FRP-reinforced Concrete Design (internal reinforcement) Properties, Safety, Design and Application

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Motivation
Corrosion

- Ingress of deicing salts and spalling of concrete
Corrosion

- Spalling
- Propagation of corrosion within 4 years

Courtesy salit specialty rebar
Concrete Cover

Small concrete cover
Concrete Cover

- Low concrete cover leads to ingress of chlorine and carbonation through diffusion

Corrosion over the whole length of the bar
Concrete Cover

- Low concrete cover leads to ingress of chlorine and carbonation

Big concrete cover
Concrete Cover

- Big concrete cover leads to bigger cracks and local ingress of chlorine

![Diagram showing big concrete cover with cracks and ingress of chlorine]
Concrete Cover

- Big concrete cover leads to bigger cracks and local ingress of chlorine

Spalling through local corrosion
Concrete Cover

Small concrete cover
Concrete Cover

- No corrosion, small cracks
- But: Cracking/Spalling from bond or from thermal actions has be excluded!
- If upper layer: good concrete cure treatment is important
- \( c_v = d_f + 10\text{mm} \) for Combar. Each material may have different minimum values
Minimum reinforcement to ensure ductile behaviour

- After formation of first crack tensile stress is in bar 1
- Strength must be high enough to crack concrete of the next section 2
- Calculation according EC2
Contents

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- Building Code Structure in Europe
- European Standardisation
- European Technical Approval
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- Design Example Shear
- References in Different Applications
Main References

- Draft EN 1992-1-1 Design (2023?)
- CSA S 807 (2013) Material
- Fib bulletin 40 (2007) Material and Design
- Fib Model Code (2010)
- ACI 440.1 Design
- ACI 440.6 Product Specifications
- JSCE 1997
European Standardisation

- EC2 (EN 1992-1-1) does not include clauses for the design with FRP materials
- Design clauses for composite rebars as internal reinforcement external reinforcement will be included/added to the new EN 1992-1-1 2023
- No European material standard for FRP rebars or Laminates
- European material approval => ETA European Technical Assessment
European Standardisation vs. Approval

- ETAs shall define material properties and no design (small product standard including testing guide in EAD)

- Design values (100 years long term) / characteristic values
- Same level of safety for concrete, steel and FRP is needed and accepted
- => failure probability is equal, not safety factor is equal
European Technical Approval

- No (European) Standard for reinforcing bars
- EAD European assessment document  = testing and quality rules
- ETA defines material properties
Basic Assumptions: CTE / thermal compatibility

If anything is embedded in concrete CTE should fit together in all directions.

Steel and concrete are seen as compatible: CTE = 10 x 10^-6

What about the different FRPs and other known materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus in MPa</th>
<th>CTE lengthwise in 10^-6 /K</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>B500</td>
<td>200000</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>GFRP</td>
<td>60000</td>
<td>6</td>
<td>-1,2</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>160000</td>
<td>17</td>
<td>14,4</td>
</tr>
<tr>
<td>CFRP</td>
<td>120000</td>
<td>0</td>
<td>-9,6</td>
</tr>
</tbody>
</table>

Greater differences in perpendicular direction may cause longitudinal cracks, or spalling, but perpendicular modulus of composite rebar is much smaller. So typical concrete covers diameter + 10mm or less are generally no problem.
Basic Assumptions: Modulus

Most reinforcement bars are unidirectional (pultruded) FRPs
The modulus of elasticity can be calculated according laminate theory

Simplified: vol. fibre content x modulus of the fibre = modulus of the bar
Example Combar:
75% x 80000 MPa = 60000 MPa
Basic Assumptions: Strength

Can strength of pultruded shapes be computed from fibre volume and strength of fibres?

75% x 3500 Mpa = ?

Video zeigen?
Basic Assumptions Bond Behaviour: Failure Mode

- **Combar (Schöck)**
- **C-BAR P2 (MIC)**
- **C-BAR P1 (MIC)**

Shear off ribs

Shear off concrete corbels

Splitting
Bond Behaviour: What has to be regulated?
What has to be known for design?

- Bond strength as function of the concrete strength
  Bond strength for crack limitation/spacing (short term, long term) little bond creep

- Bond strength for safety of anchoring (from long term values)

- Concrete cover (Different splitting action for different products)
  Exhibition classes do not apply!
Basic Assumptions: Fire

Glass, Basalt, Carbon and Aramid fibres can withstand high temperatures. The fibres soften at different temperature ranges 300-1000°C.

Generally resins do not withstand high temperatures. They soften in the range between 100-300°C.

In addition resins are combustible.

What is the difference between flammability (fire rating of a material) and fire rating of a construction? (fire rating of an building element)

What does the GTT (glass transition temperature) mean?
Basic Assumptions: Fire strength

E-CR glass fibre bar:

Temperature dependance tensile strength of Combar

strength in N/mm²

temperature in °C
Basic Assumptions: Fire Bond

ComBAR bond tests different diameter elevated temperature

Difference Tg vs. bond limit
Anchoring limits fire design
For „cold“ anchoring >400°C limit temperature
Avoid lap splice in exposed high loaded sections!
Historical development

- International Research worldwide since 80s
- Creep rupture tests and residual strength tests with different materials
  - 1995: Durability of GFRP questionable, failure at 30% stress for 100a
  - =>JSCE 1997 no GFRP allowed for structural applications
  - =>ACI 1998 stress limit 20% of ultimate strength (14-16% including environmental factor)
- Most researcher test GFRPs with the ACI limit
  - Real long term performance not known
  - Long term limit only from old literature
- DIBt approval Schöck Combar 2008, fib bulletin 40 2007: KOMO certificate 2010: Performance based limits: Creep rupture and chemical durability are tested in one test
  - (load and environment are always connected for reinforcement)
Design (ULS, SLS)

ULS (factored load) against all actions leading to a failure
- Bending (short and long term)
- Shear (short and long term)
- Anchoring/Development length
- (Fatigue)

SLS (unfactored load)
- Deflection
- Crack width
- (Fatigue)
Design value long term strength (ULS)

Testing conditions shall represent the service life conditions

- Sustained and variable stresses
- Ageing: Chemical ingress (wet) at elevated temperature under stress

Conditions for test in European code family

5% failure probability = characteristic value.

⇒ Less than 1 of 20 specimen fail during service life time under this load
⇒ Reduced by material factor => design value
Long term testing Creep rupture/time to failure test

Testing conditions shall represent the service life conditions

- Constant stress
- Ageing: Chemical ingress at elevated temperature
- After a uncertain time: failure

Which conclusion can be drawn out of this test?

If the ageing represents the service life, which load can be sustained how long in this environment …

What is the short term strength?

What is the probability of a failure? 5% percentile for 100a service life
Design approach

- Plane sections remain plane
- Moment and force equilibrium
- Perfect bond

... ...

- Same design principles like for R/C
- Same level of safety
- But: Different ductility/deformability requirements

Time dependent properties:

- Strength
- Bond strength
- Creep rupture and chemