-Demand Equation is: $M_n = T_s \times z_s + T_f \times z_f \geq M_u$ (6.24)

6.3.3 Notes relating to the Balanced Moment of Resistance.

Whilst TR55 follows the "balanced failure" moment of the section, other guidelines point out the significance of restricting the neutral axis depth, c, to ensure that the ultimate strain in the concrete is not reached (ductile flexural behaviour of the element being one objective). Most codes limit c for this reason.

For balanced moment of resistance, $c = c_b = \dfrac{h}{[\frac{e_{fu}}{e_{cu}} + 1]}$ (6.25)

As examples,

- NZS 3101 limits c to $\leq 0.75c_b$, where c_b is the neutral axis depth at the "balanced state".
- EC2 limits c according to the following: $x \leq 0.45$ for concrete types C35/C45 or lower, and $x \leq 0.35$ for concrete types higher than C35/C45, where $x = \dfrac{c}{d}$ and d is the effective depth of the beam.

The advisability of ensuring that the ULS failure mode is either yielding of the steel followed by rupture of the FRP or, yielding of the steel followed by crushing of the concrete and never crushing of the concrete before yielding of the steel, indicates that good designs will never allow the strain in the extreme concrete fibre to reach its limit. **Thus the Balanced Moment of Resistance method would appear to unsuitable for good retrofitting design philosophy.**

Under these "ductility inspired" limitations to the depth of the compression zone, the stress block at this stage is not actually near that represented by the "equivalent rectangular stress block". However the effect on the design flexural capacity is often assumed to be small and is typically neglected.

Bull and Sivyer [R6.8] point out that when satisfying internal equilibrium in a member, it can be shown that the strain in the extreme concrete compression fibre of the member e_c will often be less than the conventionally accepted 0.003 (0.0035 in some codes), the crushing strain of the concrete, e_{cu}. They state that the following observations can be made:

- The equivalent rectangular stress block used to represent the actual stress state in the compressed concrete, assumes an $e_{cu} = 0.003$
- The use of the equivalent rectangular stress block will produce a nominal flexural capacity M_n which is greater than that determined from a representative concrete stress distribution, when e_c does not approach a value of 0.003. This is non-conservative

- Therefore the equivalent rectangular stress block should not be used if the strain in the extreme compression fibre e_c does not approach a value of 0.003.

Under such conditions, a more accurate assessment of the moment capacity provided by the retrofitted member should be considered, such as a moment-curvature analysis. It is normal to use spreadsheets in this method which contain algorithms for generating the actual shape of the stress block. Thus the stresses derived are directly associated with the strain in the concrete. Such an approach is also recommended by ACI 440 Section 9.2.3.

There is a limit state for flexure where the tension steel does not yield, while the FRP has reached its maximum usable strain. In this situation the concrete will reach a crushing strain and the flexural capacity of the member is limited by this. In this case, the equivalent rectangular stress block may be used along with specific strains calculated in the FRP and tension steel.

6.4 End conditions and development lengths

6.4.1 Introduction

Members strengthened externally with FRP can fail prematurely as a result of local FRP separation. This can be caused by three different mechanisms: peeling, debonding and cover tension delamination.

Peeling failure may occur at the ends of the FRP where a discontinuity exists as a result of the abrupt termination of the plate. TR 55 [R6.1] reports this phenomenum is normally associated with concentrated shear and normal stresses in the adhesive layer due to the FRP deformation that takes place under load. Peeling failure usually results in ripping of the cover concrete off the adjacent layer of steel reinforcement.

Debonding, unlike peeling, mostly occurs away from the plate end. It occurs if the bonding material is not up to specified strength or has not been properly applied. Debonding failure may also be indicative of inadequate preparation of the concrete substrate. More commonly, however, it is associated with the formation of wide flexural and shear cracks that occur as a result of the yielding of the embedded steel bars. The wide cracks generate high stresses in the FRP across the crack, which can only be dissipated by debonding. The cracks can then propagate towards the plate end, leading to FRP separation failure.

Cover tension delamination results from the normal stresses developed in a bonded FRP laminate. With this type of delamination, the existing reinforcing steel essentially acts as a bond breaker in a horizontal plane, and the reduced area of bulk concrete pulls away from the rest of the beam. The result is the entire cover layer of concrete delaminating from the member.

6.4.2 Peeling failure.

End plate separation failure will be avoided by addressing two criteria:

(i) Limiting the longitudinal shear stress between the FRP and the substrate

(ii) Anchoring the FRP by extending it beyond the point at which it is theoretically no longer required.

The word “theoretically” has produced intense international discussion. See section 6.4.2.2 for BBR’s recommendations in this regard.

6.4.2.1 <u>TR 55 Recommendation</u>

In respect of the first criterion (i) of 6.4.2, TR 55 reports that field experience of installing FRP systems suggests that, provided that the longitudinal shear stress at the ultimate limit state does not exceed 0.8 MPa, premature peeling failure will be avoided.

According to TR 55, the longitudinal shear stress, t , can be calculated using the expression:

$$t = Va_f A_f (h - c) / I_{cs} b_a \tag{6.26}$$

where V = ultimate shear force

a_f = short-term modular ratio of FRP to concrete

= E_f / E_c

A_f = area of FRP laminate

c = depth of neutral axis of strengthened section

I_{cs} = moment of inertia of strengthened concrete equivalent cracked section

b_a = width of adhesive layer

The longitudinal shear stress should be checked at both the plate ends, where the shear force acting on the strengthened portion of the member will be at its greatest and at the location in the span where the steel reinforcement first yields. This is because beyond this point the elasticity of the steel is theoretically zero, and the tensile stresses due to the bending moment will be carried by the FRP alone. At this location, both c and I_{cs} in Equation 6.26 should be calculated ignoring the presence of steel reinforcement.

In respect of the second criterion (ii) of 6.4.2, TR 55 indicates that the model proposed by Neubauer and Rostasy [R6.6] is generally accepted as being the most up-to-date and straightforward to apply.

Figure 6.5 illustrates the model. It can be seen that the characteristic bond failure force, $T_{k,\max}$, increases with increasing anchorage length, l_t, but that there is a threshold anchorage length, $l_{t,\max}$, above which no increase in the bond failure force is possible.

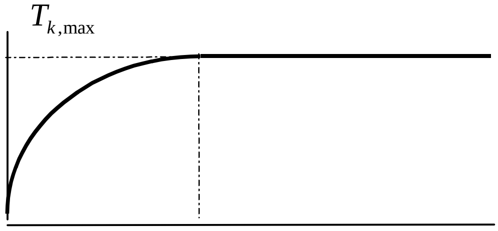


Fig 6.5 : Characteristic bond failure force vs anchorage length

The maximum ultimate bond force, $T_{k,\max,}$ and the corresponding maximum anchorage length, $l_{t,\max}$, needed to activate this bond force can be calculated using the following expressions:

$$T_{k,\max} = 0.5 k_b b_f \sqrt{E_f \times t_f \times f_{ctm}} \qquad (6.27)$$

$$l_{t,\max} = 0.7\sqrt{(E_f t_f / f_{ctm})} \qquad (6.28)$$

where $k_b = 1.06\sqrt{\dfrac{2-\dfrac{b_f}{b_w}}{1+\dfrac{b_f}{400}}} \geq 1.0$, and (6.29)

b_f = FRP plate width

b_w = beam width or FRP plate spacing for solid slab (mm)

t_f = FRP plate thickness

E_f = elastic modulus of the FRP

f_{ctm} = tensile strength of the cover concrete (obtained by insitu testing – theoretical design values **should not be used**. Note: pull-off testing to ASTM D4541 is one acceptable method for determining the insitu tensile strength of the cover concrete.)

In situations where it is not possible to provide this length, the bond force will be less than the ultimate value and may be calculated using the following expression:

$$T_k = (T_{k,\max} \times \frac{l_t}{l_{t,\max}}) \times (2 - \frac{l_t}{l_{t,\max}}) \qquad (6.30)$$

The German Guideline [R6.3] uses a similar approach for calculating the characteristic bond failure force, except for the following modified formulae:

Equation 6.27A introduces a temperature reduction factor k_t to take into account the differing thermal elongations of concrete and FRP and shear stresses in the adhesive that result from temperature variations between –20°C and +30°C.; 0.9 for changes between –20°C and +30°C (external elements) and 1.0 for interior elements.
Thus equation 6.27 becomes

$$T_{k,\max} = 0.5 k_b b_f k_t \sqrt{E_f \times t_f \times f_{ctm}} \qquad 6.27A$$

The bond length is as for equation 6.28 is also slightly different to TR 55, as follows:

$$l_{t,\max} = 0.6\sqrt{(E_f t_f / f_{ctm})} \qquad 6.28A$$

This difference relates to the fact that DIN safety concept uses a global safety factor whereas Eurocode 2 and the British code use partial safety factors. To achieve consistency between DIN and EC2 the coefficient is reduced to 0.6. Additional information is given in the German General Guideline [R6.3] or the publications by Rostasy [R6.9] and Onken [R6.7] respectively.

Note of caution:

TR 55 can be interpreted as allowing the FRP laminate to be terminated in the tension zone [see 6.3.2.(2) of TR 55] provided the longitudinal shear stress between the FRP and the substrate is limited to 0.8 MPa (at ULS) and provided the anchoring of the FRP is beyond the point at which it is no longer required. This is in contrast to the requirement of the German General Guidelines and ACI 440, which require the following:

German General Guideline: the anchorage zone must be outside of the zone of tension (positive or negative moment = 0; ie, the point of inflexion).

ACI 440: for continuous beams, beyond the point of inflexion; for simply supported beams, beyond the point of cracking moment for factored loads.

Designers should satisfy themselves as to which recommendation they use, bearing in mind that the formation of tensile cracks in the anchorage zone can lead to premature failure of the bond.

In addition, ACI 440 requires that in the case where the factored shear force at the termination point is greater than $^2/_3$ of the concrete shear strength, the FRP flexural reinforcement should be anchored with transverse reinforcement (shear straps) to prevent the cover concrete from delaminating.

The German General Guidelines go a step further and say that u-shaped shear straps must be used to anchor laminates used to flexurally strengthen beams, regardless of whether additional shear reinforcement is needed, or not. This is a belt-and-braces approach.

The question of end anchorage of laminates used in flexure is the subject of much discussion and research worldwide. In the absence of a clear and common agreement on this subject, BBR recommends that designers take a conservative approach.

6.4.2.2 Design method by Onken & vom Berg

Onken and vom Berg [R6.7] provide a calculation method for determining the required bond length, which is practical and is the one used in the design programme mentioned on page 6.1. In their method, the design bond length is calculated from the bending moment diagram and allows for "Tension Shift" or "Tjd" effect. This is different from the system proposed by TR 55 which uses the ultimate shear as the criterion for calculating the required bond length.

BBR prefers and recommends the Onken & vom Berg method, which is based upon the strut and tie model concept , takes into account the "Tension Shift" or "*Tjd*" effect and allows the application of the German General Guideline bonding check to the partial safety concept of EC2.

Case A: End Support (fig 6.6)

The design bond length l_{bd} is the bond length needed to transmit the maximum bond force F_{bd}. This force is compared to the tensile force in the laminate $F_{f,E}$ which may be calculated (iteratively) from a given moment $M_{uf,E}$. This moment can be derived from the moment diagram at the distance x_E from the axis support, where

$$x_E = a_i + f + l_{bd} + a_L \qquad (6.31)$$

The design anchorage length

$$l_{bd} = 0.6\sqrt{\frac{E_f \times t_f}{f_{ctd}}} \qquad (6.32)$$

where $f_{ctd} = f_{ctm} / g_c$, t_f = thickness of the laminate and f_{ctm} = mean substrate strength found from site pull-off testing.

The design bond force

$$F_{bd} = 0.5 \times w_f \times k_b \times k_t \sqrt{(E_f \times t_f \times f_{ctd})} \qquad (6.33)$$

where k_t = temperature coefficient = 1.0 for internal elements and 0.9 for external elements,

w_f = width of the laminate

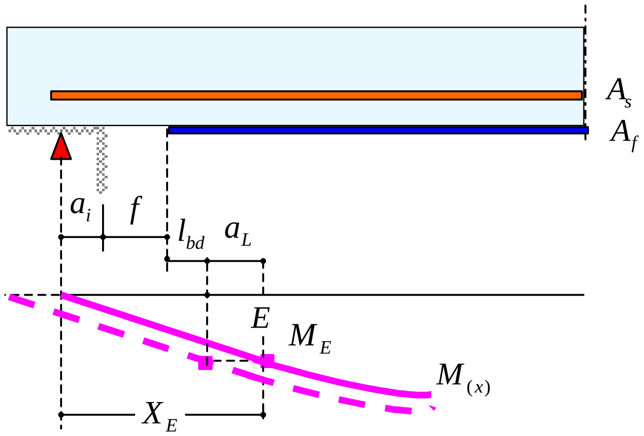


Fig 6.6: End support conditions for bond development

and k_b = width coefficient

where $k_b = 1.06\sqrt{\dfrac{2-(n \times w_f / b_w)}{(1+[n \times (w_f / 400)]}}$ <u>for beams</u> (6.34)

and $k_b = 1.06\sqrt{\dfrac{[2-(w_f / s_{prov})]}{[1+(w_f / 400)]}}$ <u>for slabs</u> (6.35)

For slabs, $F_{f,E} < \dfrac{F_{bd}}{1.2}$ should be used in the calculation of the required bond length l_{bd}. This allows for the fact that the FRP cannot be secured by strap binders at its ends, in slabs.

Case B: Centre Support (fig 6.7)

The German General Guideline requires a bond length l_b of 1.0m from the point of zero moment. (Note this position may change due to different load combinations).

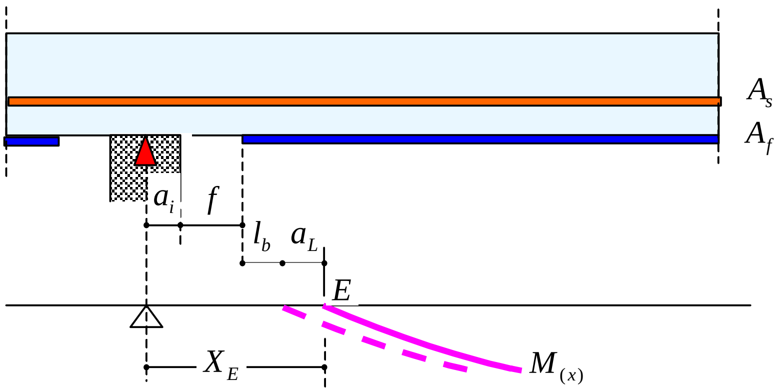


Fig 6.7: Centre support conditions for bond development

Then $$f_{max} = x_E - a_i - a_L - l_{bd} \tag{6.36}$$

BBR recommends

$$f = x_E - a_i - a_L - l_b$$
$$= x_E - a_i - a_L - 1.0m \tag{6.37}$$

Case C: Negative moment at support

The calculation is the same as for an interior support.

$$f_{min} = x_E + a_L + l_{bd} - a_i \tag{6.38}$$

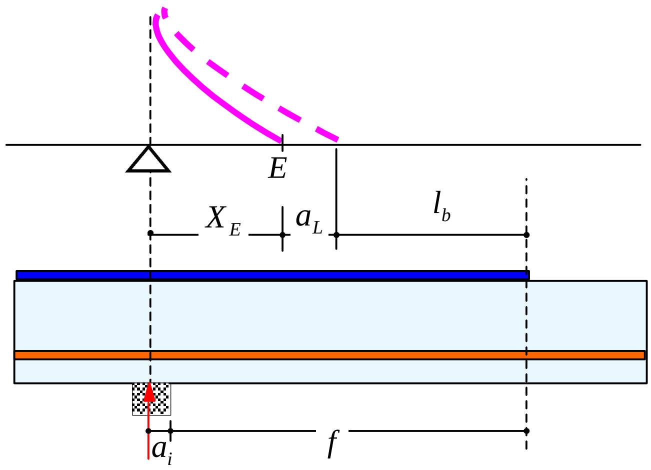


Fig 6.8: Centre support – negative moment bond conditions

BBR recommends:

$$f_{min} = x_E + a_L - a_i + l_b \tag{6.39}$$

$$= x_E + a_L - a_i + 1.0m \tag{6.40}$$

6.4.3 Debonding

The risk of debonding failure is exacerbated by the formation of wide flexural and shear cracks. A direct way of avoiding this potential failure mode is simply to limit the strain in the FRP. Neubauer and Rostasy [R6.6] suggest an ultimate limit of $5e_y$ (critical for mild steel) or half the ultimate laminate strain, which for the materials tested was 0.75%.

This fact is recognised in the various Guidelines and varies from one document to the other. It

lies in the range 0.5% - 0.8%.

It should be noted that the above limits are largely based on laboratory and field data obtained from strengthening schemes using CFRP and therefore these values may not be applicable to other composite materials. There is some evidence that AFRP will fail at a lower ultimate strain than CFRP. For this reason BBR recommends it is essential that designers verify the suitability of these strain limits for particular FRP strengthening systems.

6.5 Shear

Bonding of FRP to the tension face will most likely increase flexural capacity but will leave the shear capacity of the member largely unaltered. The member may therefore fail in shear rather than flexure. Shear failures are brittle in nature and should be avoided. Where a possibility of shear failure exists, a shear strengthening system based on FRP as discussed in Section 7 should be considered.

6.6 Design Example No 1.

The following example is provided simply to show the different approach of each Guideline and the differing requirements of FRP demanded. For purposes of simplification, the design is applied only to the flexural strengthening and concrete and steel stresses are not checked. The Balanced Moment solution is used for each example, for simplicity, it being accepted that a balanced moment situation will not normally be achieved in practise.

A 6m long by 300 mm wide by 500 mm deep reinforced concrete beam was designed to carry 1.2 kN/m of superimposed dead load and a live load of 10 kN/m. The reinforcing steel at the bottom of the beam consists of three bars with an area $A_s = 540mm^2$ *and* $f_y = 430MPa$. *The beam is required to be strengthened in flexure to carry an additional live load of* $7kN/m$. *Design a strengthening system using BBR CFL 165 laminates, if the equivalent concrete cube strength in the "as built" beam is* $f_{ck} = 23.5MPa$.

Note: $f_{ck,cylinder} = 0.85 f_{ck,cube}$; $C_E = 0.90$; $y_f = 0.85$.

6.6.1 Design according to UK Concrete Society TR 55

Design ultimate failure strain of FRP, $e_f = 0.014/1.4 \times 1.1 = 0.009$ but maximum design strain is limited to 0.008 when loading is an UDL – hence use 0.008)

Factored loads are:

$$1.4W_G = 1.4(3.6+1.2) = 6.72kN/m$$

$$1.6W_Q = 1.6(10) = 16.0kN/m$$ ("as built")

$$1.6W_Q = 1.6(10+7) = 27.2kN/m$$ (strengthened)

Design moment of the "as built" beam is:

$$M_0 = (6.72 + 16) \times 6^2 / 8 = 102.24 kN.m$$

Design moment of the strengthened beam is:

$$M = (6.72 + 27.2) \times 6^2 / 8 = 152.64 kN.m$$

Balanced moment of resistance:
Neutral axis depth from top fibre, c at the balanced failure

$$c = \frac{h}{\left[\frac{e_f}{e_c} + 1\right]}$$ from equation 6.25, i.e.

$$c = 500 / (0.008 / 0.0035 + 1) = 152.18 mm$$

Lever arm $z = (500 - 50) - 0.9 \times 152.18 / 2 = 381.52 mm$

Taking moments about the bottom face, the balanced moment of resistance is:

$$M_{r,b} = (0.67 f_{cu} / g_{mc}) \times b \times 0.9 \times c[z + (h - d)] - (f_y / g_{ms}) A_s (h - d)$$, i.e

$$M_{r,b} = (0.67 \times 23.5 / 1.5) 300 \times 0.9 \times 152.18 \times [381.52 + (500 - 450)] / 10^6$$
$$- (430 / 1.15) \times 540 \times (500 - 450) / 10^6$$
$$= 176.01 kN.m > 152.64 > M$$

Area of FRP required:

$$M_{add} = 152.64 - 102.24 = 50.40 kN.m$$

From equation 6.10

$$E_f = E_{fk} / g_{mE} = 165{,}000 / 1.1 = 150{,}000 MPa$$

$$f_f = 0.008 \times 150{,}000 = 1{,}200 MPa$$

The required area of FRP laminate is:

$$A_f = 50.40 \times 10^6 / (1200 \times 381.52) = 110.10 mm^2$$

Use one 80x1.4 BBR CFL 165 laminate that has an area of: $\underline{80 \times 1.4 = 112mm^2}$

6.1.2 Design using ACI 440 (draft)

Ultimate strain of FRP, from equation 6.14, is $e_{fu} = C_E \times e^*_{fu}$

where C_E = 0.90 and $e^*_{fu} = y_f \times e_{fu}$ where $y_f = 0.85$

ACI 440 requires that the FRP strain at SLS does not exceed $0.55e_{fu}$ for creep rupture purposes. Normally one would calculate the effective stress in the FRP and check it does not exceed the limited value. However, for the purpose of this example, which uses the simplified Balanced Moment approach, we will assume a value for e_{fu}

Hence use ultimate design strain

$$e_{fu} = 0.014 \times 0.9 \times 0.55 = 0.00693$$

Factored loads (from ACI) are:

$$1.4W_G = 1.4(3.6 + 1.2) = 6.72kN/m$$

$1.4W_Q = 1.7(10) = 17kN/m$ “as built”

$1.7W_Q = 1.7(10 + 7) = 28.9kN/m$ (strengthened)

Design moment of the “as built” beam is:

$$M_0 = (6.72 + 17) \times 6^2 / 8 = 106.73kN.m$$

Design moment of strengthened beam is:

$$M = (6.72 + 28.9) \times 6^2 / 8 = 160.29kN.m$$

Balanced moment of resistance:

Neutral axis depth from top fibre, c at the balanced failure

$$c = 500/(0.00693/0.0035 + 1) = 180.60mm$$

Lever arm $z = (500 - 50) - 180.60/2 = 359.70mm$

Taking moments about the bottom face, the factored balanced moment of resistance is:

$$fM_{r,b} = 0.9\times 0.67\times 23.5\times 0.85\times 300\times 0.9\times 184.21[359.70+(500-450)]/10^6$$
$$-0.9\times 430\times 540\times (500-450)/10^6$$
$$= 233.91kN.m > 160.29 > M$$

Area of FRP required:

Additional moment is:

$$M_{add} = 160.29 - 106.83 = 53.46kN$$
$$f_f = 0.006\times 165{,}000 = 990MPa$$

The required area of FRP laminate is:

$$A_f = 53.46\times 10^6 / 990\times 357.90 = 150.88mm^2$$

Use one 120x1.4 BBR CFL 165 laminate that has an area of: $\underline{120\times 1.4 = 168mm^2}$

6.6.2 Design using German General Guidelines and Eurocode 2

Design ultimate strain of FRP, $e_f = 0.5\times 0.014/g_{BBR} = 0.5\times 0.014/1.0 = 0.007$

Factored loads are:

$$1.35W_G = 1.35(3.6+1.2) = 6.48kN/m$$

$1.5W_Q = 1.5(10) = 15.0kN/m$ (“as built”)

$1.5W_Q = 1.5(10+7) = 25.5kN/m$ (strengthened)

Design moment of the “as built” beam is:

$$M_0 = (6.48+15)\times 6^2/8 = 96.66kN.m$$

Design moment of the strengthened beam is:

$$M = (6.48+25.5)\times 6^2/8 = 143.91kN.m$$

Neutral axis depth from top fibre, c at balanced failure

$$c = 500/(0.007/0.0035+1) = 166.67mm$$

Lever arm $z = (500-50) - 166.67/2 = 366.67mm$

Taking moments about the bottom face, the balanced moment of resistance is:

$$M_{r,b} = 0.67 \times 23.5/1.5)300 \times 0.9 \times 166.67 \times [366.671 + (500 - 450)]/10^6$$
$$- (430/1.15) \times 540 \times (500 - 450)/10^6$$
$$= 186.72 kN.m > 143.91 > M_u$$

Area of FRP required:

Additional moment is:

$$M_{add} = 143.91 - 96.66 = 47.25 kN.m$$

$$E_f = 165{,}000 MPa$$

$$f_f = 0.007 \times 165{,}000 = 1{,}155 MPa$$

The required area of FRP laminate is:

$$A_f = 47.25 \times 10^6 /(1155 \times 366.67) = 115.57 mm^2$$

Use one 100x1.4 BBR CFL 165 laminate that has an area of: $\underline{100 \times 1.4 = 140 mm^2}$

6.6.3 Summary of three methods

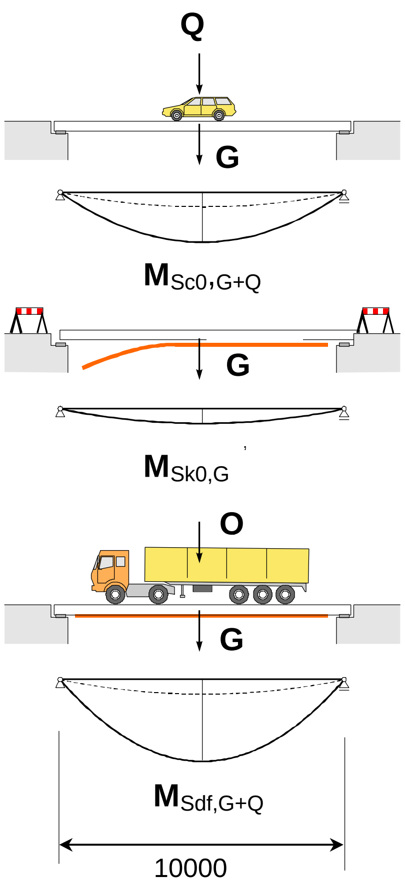
Guideline	Code	FRP Area Required (mm^2)	Laminate used	FRP Area actually used (mm^2)
UK Concrete Society TR 55	BS 8110	112.33	BBR CFL 165 80x1.4	112.00
ACI 400 Draft Guideline	ACI 318	150.88	BBR CFL 165 120x1.4	168.00
German General Guideline	Eurocode 2	115.57	BBR CFL 165 100x1.4	140.00

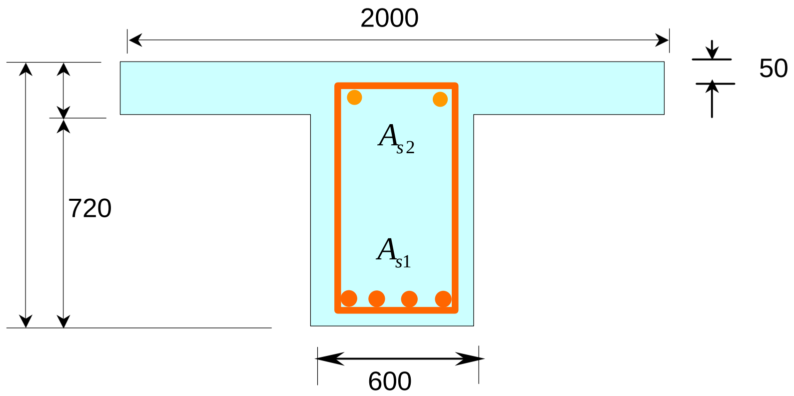
Thus it can be seen that there is quite a spread of FRP requirements, depending on the Guideline and/or loadings code adopted.

6.7 Worked Example No.2

The following worked example is carried out according to the German General Guideline and EC2.

The T-beam bridge requires it live load to be increased from 17.5 kN/m to 50 kN/m Property dimensions are given below:





$$A_{s1} = 4{,}310 mm^2 \qquad G = 35 kN/m \ (including\ slab)$$
$$A_{s2} = 402 mm^2 \qquad Q_{old} = 17.5 kN/m$$
$$A_{s3} = 502 mm^2 \qquad Q_{new} = 50 kN/m$$
$$f_{s,y} = 460 MPa$$
$$f'_{c,cube} = 20 MPa$$
$$FRP = BBR \cdot CFL \cdot 165$$
$$Shear \cdot FRP = BBR \cdot CFS \cdot 640$$

Find the required strengthening using BBR CFL 165 laminates for flexure and BBR CFS 640 sheet for shear.

Initial strain state:

During the application of the FRP, the only loads on the effective T-beam section are the dead load, then:

$$M_{sk0} = 35 \times 10^2 / 8 = 437.40 kN/m$$

Strengthened state:

For the design of the strengthening at both ULS and SLS , the partial safety factors according to EC2 will be used in this example.

$Q_d = 1.35 \times 35 + 1.50 \times 50 = 122.25 kN/m$ = ULS dead load + live load

$Q_k = 35 + 50 = 80 kN/m$ = SLS dead load + live load

$M_{sdf} = 122.25 \times 10^2 / 8 = 1{,}528 kN.m$ = ULS moment

$M_{skf} = 85 \times 10^2 / 8 = 1062.5 kN.m$ = SLS moment

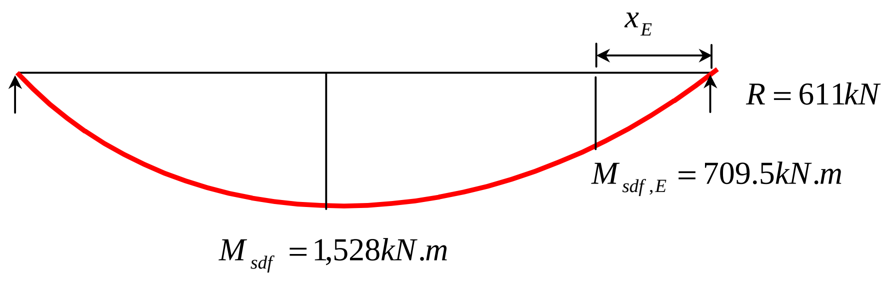


Figure 6.9: Moments of strengthened state.

The as-built moment of resistance $M_{Rd0} = 1{,}367 kN.m$ and the depth to the neutral axis can be calculated according to conventional methods. The neutral axis in this example is located 95.45 mm from the top fibre. The failure mechanism is by steel yielding.

The required design moment in the strengthened state $M_{Sdf} = 1{,}528 kN.m$

The required moment to be resisted by the FRP is $M_{add} = 1{,}528 - 1{,}367 = 161 kN.m$

$E_f = 165{,}000 MPa$

$e_f = 0.0075 = e_{fd}$ for BBR CFL 165

$f_f = 0.0075 \times 165{,}000 = 1{,}237.5 MPa$

The required area of laminate is calculated from the formula:

$$A_f = \frac{M_{add}}{f_{fd} \times z} = \frac{161 \times 10^6}{1{,}237.5 \times (900 - \frac{0.85 \times 95.45}{2})} = 151 mm^2$$

Select 2 laminates BBR CFL 165-80 x 1.4 mm. $A_f = 2 \times 80 \times 1.4 = 224 mm^2$

Check for Bond Conditions:

From the geometry of the support (see Fig. 6.6) and the structural analysis, the following details may be obtained:

$f = 50mm$ = distance from the laminate to edge of the support

$a_i = 150mm$ = distance from support axis to edge of support

$a_L = 875mm$ = horizontal displacement of the tensile force line = tension shift

= Tjd shift

The design value of the substrate strength must be obtained by site testing. The minimum value for laminates is 1.5 MPa.

$$f_{ctm} = 1.5MPa$$

$$f_{ctd} = \frac{f_{ctm}}{g_c} = \frac{1.5}{1.5} = 1.0$$

The maximum bonding force and the design bonding length are able to be derived from the formulae given in equations 6.32 & 6.33, which are obtained from the German Guideline.

$$l_{bd} = 0.6\sqrt{\frac{E_f \times t_f}{f_{ctd}}} = 0.6\sqrt{\frac{165{,}000 \times 1.4}{1.0}} = 288.38mm$$

$$F_{bd} = 0.5 \times b_f \times k_b \times k_t \sqrt{E_f \times t_f \times f_{ctd}}. = 0.5 \times 2 \times 80 \times 1.179 \times 1\sqrt{165{,}000 \times 1.4 \times 1.0}$$

$$= 45{,}333N = 45.33kN$$

where

$$k_b = 1.06\sqrt{\frac{2 - b_f / b_w}{1 + b_f / 400}} = 1.06\sqrt{\frac{2 - 2 \times 80 / 600}{1 + 2 \times 80 / 400}} = 1.179$$

The bond check carried out at point E, which is determined from the geometry of the support and the required bond length for bond force F_{bd}.

$$x_E = l_{bd} + a_i + f + a_L = 288.37 + 150.0 + 50.0 + 875.0 = 1{,}363.37mm$$

Using the distance $x_E = 1{,}363.37mm$ and a reaction at the supports of $R = 611kN$, the bending moment at point E in the ULS is:

$M_{Sdf,E} = 709.5kN.m$ calculated from the structural analysis

The strain in the laminates at the point E is calculated by trial and error (iteration) of the equilibrium state and the resulting force in the laminates is determined.

$$e_{f,E} = 0.0011373$$

$$F_{Fd,E} = E_f \times A_f \times e_{f,E} = 165{,}000 \times 2 \times 80 \times 1.4 \times 0.0011373 = 42{,}035N = 42.04kN$$

$$F_{bd} = 45.33 > F_{fd,E} > 42.04$$

i.e. bonding check is OK

Shear Check:

According to EC2, the design shear force is assumed to be located at a distance d_m from the edge of the support.

$$a_i + d_m = 150 + (900 + 850)/2 = 1{,}025mm$$

$$V_{sdf} = 611 - 122.25 \times 1{,}025/10^3 = 485.4kN$$

It is necessary to calculate the internal lever arm $(z_m = \dfrac{z_s + z_f}{2})$ of the stress diagram from normal principles. For the purpose of this example, z_m is taken to be 827.6mm

The maximum shear resistance is limited to $0.5V_{Rd2}$ by the German General Guideline

$$V_{Rd2} = 0.5 \times n \times f_{ctd} \times b_w \times z_m = 0.5 \times 0.6 \times 2/1.5 \times 600 \times 827.6/10^2 = 1986.24kN$$

where $n = 0.7 - \dfrac{f_{ck}}{200} = 0.6$

$$V_{max} = 0.5 \times V_{Rd2} = 993.12kN$$

$V_{Sdf} = 486kN < V_{\max} = 993.1kN$ Shear check is OK

The proportion of shear force transmitted by the concrete alone is derived from the following:

$$V_{Rd1} = t_{Rd} \times k \times (1.2 + 40 r_1) \times b_w \times d_m$$

where t_{Rd} = shear stress resulting from V_{Rd1}

$$r_1 = \frac{A_{sl}}{b_w \times d_s} = \frac{3030 + 1230}{600 \times 850} = 0.00845$$

$$V_{Rd1} = 0.02578 \times 1 \times (1.2 + 40 \times 0.00845) \times 600 \times 875 / 10^3 = 208.12kN$$

$V_{Sdf} = 486kN > V_{Rd1} = 208kN$ ie, external shear reinforcement is required.

The existing stirrups and the concrete section can transmit the proportion V_{Rd3} of the shear force.

$$V_{wd} = a_{sw} \times f_{yd} \times z_s = 0.0502 \times \frac{460}{1.15} \times \frac{780.1}{10^2} = 156.64kN$$

$$V_{Rd3} = V_{Rd1} + V_{wd} = 208.17 + 156.64 = 364.82kN$$

$$V_{Sdf} = 486kN > V_{Rd3} = 365kN$$

Therefore the strap binder must be anchored in the compression zone.

The shear strengthening is designed for the remainder of the shear force ΔV, however, the minimum required by the German General Guideline is checked.

$$V_{\min} = \frac{h - 1}{h} \times V_{Sdf} = \frac{1.12 - 1}{1.12} \times 486 = 52.05kN$$

$$\Delta V = V_{Sdf} - V_{Rd3} = 486 - 364.81 = 121.19kN > V_{\min}$$

The strain in the steel stirrups and FRP at the section being considered is limited to $e_{\lim} = 0.002$. This ensures that there is an even deformation of the section and avoids shear offset.

Because the shear straps will be hand laminated on site, the reduction faction $S = 1.2$ (see table 6.5) is used.

Hence $$E_{f,d} = \frac{640{,}000}{1.2} = 533{,}333 MPa$$

The stress in the CFRP sheets at a strain of 0.002 is:

$$s_w = e \times E_{f,d} = 0.002 \times 533{,}333 = 1{,}066.67 MPa$$

The theoretical FRP required is determined as follows:

$$a_f = \frac{\Delta V}{s_f \times z_f} = \frac{121.19 \times 10^6}{1066.67 \times 852.6} = 133 mm^2 / mm$$

For each side of the web, half of this area is required.

The design thickness of the BBR CFS 640 is:

$$t_f = \frac{mass\ of\ sheet}{density\ of\ sheet} = \frac{400(gm/m^2)}{2.1(gm/cm^3)} = 0.19 mm$$

Thus the required strap width is:

$$w_f = \frac{a_f/2}{t_f} = \frac{133/2}{0.19} = 350 mm/m$$

A roll of BBR CFS 640 has a width of 300mm. Thus the required spacing of the strap binder is calculated as:

$$req\ s_w = \frac{300}{350} = 0.857 m = 857 mm$$

The maximum spacing as determined by the truss model must be considered:

$$\max s_w = d_m = \frac{900 + 850}{2} = 875 mm$$

$req\ s_f < \max s_f$ therefore space at 857mm, say, 860mm

As the internal shear reinforcement is not sufficient to carry the required shear force, the additional strap binders must be anchored in the concrete compression zone.

As a check to this manual calculation, the programme for EC2 given on the web page **www.frp.at** may be used.

6.8 References

R6.1 The Concrete Society (UK): *Technical Report No. 55 – Design guidance for strengthening concrete structures using fibre composite materials* – ISBN 0 946691 843, 2000.

R6.2 American Concrete Institute ACI 440: *Guide for the Design and Strengthening of Externally Bonded FRP Systems for Strengthening Concrete Structures*-draft report dated 12 July 2000 by ACI Committee 440, American Concrete Institute, 2000.

R6.3 German General Guideline: *Richtlinie für das Verstärken von Betonbauteilen durch Ankleben von unidirektionalen kohlenstoffaserverstärken Kunststofflamellen*, Fassung September 1998, Deutsches Institut für Bautechnik, Berlin.

R6.4 Clarke J.L: *Structural design of polymer composites* – EUROCOMP design code and handbook – E & F N Spon, London, 1996.

R6.5 Blaschko, M; Neidermeier, R and Zilch, K: *Bond failure modes of flexural members strengthened with FRP* – Proceedings of the Second International Conference on Composites in Infrastructure, University of Tucson, Arizona, 1998, Vol1, pp 315-327.

R6.6 Neubauer, U and Rostasy, F.S: *Design aspects of concrete structures strengthened with externally bonded CFRP plates* - Concrete and Composites, Proceedings of the 7th International Conference on Structural Faults and Repair, 1997, Vol 2, pp 109 – 118, ECS Publications, Edinburgh.

R6.7 Onken, P and vom Berg, W: *Biegezugverstärkung mit CFK Lamellen –Neues Bemessungsmodell nach EC2 und DIN 1045-1*, Beton und Stahlbetonbau 96,,2/2001, pages 61-70.

R6.8 Bull, D and Sivyer, Z: *Retrofit with FRP Composites*- Holmes Culley Technical Memorandum October 2001

R6.9 Rostasy, FS; Holzenkämpfer, P and Hankers, C:- *Geklebte Bewehrung für die Verstärkung von Betonbauteilen*; - Beton-Kalender 1996, T.II, Berlin: Ernst & Sohn 1996.

7. Design for Shear Strengthening

7.1 Introduction

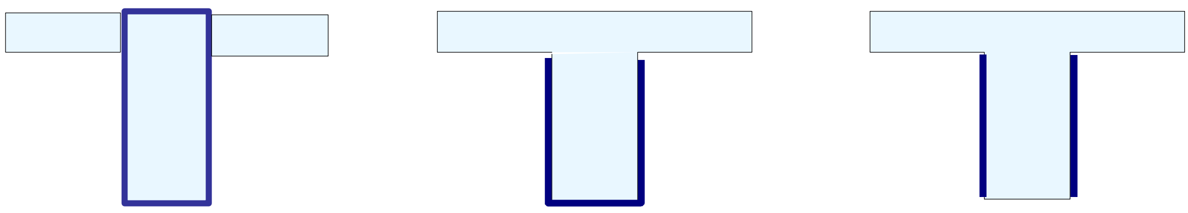
Externally bonded FRP sheets can be used to increase the shear strength of reinforced concrete beams and columns. The shear strength of columns can be improved by wrapping with a continuous sheet of FRP to form a complete ring around the member. Shear strengthening of beams however, is likely to be more problematic when the beams are cast monolithically with slabs. Attention needs to be paid to anchoring the FRP at or through the beam/slab junction, ensuring that full anchorage occurs above the neutral axis (ie, in the compression zone). The FRP should be placed such that the principal fibre orientation, b , is either 45^o or 90^o to the longitudinal axis of the member.

Increasing the shear strength can also promote ductile flexural failures.

ACI 440 [R7.5] recommends that beams and columns on moment frames resisting seismic loads, at locations of expected plastic hinges, or at locations where stress reversal and post-yield flexural behaviour is expected, should only be strengthened for shear by completely wrapping the section with strips spaced less than $h/4$ (clear spacing) where h is the depth (width) of the member.

7.2 Types of shear wraps

There are three types of shear wraps suitable for increasing the shear strength of rectangular beams or columns (Figure 7.1).



Full wrap ***3-sided wrap*** ***2-sided wrap***

Fig 7.1: Types of wrapping systems for shear enhancement

Complete wrapping of the FRP around the section is the most efficient, followed by the 3-sided and the 2-sided wrap. In beam applications, especially T-beams where the neutral axis is mostly found in the slab portion of the beam, it is necessary to ensure the FRP is anchored in the compression zone (above the neutral axis). This is achieved by passing the FRP strip through slots cut in the slab and anchoring it on the top of the slab. Alternatively, anchors capable of transmitting the force from the FRP through into and beyond the mild steel reinforcement stirrups, can be used, if proper detailing of the load transfer from FRP to anchor is considered. **The 3-sided and 2-sided wraps should be used with absolute caution.**

7.3 Design principles

7.3.1 Introduction and Background

The UK Concrete Society TR 55 [R7.1], German General Guideline and ACI 440 (draft) [R7.5] all treat the shear situation differently. Depending on whether you are in an area where ACI 318 is used (global safety factors), or in Europe (partial material reduction factors), the requirements are quite different. Users of this manual are recommended to study the appropriate code/guidelines, for detailed use.

Current research on shear strengthening with bonded FRP suggests that, as with conventional reinforced concrete, shear failure will occur due to two basic mechanisms, diagonal tension (resisted by shear stirrups) and diagonal compression (resisted by inclined concrete compression struts in tie and strut model).

We set down below a summary of the requirements of each of the three guidelines. This is not exhaustive and readers are advised to consult the appropriate document they are working to.

7.3.2 UK Concrete Society TR 55 – BS8110

7.3.2.1 General Principles

According to TR 55, diagonal compression failure is normally avoided by limiting the maximum shear stress in the concrete. Clause *3.4.5.2* of BS 8110, postulates that the maximum permissible shear stress, $n_{\max}$ should be taken as the lesser of $0.8\sqrt{f_{cu}}$ or *5* MPa, regardless of the what shear reinforcement is provided. TR 55 recommends therefore, that the same criterion be used in the design of FRP shear-strengthened members. The maximum allowable design shear force due to ultimate loads, $V_{R,\max}$, at any cross-section, is then obtained from:

$$V_{R,\max} = n_{\max} b_w d \tag{7.1}$$

where $b_w =$ width of section

$d =$ effective depth of section

Diagonal tension failure is possible if the shear demand force, V_{sd} , is greater than the shear resistance of the existing section, V_{Re} . The latter can be evaluated if the shear resistance of the concrete and the shear resistance provided by any steel links (stirrups) in the member are known, i.e.

$$V_{\mathrm{Re}} = V_{Rc} + V_{Rs} \tag{7.2}$$

The shear resistance of the steel links (stirrups), V_{Rs}, and of the concrete, V_{Rc}, should be determined in accordance with standard procedures described in various codes.

The design shear stress n can be calculated from the imposed shear force V_{sd} and the geometry of the section. Failure plains inclined at 45^0 are assumed.

The flowchart (Fig.7.3) indicate the respective equations for determining the shear stress and hence the amount of FRP reinforcement.

- n_c is the shear resistance without shear reinforcement – shear force is transmitted by concrete alone
- $n_{\max}$ is the maximum shear resistance – the capacity of the inclined compression struts is essential for the shear resistance
- n_{c+s} is the shear resistance with shear reinforcement – the shear force transmission results from the sum of resistance from the concrete and steel shear reinforcement.

The design stress n_c is the value used for slabs which are usually built without shear reinforcement. $n_{\max}$ is the uppermost limit which must not be exceeded. In the case of elements without shear reinforcement (usually slabs), the partial safety factor for concrete g_c may be reduced to 1.25 according to BS 8110.

BS 8110, in a similar way to the German General Guideline, makes a distinction between several different cases for the shear force capacity of a member.

- $n \le n_c$ No additional strengthening is required and n is determined with partial factors of safety given in table 6.1.

- $n \le n_{c+s}$ Where the shear demand is completely covered by the existing stirrups, it is still necessary to use additional FRP strengthening straps to complete the truss model. The shear stress difference Δn depends on the strengthening ratio h and links the additional tension chord force of the laminates with the internal tension struts of the truss model.

$$\Delta n = \frac{h-1}{h} \times n$$

In such a case, it is not necessary to anchor the reinforcement straps in the compression zone. The fact that the additional shear reinforcement in the form of external bonded straps is necessary despite the sufficient internal shear reinforcement is justified by the beam design truss analogy. The externally bonded FRP laminates must be connected to the internal stirrups for completion of the truss model (see Fig. 7.5).

- $n > n_{c+s}$

$$\Delta n = n - n_{C+S}$$

Where the shear stress demand in the strengthened state exceeds the shear capacity of the existing section, strengthening must be designed for the excess Δn. As the additional reinforcement must cover Δn over the full section, the external straps must be anchored in the compression zone.

- $n \le n_{\max}$

$$n_{\max} = 0.5^{*}(0.8\sqrt{f_{cu}}) \le 2.5MPa$$

The maximum shear resistance $n_{\max}$ is the upper limit of shear resistance in the strengthened state. The German General Guideline does not allow the strengthening of beams with very high shear forces. (*)BBR recommends that this limitation be imposed also, when using BS 8110. Reducing the maximum shear capacity to 50% corresponds more-or-less with the limitation given in the German General Guideline.

Even if additional shear straps are not required to satisfy the shear force condition**, it is recommended by BBR that the FRP laminates be bound at their ends with at least 2 strap binders, which are anchored in the compression zone.**

Where the design shear force exceeds the combined shear resistances of the concrete and steel links, FRP shear reinforcement will be needed. The amount of FRP required can be calculated using the same principles as in conventional reinforced concrete design, that is, assuming a crack pattern and multiplying the area of the FRP reinforcement intersecting the potential crack, $A_{fs}(d_f / s_f)$ by the failure stress $E_{fd} e_{fc}$. Thus, assuming that shear cracks are inclined at 45^{o} to the longitudinal axis of the member, TR 55 provides that the shear resistance of the FRP is given by:

$$V_{Rf} = (1/g_{mF}) A_{fs} (E_{fd} e_{fe}) \sin b (1 + \cot b)(d_f / s_f) \tag{7.3}$$

where A_{fs} = area of FRP shear reinforcement

= $2 t_f w_{fe}$ assuming that the FRP is placed on both sides of the member

w_{fe} = effective width of the FRP, which is a function of the shear crack angle and FRP strengthening configuration, equal to $d_f - L_e$ where FRP is in the form of a U-jacket (see fig 7.1) and $d_f - 2L_e$ where FRP is bonded to the side faces only (see fig 7.2)

L_e = effective bond length $= 461.3/(t_f E_{fd})^{0.58}$

e_{fd} = design strain in the FRP

b = angle between FRP and the longitudinal axis of the member (45^o or 90^o)

d_f = effective depth of FRP shear reinforcement, usually equal to d for rectangular sections and ($d -$ slab thickness) for T-sections

s_f = spacing between the centre line of FRP plates (see Section 7.4). Note that for continuous sheet reinforcement $s_f = w_{fe}$

l_{mF} = partial safety factor for FRP

To calculate the shear resistance of the FRP, the design strain in the FRP must be evaluated. Its value depends on the failure mode of the FRP-strengthened member. Basically, failure can arise from three possible mechanisms:

- loss of aggregate interlock
- FRP rupture
- Delamination of the FRP from the concrete surface.

7.3.2.2 Limiting Design strain in FRP

The following section, taken from TR 55 [R7.1], briefly discusses each of these mechanisms and gives guidance to the calculation of the design strain in the FRP.

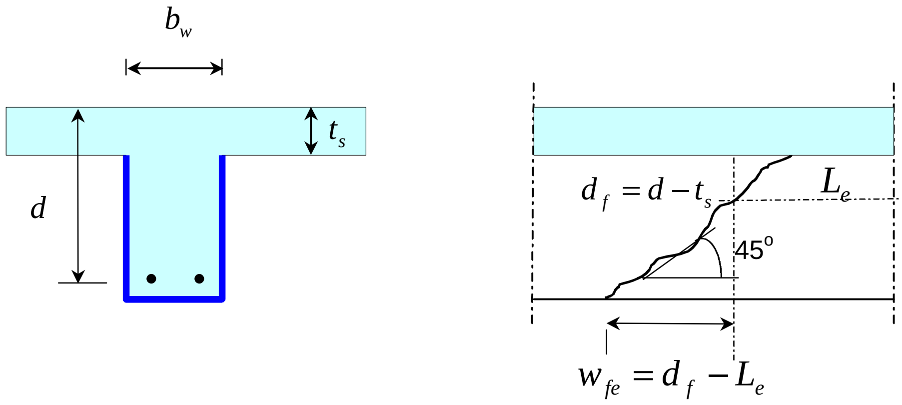


Fig 7.2: FRP in the form of a U-jacket

"*It is well established that the shear capacity of a reinforced concrete beam without links (stirrups) is a function of the aggregate interlock across flexural cracks. This is estimated to account for between 35% and 50% of the total shear resistance of the member. If the shear crack width becomes too large, aggregate interlock will be lost, and this will significantly reduce the shear capacity of the member. The strain in the FRP must therefore be limited. A steel strain limit of 0.0023 is implied in BS 8110, which specifies that the characteristic strength of steel shear reinforcement should not be taken as greater than 460 MPa. However, laboratory tests on FRP wrapped beams and columns show that this strain limit is conservative and that a value of 0.004 is more realistic. On this basis it is recommended that the maximum strain in the FRP should not exceed 0.004".* – TR 55

Because of stress concentrations at corners, debonded areas, etc, TR 55 points out that FRP rupture can occur at strains far below the ultimate value. Triantafillou [R7.2] has shown that the failure strain is a function of the axial rigidity of the FRP sheet. This approach has been used by Khalifa et al. [R7.3] to derive the following relationship (assuming $r_f E_f < 1.1$ MPa) to estimate the failure strain, e_{fe}, in the FRP due to this mechanism:

$$e_{fe} = e_{fu}[\{0.5622(r_f E_{fd})^2 - 1.2188(r_f E_{fd}\} + 0.778] \qquad (7.4)$$

where e_{fu} = design ultimate failure strain in FRP

= e_{fk} / g_{mf} (from TR 55)

r_f = FRP shear reinforcement ratio

= $(2t_f / b_w)(w_f / s_f)$ for beams strengthened with FRP laminate strips,

and $2t_f / b_w$ for beams strengthened with continuous FRP sheet.

E_{fd} = design elastic modulus of FRP (GPa)

TR 55 points out that Equation 7.4 is essentially empirical and based predominately on tests on small beams strengthened with carbon FRP. Extrapolation of this equation to large beams or those strengthened using other materials should be undertaken with caution.

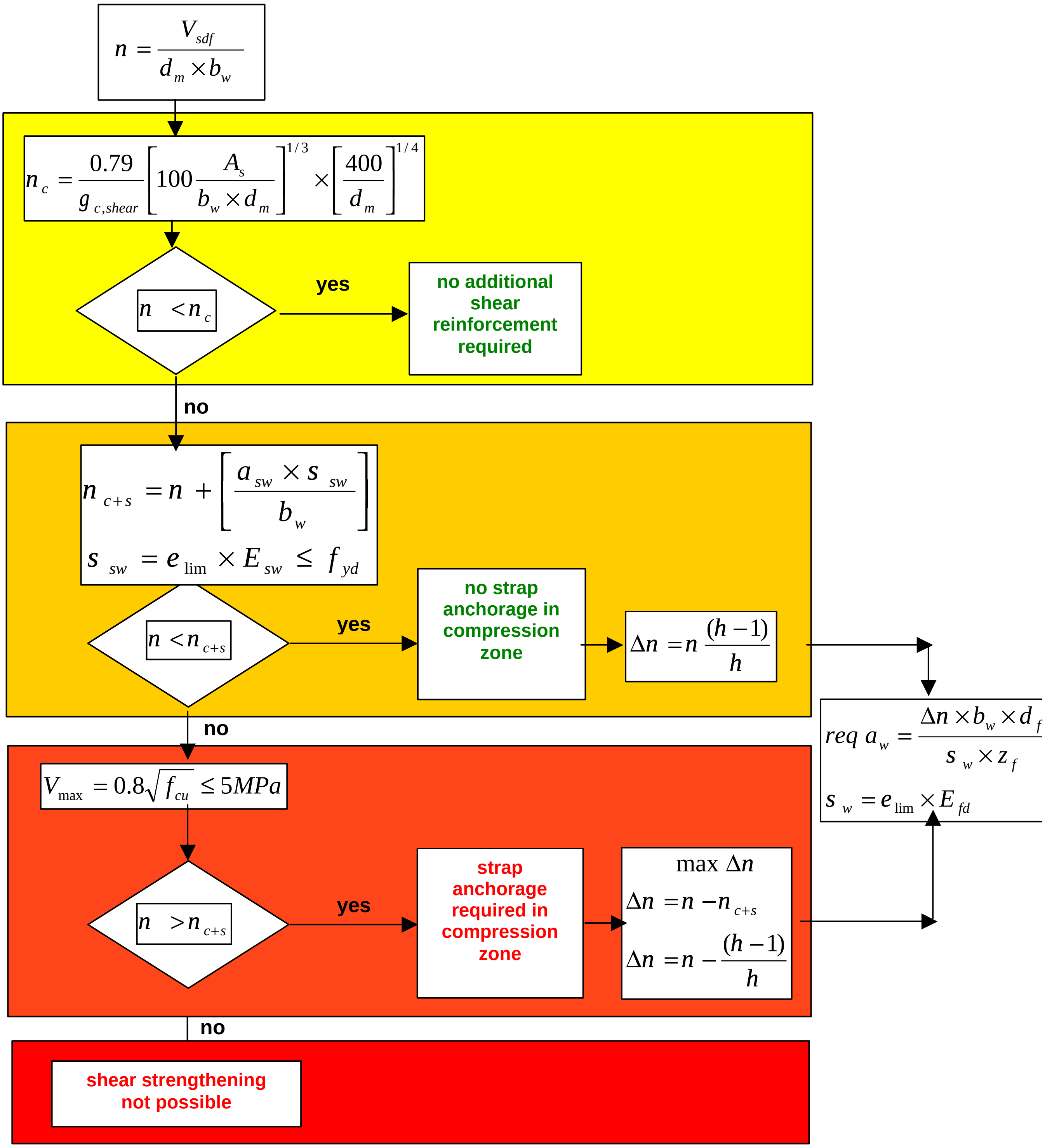


Fig 7.3: Flowchart for check of shear, according to BS 8110 [R7.8]

Circumferential wrapping of concrete members with FRP avoids the problem of bond failure, although care should be taken before neglecting the possibility of debonding of the FRP from the concrete for large beams or when the thickness of the FRP provided is in excess of the range of thicknesses used in the tests summarised by Khalifa et al. [R7.3] Where circumferential wrapping is not possible, the risk of debonding failure is high. Based on work by Maeda et al. [R7.4], Khalifa et al. [R7.3] have proposed the following expression, which can be used to estimate the failure strain in the FRP due to bond failure

$$e_{fe} = \frac{0.0042 \times [(0.835 f_{cu})^{2/3} \times w_{fe}]}{[(E_f tf)^{0.58} \times d_f]} \tag{7.5}$$

where f_{cu} = cube strength of concrete (MPa)

w_{fe} = effective width of FRP (mm) (see Figure 7.2)

E_{fd} = design elastic modulus of FRP (GPa)

A member will fail in shear when any of the above limiting strains are exceeded. TR 55 recommends therefore that the design strain should be taken as the lesser of 0.004 and the strains given by Equations 7.4 and *7.5.*

For large structures TR 55 points out that it will also be necessary for the designer to consider whether it is reasonable to assume that such limiting strains will be achieved along the full length of a shear crack or whether a propagating failure might be initiated. Experimental work on large specimens has been limited. However, because of the brittle nature of FRP and its bond characteristics, some size effect would seem to occur, whereby strength does not increase in proportion to size.

7.3.3 ACI 440 Draft

7.3.3.1 General Principles

As for other guideline principles, ACI 440 requires that the ultimate shear strength of a concrete member strengthened with an FRP system must exceed the shear demand. It recommends that the shear demand on an FRP strengthened concrete member be calculated with the load factors required by ACI 318 and the shear strength be calculated using the strength reduction factor f , required by ACI 318.

$$f V_n \geq V_u$$

ACI 440 postulates that the nominal shear capacity of an FRP strengthened concrete member is determined by adding the contribution of the FRP reinforcing to the contributions from the reinforcing steel (stirrups, ties or spirals) and the concrete. An additional reduction factor, y_f , is applied to the contribution of the FRP system.

Hence $fV_n = f(V_c + V_s + y_f V_f)$

The additional reduction factor, y_f, is selected based on known characteristics of the application but should not exceed 0.85 for two or three sided wraps. ACI 440 suggests the following values:

$y_f = 0.95$ for completely wrapped elements

$y_f = 0.85$ for two or three sided wraps or bonded face plates.

7.3.3.2 Limiting Design strains on FRP

ACI 440 (draft) bases strain limitations on work carried out by Priestley et al [R7.6] and differentiates between the three types of shear wrap illustrated in Figure 7.1. In general:

$e_{fe} = 0.004 \leq 0.75e_{fu}$ (for completely wrapped applications)'

For bonded 3-sided wraps or 2-sided face plies, the allowable strain is reduced by a factor k_v, which takes into account the bond stresses and the usefulness of such systems. In such cases

$$e_{fd} = k_v e_{fu} \leq 0.004 \leq 0.75e_{fu}$$

where k_v is known as the bond reduction coefficient which varies from 1.00 for a 4 sided wrap to something less for other wraps. It depends on the type of wrapping, the concrete strength and the stiffness of the laminate. For further information, see sections 10.4 of ACI 440 (draft) [R7.5].

7.3.4 German General Guideline and EC2

EC2 and the German General Guideline are very precise in their treatment of concrete elements strengthened in shear with FRP.

Similar to BS 8110, there are three categories of shear, viz;

- V_{Rd1} shear resistance without shear reinforcement – shear force is transferred by concrete alone.
- V_{Rd2} maximum shear resistance – the capacity of the inclined compression struts is essential for the shear resistance.

- V_{Rd3} shear resistance with shear reinforcement – the shear force transmission results from concrete and shear reinforcement.

Hence a distinction must be made between the different cases when considering the shear capacity of a strengthened concrete structure.

- $V_{Sdf} \leq V_{Rd1}$, no additional strengthening is required.

- $V_{Sdf} \leq V_{Rd3}$, the shear force in the strengthened state can be completely carried by the existing stirrups. Additional shear reinforcement is still necessary to complete the mechanical truss model then the difference ΔV is carried by additionally placed FRP, depending on the strengthening ratio. It links the additional tension chord force of the laminates with the internal tension struts of the truss model [R7.5].

$$\Delta V = \frac{h-1}{h} \times V_{Sdf}$$

In such a case, it is not necessary to anchor the additional shear reinforcement in the compression zone.

The fact that additional shear reinforcement in the form of external strap binders is necessary despite the adequacy of the internal steel shear reinforcement is justified by the beam design truss analogy (Fig 7.5).

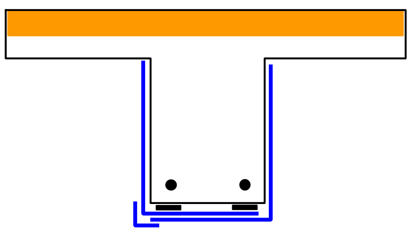


Fig 7.4: No anchorage in the compression zone

- $V_{Sdf} \geq V_{Rd3}$, ie the shear force demand in the strengthened state exceeds the shear capacity of the existing section, the shear strengthening must be designed to carry the remaining amount of shear force.

$$\Delta V = V_{Sdf} - V_{Rd3}$$

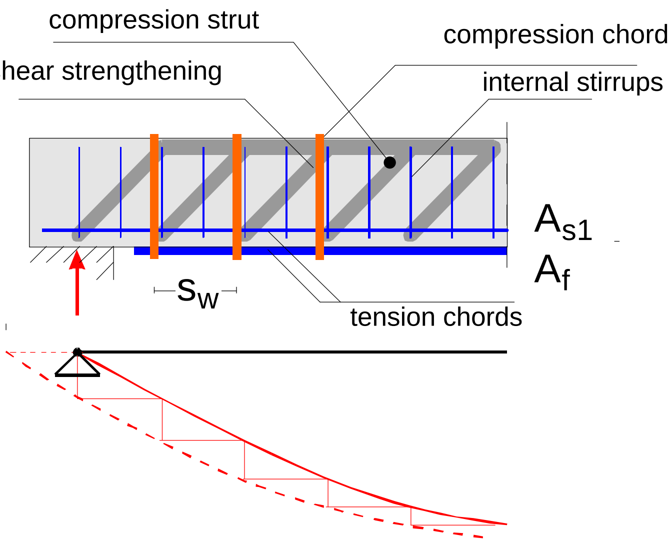


Fig. 7.5: Connection of the FRP shear strengthening to the internal truss structure [R7.8]

Since the additional shear reinforcement is required to cover the total shear force of the section, the external strap binders must be anchored in the compression zone (fig. 7.5)

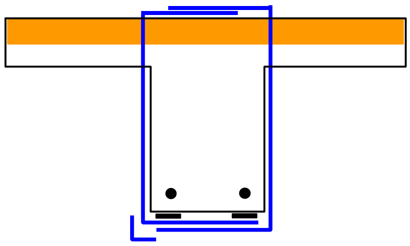


Fig 7.6: Anchorage in the compression zone required

The maximum shear resistance V_{Rd2} is the upper limit of the shear force for the strengthened state as well. However, the German General Guideline [R7.7] does not permit shear strengthening of beams with very high shear force and limits the maximum shear capacity to 50% of the maximum shear force.

Thus: $V_{Sdf} \leq V_{\max}$

$$V_{Sdf} \leq 0.5 \times V_{Rd2}$$

Even if additional shear straps are not required to satisfy the shear force condition**, it is recommended that the FRP laminates be bound at their ends with at least 2 strap binders, which are anchored in the compression zone.**

The development of the shear force reinforcement design is summarised in the flowchart given in Fig, 7.7[R7.8].

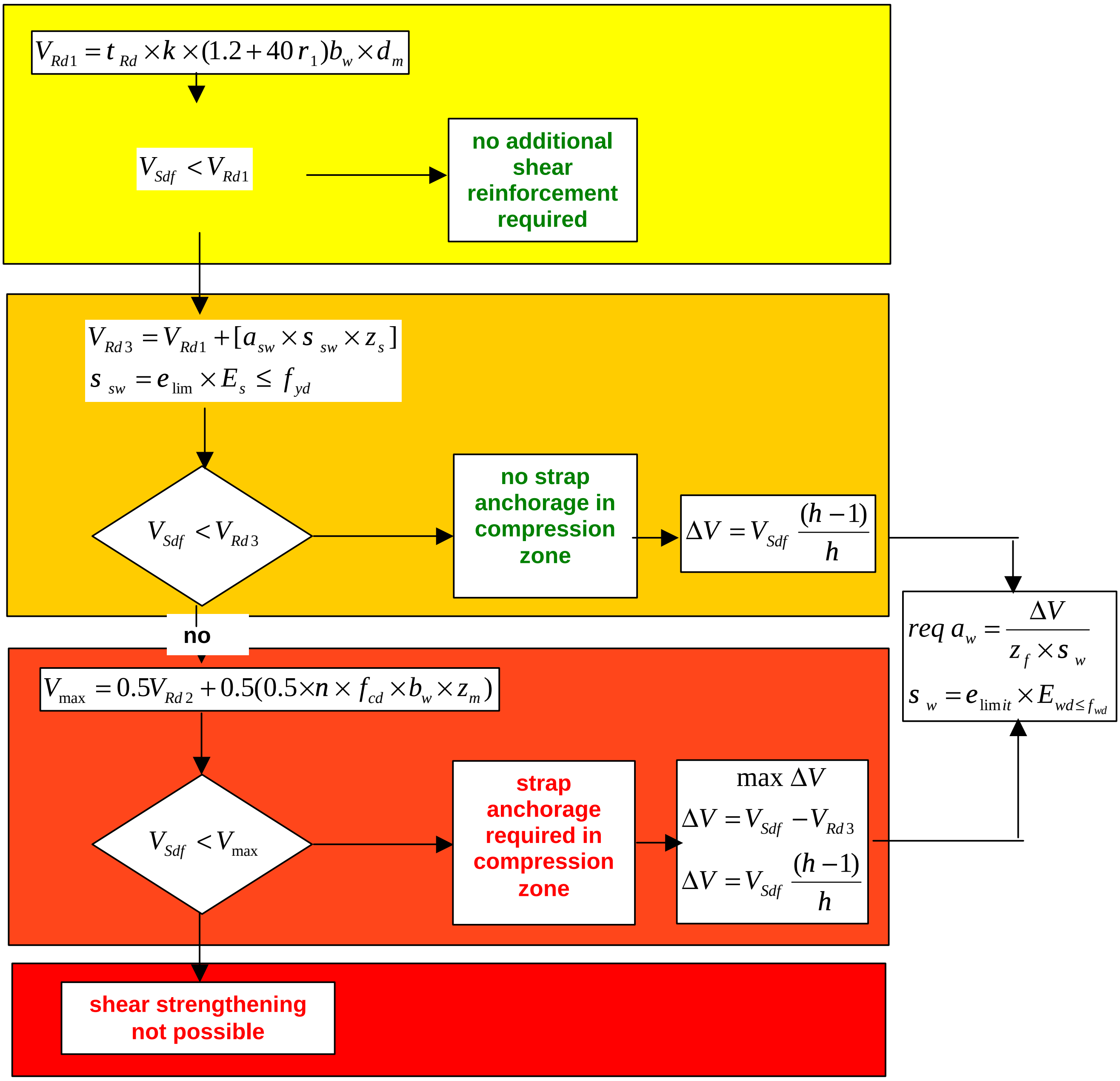


Fig 7.7: Flowchart for check of shear, according to EC2

7.4 Additional Axial FRP

TR 55 postulates that by using the truss analogy it can be shown that beam and column elements subject to a shear force will experience axial tensile forces, additional to those due to bending. Additional axial reinforcement may therefore be required when strengthening for shear. The standard method is to simply extend the axial FRP reinforcement a distance of half the effective depth beyond the point at which it is no longer required for bending. If this is not possible, extra axial FRP, A_{fa}, should be determined from:

$$A_{fa} = V_s / 2 f_f \tag{7.6}$$

where V_s = shear force due to ultimate loads

f_f = strain in the FRP equal to the strain at the same location determined from a flexural analysis.

A third possibility arises when no axial FRP is present for bending. In this case, the ultimate bending capacity of the member should be re-evaluated assuming the area of each axial reinforcing bar between the tension face and the mid-depth of the section is reduced by an amount equal to:

$$\frac{V_s}{2n_e(f_y / g_{ms})} \tag{7.7}$$

where n_e = total number of effective axial reinforcing bars within this region in the section being considered.

Any shortfall in bending capacity should be compensated for by providing axial FRP reinforcement.

7.5 Spacing of FRP Laminate Strips

As in the case with steel shear reinforcement, the spacing of FRP laminate strips should not be so wide as to allow the full formation of a diagonal crack without intercepting a strip. For this reason, if laminate strips are used, their spacing should not exceed the lesser of $0.8d$ and $w_f + d/4$ where d the effective depth of the beam and w_f the width of the FRP laminate strips.

7.6 References

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8. Design for Axial Load Enhancement

8.1 Introduction

Retrofitting to enhance the axial compressive strength of concrete members using FRP material is commonly used. By wrapping a column with an FRP jacket, the shear, moment and axial load capacity, as well as the ductility, are improved. The column is wrapped with the FRP fibres in the hoop direction and this provides significant confinement to the concrete, thus leading to improvement in performance.

Both GFRP and CFRP are very effective in enhancing axial performance. Creep of GFRP is not a concern with column wrapping because under normal service loads, the jacket remains virtually stress free.

Both circular and rectangular columns are able to be enhanced with FRP jackets. The most effective situation is the circular or oval jacket, but reasonable enhancement of rectangular columns is achievable, although less than that of square or circular columns.

The original theory and experimental work was carried out by Priestley [R8.1] in 1988 and this has been followed by much research by others. The basis of the theory given below comes from the research work carried out by Wang Yung-Chih from 1996 – 2000, at the School of Engineering, University of Canterbury, New Zealand [R8.2].

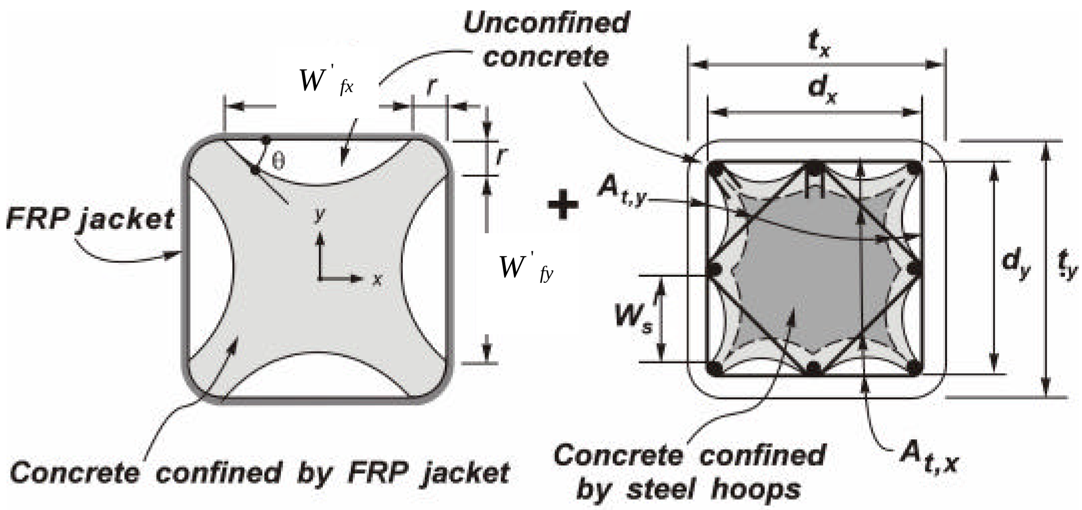

Figure 8.1 Dual Confinement Effect on a Rectangular Column with a FRP Jacket and Internal Steel Hoops

8.2 Evaluation of the Axial Compressive load – Axial Deformation Response

Figure 8.1 shows a cross section of a reinforced concrete rectangular column that is confined by an FRP jacket.

The concentric compressive load carried by a short reinforced concrete column, P , is given by

$$N = N_c + N_s \tag{8.1}$$

where $$N_s = f_s A_s \tag{8.2}$$

and $$N_c = N_{c0} + N_{cc,f} + N_{cc,fs}$$

$$= f_{c0} A_{cu} + f_{cc,f} A_{cf} + f_{cc,fs} A_{c,fs} \tag{8.3}$$

where N_c and N_s are the compressive loads carried by the concrete and the longitudinal reinforcing bars, respectively. A_s is the area of longitudinal reinforcement and f_s is the compressive stress in the longitudinal reinforcement.

The concentric compressive strength N_n is, from equation (8.1):

$$N_n = N_{cn} + N_{sn} \tag{8.4}$$

where N_{cn} and N_{sn} are the nominal compressive strengths carried by the concrete and the longitudinal reinforcing steel bars, respectively, when the axial compression reaches the ultimate state of the column. Wang et al [R8.2] assume that the ultimate limit state in a concentrically loaded column is associated with 1% axial strain. With Poisson's ratio conservatively assumed to equal n = 0.5, at this strain level, the transverse strain at 1% axial strain is equal to 0.5%.

Wang et al [R8.2] have assumed the reinforcing steel behaves as an elasto-plastic material. The nominal compressive strength carried by the concrete, N_{cn}, results from the stresses in three distinct regions shown in **Figure 8.1**. At 1% axial strain the unconfined concrete has reached its peak strength, f'_c, and has degraded to a residual strength to $0.3 f'_c$ [R8.7]. From Eqs.8.2 & 8.3 with $f_{c0} = 0.3 f_c'$

$$N_{sn} = f_{sy} A_s \tag{8.5}$$

$$N_{cn} = 0.3 f'_c A_{cu} + f'_{cc,f} A_{cj} + f'_{cc,fs} A_{cfs} \tag{8.6}$$

where $f_{cc,f}$ and $f_{cc,fs}$ are the confined concrete compressive strengths due to the single confinement of the external jacket and the dual confinement of the jacket and steel hoops, respectively. A_{cu} , A_{cf} , and

A_{cfs} are the confined areas with respect to different confining regions. f_{sy} is the yield strength of longitudinal reinforcement and A_s is the area of longitudinal reinforcement.

For design purposes it is necessary to reduce the nominal concentric strength given in Eq.8.4, to account for variations in the materials properties, scatter in the design equation, bending of the columns, nature and consequences of failure and reduction in load carrying capacity under long-term loads. For the purpose of this discussion, the method of partial safety factors, as used by BS 8110 and EC2 is used. This reduction results in a dependable concentric strength, N_n, for short columns given by,

$$N_{nd} = \frac{0.67}{g_{mc}} N_{cnk} + \frac{N_{sn}}{g_{ms}} \qquad (8.7a)$$

or

$$N_{nd} = \frac{0.788}{g_{mc}} N_{cnc} + \frac{N_{sn}}{g_{ms}} \qquad (8.7b)$$

where g_{mc} and g_{ms} are the partial safety factors for concrete and steel respectively, N_{cnk} and N_{cnc} are the compressive forces carried by the concrete if derived from the cube or cylinder strengths respectively and N_{sn} is the compressive force carried by the reinforcing steel.

Using $g_{mc} = 1.5$ and $g_{ms} = 1.15$, equation 8.7 can be written as:

$$N_{nd} = 0.447 N_{cnk} + 0.87 N_{sn} \qquad (8.8a)$$

or

$$N_{nd} = 0.525 N_{cnc} + 0.87 N_{sn} \qquad (8.8b)$$

Therefore, Eq.8.8 becomes,

$$N_{nd} \geq N^* \qquad (8.9)$$

where N^* is the design concentric axial load in the column.

The compressive load carried by the concrete, N_c, results from the loads sustained by three distinct regions. In Eq.8.3, N_{c0} is the load carried by the unconfined concrete region, A_{cu}, and f_{c0} is the compressive stress of unconfined concrete. $N_{cc,f}$ is the load carried by the effective area of concrete confined by the FRP jacket, $A_{c,f}$, and $f_{cc,f}$ is the confined area and compressive stress of concrete confined by the FRP jacket, respectively. $N_{cc,fs}$ is the load carried by the effective area of concrete A_{cfs}, confined by both the FRP jacket and the steel hoops, and $f_{cc,fs}$ is the corresponding stress. Hence, the entire uni-axial stress-strain relationship for a concentrically loaded column wrapped with an FRP jacket can be obtained if the constitutive stress-strain relationships for each of the regions and for the reinforcing steel are known.

The area of effective confining core confined by the steel hoops can be ignored in most practical applications. The area of effective confining core for the FRP jacket is given by the following expression:

$$A_{cu} = A_{cc,f} - A_{e,f} \tag{8.10}$$

where $A_{cc,f}$ is the area of concrete confined by the jacket and $A_{e,f}$ is the area of concrete effectively confined by the jacket.

In the case of a rectangular column, the areas, $A_{cc,f}$ and $A_{e,f}$ are given by,

$$A_{cc,f} = t_x t_y - A_s - (4 - pr^2)r^2 \tag{8.11}$$

$$A_{e,f} = t_x t_y - \frac{w'_{fx}{}^2 + w'_{fy}{}^2}{3} - A_s - (4 - p)r^2 \tag{8.12}$$

Figure 8.1 defines the variables used in above equations. The area of concrete effectively confined by the jacket, $A_{e,f}$, is limited by $w'_{fx} < 2w'_{fy}$ when the longer side is w'_{fx} or by $w'_{fy} < 2w'_{fx}$ when the longer side is w'_{fy}.

In the case of a circular column, see Figure 8.2,

$$A_{cc,f} = A_{e,f} = \frac{pD^2}{4} - A_s \tag{8.13}$$

where D is overall column diameter. It can be seen that $A_{cc,f} = A_{e,f}$ makes $A_{cu} = 0$ and consequently the confined effectiveness of circular column is greater than that for a rectangular column.

8.3 Determination of the Compressive Strength of the Confined Concrete

The compressive strength of confined concrete, as proposed by Mander et al [R8.6], f'_{cc} is given by:

$$f'_{cc} = k_c f'_c \tag{8.14}$$

in which f'_c is the cylinder concrete strength and k_c is the concrete strength enhancement factor. Factor k_c depends on the bi-axial state of stresses induced by the lateral confining pressures. This factor is expressed as:

$$k_c = a_1 a_2 \tag{8.15}$$

where a_1 is a strength enhancement factor that considers the concrete to be subjected to a tri-axial stress state with bi-equal confining stresses and a_2 is a reduction factor that considers any deviation from bi-equal confining stress concept.

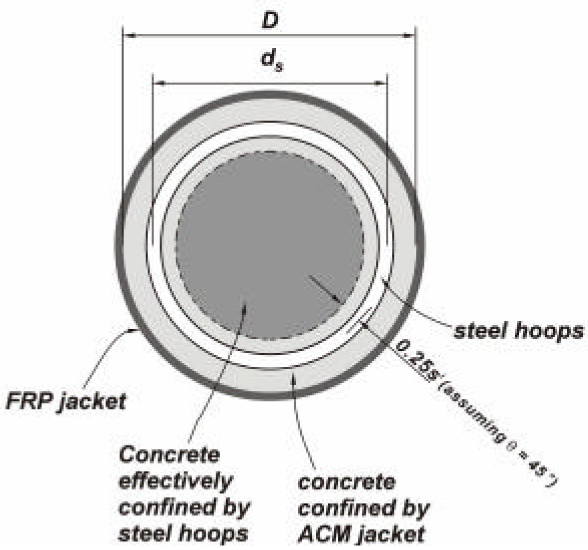

Figure 8.2 Dual Confinement Effect on a Circular Column with an FRP Jacket and Internal Steel Hoops

Mander further proposed that:

$$a_1 = 1.25\left(1.8\sqrt{1+7.94\frac{F_l}{f'_c}} - 1.6\frac{F_l}{f'_c} - 1\right) \tag{8.16}$$

and that

$$a_2 = \left[1.4\frac{f_l}{F_l} - 0.6\left(\frac{f_l}{F_l}\right)^2 - 0.8\right]\sqrt{\frac{F_l}{f'_c}} + 1 \qquad (8.17)$$

In the above equations, F_l and f_l are the maximum and minimum confining lateral stresses, respectively.

8.4 Evaluation of the Lateral Confining Pressure

To calculate the concrete strength enhancement factors, the lateral confining pressure must be found. The evaluation of the lateral confining pressure due to an elastic jacket and internal reinforcing steel hoops for rectangular and circular columns is derived below.

8.4.1 Confinement provided by the FRP Jacket

8.4.1.1 Rectangular columns

The lateral confining stresses induced by an FRP jacket in the x and y directions, $f_{l,fx}$ and $f_{l,fy}$, are,

$$f_{l,fx} = r_{fx} f_f \qquad (8.18)$$

$$f_{l,fy} = r_{fy} f_f \qquad (8.19)$$

where f_f is the stress in the FRP jacket. The reinforcement ratios r_{fx} and r_{fy} are defined as,

$$r_{fx} = 2\frac{t_f}{t_y} \qquad (8.20)$$

$$r_{fy} = 2\frac{t_f}{t_x} \qquad (8.21)$$

where t_f is the nominal jacket thickness and t_x and t_y are the overall column cross section dimensions.

The stress in the jacket can be found from transverse strain compatibility. Assuming $n = 0.5$ and for 1% axial strain, the transverse strain is 0.5%, hence the stress in the jacket is:

$$f_f = 0.005 E_f / g_{mE} \qquad (8.22)$$

where E_f is the modulus of elasticity of the FRP material and g_{mE} is the partial safety factor for the modulus of elasticity. [R8.9] recommends $g_{mE} = 1.1$ for CRFP.

8.4.1.2 Circular Columns

The lateral confining stress induced by the jacket, $f_{l,f}$ is:

$$f_{l,f} = r_f f_f \qquad (8.23)$$

where f_f is the stress in the jacket determined from equation 8.22 . The confinement reinforcement ratio r_s is defined as,

$$r_f = 4\frac{t_f}{D} \qquad (8.24)$$

where t_f is the nominal jacket thickness and D is the overall column diameter.

8.5 Design Example

A 300 mm by 450 mm rectangular column is reinforced with 6 bars with $A_s = 1{,}884mm^2$ The concrete cube strength $f_{cc} = 22.4MPa$ and the yield strength of the reinforcing bars $f_y = 400MPa$. Determine the axial load carrying capacity if the column is to be jacketed with 4 wraps of BBR CFS 240 –300gm/m^2. The jacket will be applied using the wet lay-up technique.

Solution

A: Determine the design properties of the BBR CFS 240/300 sheet.

- Design ultimate strain:

$e_{fd} = e_{fu} / g_{mF}$ and

$$g_{mF} = g_{mf} \times g_{mm} = 1.4 \times 1.4 = 1.96$$

$$\therefore e_{fd} = 1.5\% / 1.96 = 0.77\% \qquad \text{(E.1)}$$

$\Rightarrow e_{fd} > 0.5\%$ as required by method proposed by Wang et al [R8.2]

- Design elastic modulus:

$$E_{fd} = E_f / g_E = 240{,}000 / 1.1 = 218{,}182 MPa \qquad \text{(E.2)}$$

B: Determine the distinct unconfined and effectively confined concrete areas.

Assume the corners will be rounded to a 50 mm radius. Hence from equations 8.10 to.8.12

$w'_{fx} = (300 - 2 \times 50) = 200 mm$. and

$$w'_{fy} = (450 - 2 \times 50) = 350 mm$$

$$A_{cc,f} = 300 \times 450 - 1884 - (4 - p)50^2 = 132{,}064 mm^2 \qquad \text{(E.3)}$$

$$A_{e,f} = 300 \times 450 - \frac{200^2 + 350^2}{3} - 1884 - (4 - p)50^2 = 77{,}898 mm^2 \qquad \text{(E.4)}$$

$$A_{cu} = 132{,}064 - 77{,}898 = 54{,}166 mm^2$$

C: Determine the confined concrete properties

$$f'_c = 0.85 f_{ck} = 0.85 \times 22.4 = 19.0 MPa \qquad \text{(E.5)}$$

Now, find the lateral confining stresses from equations 8.18 to 8.22

$$f_f = 0.005 \times 218{,}182 = 1{,}091 MPa \qquad \text{(E.6)}$$

$$t_f = 4 \times 0.176 mm = 0.704 mm \qquad \text{(E.7)}$$

$$r_{fx} = \frac{2 \times 0.704}{450} = 0.31\% \qquad \text{(E.8)}$$

$$r_{fy} = \frac{2 \times 0.704}{300} = 0.47\% \qquad \text{(E.9)}$$

$$f_{l,fx} = 0.0031 \times 1{,}091 = 3.41 MPa \qquad \text{(E.10)}$$

$$f_{l,fy} = 0.0042 \times 1{,}091 = 5.12 MPa \tag{E.11}$$

$$F_l = \max(5.12;\ 3.41) = 5.12 MPa \tag{E.12}$$

$$f_l = \min(5.12;\ 3.41) = 3.41 MPa \tag{E.13}$$

D: Determine the concrete enhancement strength ratio, k_c from equations 8.15 to 8.17:

$$\frac{F_l}{f'_c} = 5.12/19 = 0.269 \tag{E.14}$$

$$\frac{f_l}{f'_c} = 3.41/19 = 0.180 \tag{E.15}$$

$$\frac{f_l}{F_l} = 0.667 \tag{E.16}$$

$$a_1 = 1.25(1.8\sqrt{1 + 7.94 \times 0.269} - 1.6 \times 0.269 - 1) = 2.20 \tag{E.17}$$

$$a_2 = [1.4 \div 0.667 - 0.6(0.667)^2 - 0.8]\sqrt{0.269} + 1) = 0.93 \tag{E.18}$$

$$k_c = 2.20 \times 0.93 = 2.04 \tag{E.19}$$

Consequently, the confined concrete strength is, from equations 8.14 and E.5

$$f'_{cc} = 2.04 \times 19.0 = 38.9 MPa \tag{E.20}$$

E: Ultimate Load of Jacketed Column

Now the axial compressive load carried by the concrete is, from equation 8.6

$$N_{cnc} = 0.3 \times 19 \times 54{,}166 + 38.9 \times 77{,}808 = 3{,}335{,}477 N = 3{,}335 kN \tag{E.21}$$

and the axial compressive load carried by the reinforcing steel is, from equation 8.5,

$$N_{sn} = 400 \times 1{,}884 = 753{,}600 N = 753.6 kN \tag{E.22}$$

The ultimate load is, from equation 8.8b,

$$N_{nd} = 0.525 \times 3{,}335 + 0.87 \times 753.6 = 2{,}409 kN \tag{E.23}$$

F: Ultimate load of "as-built" column

$$N_{nd} = 0.525[(300 \times 450 - 1884) \times 19] + 0.87(1{,}884 \times 400) = 1{,}983 kN \tag{E.24}$$

Thus the application of the jacket will result in an ultimate axial load enhancement of 426 kN or 21.5% of the "as-built" column ultimate load.

8.6 References

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Product Specification Sheet

1. BBR Carbon Fibre Laminates (BBR CFL)

Details		Mechanical Properties		
Type	Size (w x t) (mm)	E-modulus (dry fibre) (MPa)	ε_{ult} %	UTS (MPa)
CFL 205	50/1.4	205,000	1.30	2,500-2,800
CFL 205	80/1.4	205,000	1.30	2,500-2,800
CFL 205	100/1.4	205,000	1.30	2,500-2,800
CFL 205	120/1.4	205,000	1.30	2,500-2,800
CFL 165	50/1.4	165,000	1.40	2,500-3,000
CFL 165	80/1.4	165,000	1.40	2,500-3,000
CFL 165	100/1.4	165,000	1.40	2,500-3,000
CFL 165	120/1.4	165,000	1.40	2,500-3,000
CFL 165	10/1.4	165,000	1.40	2,500-3,000

2. BBR Carbon Fibre Sheet (BBR CFS)

Details		Mechanical Properties		
Type	Weight (warp x weft)) (gm/m^2)	E-modulus (Dry fibre) (MPa)	ε_{ult} %	UTS (MPa)
CFS 240	150/25	240,000	1.55	3,800
CFS 240	200/30	240,000	1.55	3,800
CFS 240	300/30	240,000	1.55	3,800
CFS 240	400/40	240,000	1.55	3,800
CFS 440	300/30	440,000	0.60	2,650
CFS 640	400/30	640,000	0.40	2,650

3. BBR Glass Fibre Sheet (BBR GFS)

3.1 E-glass

Details		Mechanical Properties		
Type	Weight (warp x weft)) (gm/m^2)	E-modulus (Dry fibre) (MPa)	ε_{ult} %	UTS (MPa)
GFS E73	175/175	73,000	4.50	2,400
GFS E73	400/40	73,000	4.50	2,400
GFS E73	800/80	73,000	4.50	2,400

BBR Fibre Product Specification Sheet (continued)

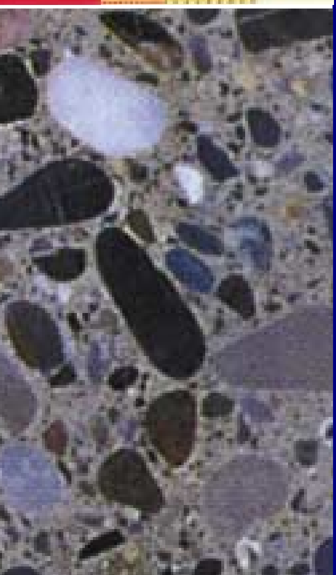
3.2 AR-glass

Details		Mechanical properties		
Type	**Weight** (warp x weft)) (gm/m^2)	**E-modulus** (Dry fibre) (MPa)	ε_{ult} %	**UTS** (MPa)
GFS AR65	175/175	65,000	4.30	1,700
GFS AR65	400/40	65,000	4.30	1,700
GFS AR65	800/80	65,000	4.30	1,700

4. BBR Aramid Fibre Sheet (BBR AFS)

Details		Mechanical Properties		
Type	**Weight** (warp x weft)) (gm/m^2)	**E-modulus** (Dry fibre) (MPa)	ε_{ult} %	**UTS** MPa)
AFS A120	290/0	120,000	2.50	2,900

FRP Strengthening Systems



CFRP Laminates

CFRP Sheets

E-glass Sheets

Aramid Sheets

Epoxies

Design services

On-site training

Carbon, Aramid and Glass Fibre Composites
for the Construction Industry

Products

BBR FRP Strengthening Systems

The advent of the use of Fibre Reinforced Polymers (FRPs) as a means of enhancing the performance of concrete and timber structures has created a huge market worldwide for the design and construction activities associated with the use of these materials.

FRPs consist of a layer or layers of fibre embedded in a matrix of epoxy resins which are either bonded to the surface of the element or bonded within the element (usually in slots).

Compared to bonded steel plate systems or concrete encasement solutions, FRPs are non-intrusive and provide aesthetically acceptable answers to strengthening requirements. Their light weight does not materially add to the dead weight of the structure. They are also extremely cost effective.

BBR Systems has now taken a leading role worldwide in the design and application of FRP materials and operates a service through affiliate companies and licensees located in many countries. BBR affiliates now have 7 years experience in their design and use, especially in seismic regions of the world.

BBR GFS E73 800/80 Glass Fibre Sheet

Advantages of BBR FRP Strengthening Systems

- Low unit weight (between 150—900 gm/m^2)
- Low profile thickness
- Ease of handling and application due to light weight
- High E-modulus — carbon modulus is greater than that of steel
- Excellent fatigue behaviour
- Alkali resistance (in the case of AR-glass—E-glass has some limitations in this respect)
- Corrosion resistant
- Able to be covered with a variety of plaster finishes and coatings.

GFRP sheet application to column

BBR FRP Applications

BBR FRP laminates and sheets are used as bonded reinforcement for the strengthening of structural elements of concrete, masonry, stone-work and timber. Such applications arise due to:

- Enhancement of load carrying capacity due to changed usage
- Upgrading to satisfy current building codes
- Seismic strengthening (increased load and ductility)
- Alteration to intended structural form
- Rectification of design or construction mistakes
- Enhanced durability

Application of CFRP laminates to bridge deck

Applications

Columns:

Axial load enhancement without increase in vertical stiffness, confinement, increased ductility and if required, increased flexural strength are all advantages offered by FRPs. Treatment of deficient lap splices in some cases can be accommodated.

Beams:

Flexural and shear enhancement can be addressed as well as seismic detailing problems such as lap splice deficiencies in some instances.

Walls:

Provision of shear and flexural strength to walls in both in-plane and out-of-plane directions. Applications include concrete and masonry walls, web elements of box girders, abutments and shear walls.

Slabs:

Flexural enhancement and deflection control, for both negative and positive moment applications.

Durability:

Confinement with FRP will protect an element against further degradation at the same time providing additional structural capacity. There is some evidence that confinement will slow the corrosion process in the case of elements with severe rebar corrosion problems. The use of a migrating corrosion inhibitor, in conjunction with the FRP jacket may give additional protection.

Selection of the BBR FRP Strengthening System

There is no fixed rule as to whether sheet or laminate should be used. Usually economy dictates the choice of one system over the other, but sometimes it is a design choice. The orientation of the main fibres in the FRP is also another important consideration. The applied forces are resisted by the main fibres, which run in a single direction (uni-directional) or orthogonally (bi-directional).

Carbon (laminate or sheet) is usually more economic for use in flexural or shear strengthening. Carbon has better fatigue properties than glass, so where the strengthening is used to carry often occurring fluctuating live loads, carbon should be chosen. Glass, because of its lower E-modulus, is more suitable for use in confinement of concrete, although it can, in certain circumstances, be used for flexural enhancement. Because of its low modulus, glass is seldom used for shear enhancement.

Laminates can only be applied to plane surfaces, therefore carbon or glass sheet are used on curved surfaces. Carbon sheet, on the other hand, is difficult to cut and handle in thin strips and therefore laminates are preferred, when narrow bands of CFRP reinforcement are required.

Bi-directional glass fabrics are used for increasing the shear strength of masonry walls. Lighter fabrics are used where the substrate strengths are low, such as in old and historic masonry or brick buildings.

Axial load enhancement of a oblong column using GFRP

Element	Application	BBR Glass Fibre Sheet (GFS)	BBR Carbon Fibre Sheet (CFS)	BBR Carbon Fibre Laminate (CFL)
	Fibre Direction	Uni-directional	Uni-directional	Uni-directional
	Fibre arrangement	Woven	Straight	Straight
Columns	Confinement	☼☼	☼☼	
	Flexure	☼	☼	o☼o
	Axial Load	☼☼	☼	o☼o
	Ductility	☼☼		
	Durability	☼☼	☼	
Beams	Flexure		☼	☼☼
	Shear		☼☼	
Walls	Shear & flexure	☼☼	☼	☼
Slabs	Flexure		☼	☼☼
Durability	Spalling	☼☼	☼	

☼ possible use ☼☼ preferred use o☼o special application

BBR

Types of BBR Fibre Product

The types of BBR Fibre Products available are shown in the table. BBR reserves the right to change the material specifications from time to time. Intending users should check with BBR Systems for current material specifications for product available.

Substrate Requirements

The substrate to which the FRP is to be bonded must have sufficient strength to transmit the loads from the FRP to the structure. Testing of the tensile strength of the substrate by pull-off tests is imperative. The following table sets out the minimum substrate strengths required for each of the BBR FRP materials:

Product	Min Tensile Strength of Substrate (MPa)
BBR Carbon Fibre Laminate CFL	> 1.50
BBR Carbon Fibre Sheet CFS	> 1.00
BBR Glass Fibre Sheet GFS	> 0.20
BBR Aramid Fibre Sheet AFS	> 1.00

Epoxy Resins

Adhesion of BBR FRP materials to substrates requires the use of epoxy resins and adhesives. BBR Systems supplies the following resins and adhesives:

- **BBR 120** Epoxy resin primer, for all sheet priming applications
- **BBR 125** Epoxy resin, for all sheet laminating applications
- **BBR 150** Epoxy Paste, for all laminate applications

Users of BBR Fibre Products are able to source their own resin products provided they meet with the prior approval of BBR Systems and have been rigorously tested for performance in conjunction with the appropriate BBR Fibre Product.

Design Assistance

BBR Systems is able to assist with design concepts using BBR FRP Products. Please contact BBR at the address below for further information.

Westgate Bridge, Melbourne,- strengthened with BBR FRP Systems

BBR Systems Ltd

Bahnstrasse 23
Postfach
CH-8603 Schwerzenbach
Switzerland
Tel: +411 806 80 60
Fax: +411 806 80 50
Email: bbr@bbrsystems.ch
www.bbrsystems.ch

Material Specifications

BBR Carbon Fibre Laminates (CFL)

Type	Size (w x t) (mm)	E modulus (GPa)	Ultimate strain ε_{ult} (%)	UTS (MPa)
CFL205	50/1.4	205	1.30	2,500–2,800
CFL205	80/1.4	205	1.30	2,500–2,800
CFL205	100/1.4	205	1.30	2,500–2,800
CFL205	120/1.4	205	1.30	2,500–2,800
CFL165	10/1.4	165	1.40	2,500-3,000
CFL165	50/1.4	165	1.40	2,500-3,000
CFL165	80/1.4	165	1.40	2,500-3,000
CFL165	100/1.4	165	1.40	2,500-3,000
CFL165	120/1.4	165	1.40	2,500-3,000

BBR Carbon Fibre Sheet (CFS)

Type	Weight (warp x weft) (gm/m²)	E modulus (MPa)	Ultimate strain ε_{ult} (%)	UTS (MPa)
CFS 240	150/25	240	1.55	3,800
CFS 240	200/30	240	1.55	3,800
CFS 240	300/30	240	1.55	3,800
CFS 240	400/40	240	1.55	3,800
CFS 400	300/30	440	0.60	2,650
CFS 640	400/30	440	0.40	2,650

BBR Glass Fibre Sheet (GFS) E-glass

GFS E73	175/175	73	4.50	2,400
GFS E73	400/40	73	4.50	2,400
GFS E73	800/80	73	4.50	2,400

BBR Glass Fibre Sheet (GFS) AR-glass

GFS AR65	175/175	65	4.30	1,700
GFS AR65	400/40	65	4.30	1,700
GFS AR65	800/80	65	4.30	1,700

BBR Aramid Fibre Sheet (AFS)

AFS A120	290/0	120	2.50	2,900

Amanpuri Villas Column Strengthening

FRP Strengthening

Location

Phuket, Thailand

Contract No

CT 4133

Client: Amanpuri Villas Body Corporate

Consultant: Consultech

Contractor: BBR Systems Ltd

Date: June - Sept 2000

The luxurious Amanpuri Villas, on the island of Phuket, Thailand, are built on slender concrete columns of 300mm diameter, up to 14.0m high. With the ocean located only 30m from these villas, the columns have been subjected to the forces of the environment, since their construction 10 years ago. Most of the columns exhibit corroded rebar and spalled concrete.

By applying two layers of BBR FRP e-glass embedded in an epoxy matrix, the durability and structural strength of the columns were enhanced.

Furthermore, the epoxy/e-glass composite protects the ingress of further pollutants, at the same time reducing over time the corrosion of the rebar within. Lack of oxygen plus the enveloping jacket will stabilise the deterioration and provide a long term solution to the problem.

100 such columns were wrapped in 2000, with a further stage due for repair in the future.

BBR Systems won the contract and its NZ subsidiary, Contech was engaged to supervise a local contracting company to carry out the work.

Saatchi & Saatchi Building

FRP Strengthening

Location | **Contract No**

Wellington, New Zealand | **W 117**

Client:	Saatchi & Saatchi
Consultant:	Sinclair Knight Merz
Main Contractor:	L.T. McGuinness
Sub Contractor:	Construction Techniques Ltd
Date:	June - July 1997

Saatchi & Saatchi House was constructed in the late 1980's. There was a tolerance problem with the construction of the columns, which was corrected with a thick plaster. This plaster was applied in several layers and to varying thickness of up to 70mm. Generally recognised good trade practice was not followed in the application of the plaster, and there were many areas where the plaster had cracked and delaminated from the concrete substrate or within the inner layers of plaster.

The main objectives of the remedial maintenance coating were to:

- Inhibit the delaminated plaster falling from the column face.
- Provide an improved finish to the column exterior surface.
- Cost effective column re-cladding system.

Contech proposed a cost effective maintenance coating system that consisted of one layer of FRP WEB fibre saturated with epoxy resin and applied to the exterior face of the columns. The application of this advanced composite material negated the need to remove any of the delaminated plaster and provided an innovative, cost effective and non intrusive solution. The suitability of the proposed system was reviewed and approved by consultants Sinclair Knight Merz.

Contech was awarded the contract to carry out installation of the composite coating to the exposed faces of the existing exterior columns in June 1997. Nine columns, up to 20.5 metres high, were wrapped with composite jackets. The crew of 4-6 men completed the whole work, including column preparation, over a period of eight weeks.

Construction Techniques Group Ltd
P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland, Wellington, Christchurch

Railway Campus Tyfo

FRP Strengthening

Location

Auckland, New Zealand

Contract No
A1521

Client: Covington Corporation Ltd

Consultant: Holmes Consulting Group

Contractor: Goodall ABL Construction Ltd

Date: November 1998

Goodall ABL won the contract to convert the old Auckland Central Railway Station into accommodation for University Students. A range of one, two and three bedroom apartments were created with the exterior shell of the building being retained.

Due to the change of use of the structure a structural assessment for earthquake loadings was carried out by Holmes. Areas that required strengthening were identified and an FRP composite material was specified for a number of walls.

This involved the installation of a total of 280m^2 of e/glass sheet at 32 different locations throughout the building. After surface preparation was complete pull-off tests were carried out to confirm the strength of the substrate. FRP was then installed in three or six layers as detailed by Holmes.

The repair areas were plastered over to match existing architectural finishes.

Princes Wharf Redevelopment

FRP Strengthening

Location

Auckland, New Zealand

Contract No

A 1616

Client: Kitchener Group

Consultant: Buller George Engineers

Contractor: Construction Techniques Ltd

Date: 1998 - 2000

The redevelopment of Princes Wharf into a retail/ commercial/residential mega centre commenced in mid 1988. Contech played a major role in the project, by securing subcontracts which included ground anchors, concrete repair and strengthening of existing columns using FRP composite materials.

Consultech was engaged by Buller George Engineers to assist in the design of the column strengthening, using FRP e-glass composites. The columns had no confining stirrups and were required to be brought up to current code requirements in this regard. The FRP composite were used to provide sufficient confinement so that curvature ductility of 10 can be developed without failure.

FRP composite wrapping was applied to more than 1,000 columns, after extensive concrete repair had been carried out to the columns and beams.

The simple wrapping with two layers of composite greatly enhanced the strength of columns but was unobtrusive, as the columns were then plastered before painting. It provided a very economical way of overcoming a very severe deficiency.

Construction Techniques Group Ltd
P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland
Wellington
Christchurch

Milton & McFadden Street Substations

FRP Strengthening

Location | **Contract No**

Christchurch, New Zealand | **C860**

Client: Orion New Zealand Ltd

Consultant: Sinclair Knight Merz

Contractor: Construction Techniques Ltd

Date: March - April 2001

Contractor Richdale Builders Ltd engaged Contech to carry out seismic strengthening of the Milton and McFadden Street Substations using FRP composite materials. As both structures are of concrete block construction, consultants Sinclair Knight Merz (Wellington) designed a system that targeted specific wall areas to strengthen, and thus ensuring the survival, of these important structures in the event of an earthquake.

Preliminary investigations revealed a thin coat of paint on the interior walls. In order for Contech to proceed we needed to satisfy ourselves that the paint could withstand the forces required. To this end we performed a 'pull-off test' using a three-legged pull-off frame with a 5 tonne jack incorporated. Results confirmed a weak bond and so the paint had to be removed from the required patches.

The whole project, including paint removal and block preparation, supply and installation of 140m^2 of composite material and supply and installation of some 100 fibre anchors, was completed in four weeks.

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P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland, Wellington, Christchurch

Ibis Hotel

FRP Strengthening

Location

Wellington, New Zealand

Contract No
W 429

Client: CBD Building Owner

Consultant: Holmes Consulting

Main Contractor: Fletcher Construction

Sub Contractor: Construction Techniques Ltd

Date: Oct - Nov 1999

In 1999, a twelve-storey office building in Wellington CBD was converted into the IBIS Hotel. Contractor Fletcher Construction engaged Contech to carry out seismic strengthening of the structure using FRP Composite Material. Structural analyses carried out by Holmes Consulting Group indicated that sixteen columns on the first four floors of the building did not meet the NZ Code requirements.

Three wraps of FRP e-glass/epoxy composite material, applied to full height of the columns, was specified to overcome this deficiency. To provide an additional fixing, FRP fibre anchors were installed, where full confinement of the column was not possible. The whole work, including column preparation, was completed over a four-week period. For some external columns, the existing precast cladding had to be removed before the FRP wrapping was installed. The flexibility and small thickness of the FRP wrap allowed for the original cladding to be reinstated, once it was installed, without the need for any modification.

Over 450m^2 of FRP composite material and more than 400 fibre anchors were installed on this project. The crew of 4-6 men completed the whole work, including column preparation, over the stipulated period of four weeks.

Construction Techniques Group Ltd
P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland
Wellington
Christchurch

HSBC Building

FRP Strengthening

Location — **Auckland, New Zealand**

Contract No — **A1511, A1578**

Client: No. 1 Queen St Ltd

Consultant: Consultech

Contractor: Construction Techniques Ltd

Date: 1998 - 1999

The HSBC Building, formerly the Air New Zealand Building, was built in the late 1960's and in 1998 underwent a complete internal and external refit. Externally, the podium was clad in black marble and the tower block, which consisted of in-situ columns with a textured plaster finish and precast spandrels, was painted a dark green. The plaster on the columns, generally up to 40mm thick began to delaminate and sections fell to the footpaths below.

Consultech was engaged to carry out two inspection surveys of the facades and identified the areas of delamination on the columns were increasing. The spandels appeared not to be suffering from any delamination. It was proposed that unsound areas of plaster at the columns be secured with an epoxy composite FRP material and this in turn fixed to the concrete substrate with FRP anchors.

Two repair contracts were awarded to Construction Techniques Ltd. The first contract was carried out in December 1998, and, following another inspection survey by Consultech in April 1999, the second contract was completed during July 1999. The repair work consisted of the removal of the bulk of the dark paint over the effected areas to expose the plaster for bond and the application of an epoxy/e-glass composite material. FRP fibre anchors were then installed. The repair areas were then painted to match the existing paint.

CBD Building Columns

FRP Reinforcement

Location | **Contract No**

Wellington, New Zealand | **W168**

Client: Wellington Developments

Consultant: Kingston Morrison

Contractor: Construction Techniques Ltd

Date: 1997 - 1998

The columns of this building were found to have insufficient confining steel according to present day seismic codes. The large spacing between the hoop bars was allowing a number of vertical bars to buckle as concrete creep imposed axial loading on to the vertical reinforcing. The retrofitting design required two layers of FRP epoxy e-glass composite material to be placed over the full height of the columns in each of the 14 floors. 66 columns were strengthened by this method.

In order to complete the project with minimum disruption to the tenants, work was carried out around the clock, over weekends. One of the requirements of the contract was to ensure retrofitting of a complete level was carried out over each 48 hour period.

Uni-directional e-glass and carbon fibre composites are very effective in providing additional confinement and axial load carrying capacity to columns subject to axial loads and bending moments. With fibres running circumferentially around the columns, no additional vertical stiffness is provided, which is usually what is required in column retrofitting.

Construction Techniques Group Ltd
P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland, Wellington, Christchurch

Central Bank of Samoa Column Cladding Repairs

FRP Strengthening

Location	Contract No
Western Samoa	A 1627

Client: Central Bank of Samoa

Consultant: Consultech

Contractor: Construction Techniques Ltd

Date: 2000

The Central Bank building was constructed in 1993 and from that date, suffered cracking to the clay pipe sections used to form the columns in the original construction. The building suffered differential settlement and this, combined with normal creep, loading and movement of the structure, lead to rotation of the columns. The stiff and brittle pipe sections cracked as a result and this worsened to the point where they presented a serious safety hazard and many were bound with wire to prevent sections falling.

Consultech carried an inspection of the columns in August 1999 and provided recommendations for remedial work to Central Bank of Samoa. Options of a) pipe removal, or b) wrapping the column with an FRP e-glass/epoxy composite material to secure the pipe cladding were suggested. Option b) was selected by the client.

A repair contract was awarded to Construction Techniques Ltd who carried out the repairs during July to September 2000. The repair work consisted of selected FRP e-glass/epoxy composite material wrapped around the columns to confine the cracked pipe sections. The rigid mortar joints were replaced with a flexible sealant and painting of the columns was undertaken once the composite material had been applied.

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P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

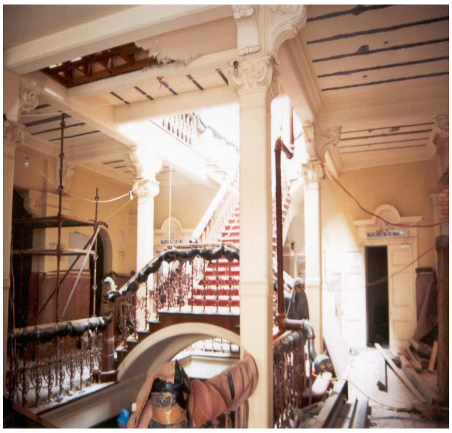
Offices in: Auckland, Wellington, Christchurch

Auckland Town Hall

FRP Strengthening

Location
Auckland, New Zealand

Contract No
A1188



Client: Auckland City Council

Consultant: Kingston Morrison

Contractor: Downer Construction

Date: November 1996

Structural strengthening has been used for many years to extend the service life of important and historical buildings and structures around the world. Traditionally, this type of retrofitting has utilised bonded steel plates or external post-tensioning. However, with the advent of composite materials consisting of synthetic fibres of E-glass, Kevlar and Carbon, immersed in a matrix of epoxy resin, the means of strengthening these structures has been significantly simplified.

Downer Construction (NZ) Ltd won the contract for the restoration of the Auckland Town Hall which, due to unique characteristics of its shape and Italian renaissance revival architecture, places it in the highest tier of the Auckland City Council schedule of listed buildings.

During the course of construction work, it was found that the two mezzanine floors in the main entrance area did not have sufficient reinforcement to comply with current codes. Engineers, Kingston Morrison Ltd investigated strengthening options and selected the Sika Carbodur system as the most appropriate for the conditions present. The Sika Carbodur system consists of bonded high strength laminates made of carbon fibre reinforced polymers. Contech was engaged to supply and install the carbodur strips to the under strength floor slab and involved some 200m of carbon fibre adhered to the floor soffit using an epoxy paste.

The use of thin lightweight carbon fibre strips ensured that disruption and replastering to the ceiling was minimised. Distinct advantages over bonded steel plates are the comparative thinness, corrosion resistance, lightweight and strength of the system as well as the ability to be installed in confined and restricted spaces. This was the first Carbodur installation in New Zealand and it has proved to be extremely successful in this application.

Aotea Quay Overbridge

FRP Strengthening

Location | **Contract No**

Wellington, New Zealand | **W 048**

Client: Wellington City Council

Consultant: Consultech

Contractor: Construction Techniques Ltd

Date: 1996

The Aotea Quay Overbridge is NZ's first bridge seismically strengthened by the use FRP composite materials.

The owner, Wellington City Council, received the benefit of substantial savings over their own-designed solution, which used steel jackets and additional piling. Landowner TranzRail experienced minimal interruption to its traffic flow during the work.

81 columns were strengthened using the FRP e-glass material. The actual wrapping took only 15 days to complete, and was achieved with no disruption to either the motor or rail traffic that passes under the bridge. Most columns had 2 - 3 layers of FRP wrap, which were placed at critical areas at the top and/or bottom of the column, depending on the design requirements.

The FRP alternative also eliminated the need for additional piles, which was enthusiastically accepted by TranzRail, as no interruption to its trains was needed.

The alternative was designed by Consultech with technical guidance from Dr José Restrepo of Canterbury University.

Construction Techniques Group Ltd
P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland
Wellington
Christchurch

St Johns Reservoir

FRP Strengthening

Location | **Contract No**

Auckland, New Zealand | **A 1381**

Client: Watercare Services Ltd

Consultant: Consultech

Contractor: Construction Techniques Ltd

Date: 1997

The St Johns water supply reservoir is an above ground reservoir that was built in 1957. It is 55m in diameter with 8m high precast concrete perimeter walls. The roof structure is supported by the perimeter walls and full height intermediate columns on a 5.5m two way grid. The roof comprises precast prestressed slabs that span between support beams on the column grid lines.

Over the years of service, concrete spalling has occurred at the column head joint adjacent to the beam seating, resulting in corrosion of reinforcing and putting the integrity of the roof support structure in doubt.

The work carried out to address this comprised repairing the deterioration and retrofitting the top 600mm of the column head with a glass fibre FRP epoxy e-glass Composite Material. A total of 44 No. columns were repaired in this manner to confine the distressed columns and prevent concrete from future cracking and spalling. A protective coating conforming to requirements for use in potable water tanks was applied to the retrofitted regions ensuring nil contamination of the water supply.

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P.O. Box 51 391, Pakuranga, Auckland, New Zealand
Tel: ++649 274 9259; Fax: ++649 274 5258; email: info@contech.co.nz

Offices in: Auckland
Wellington
Christchurch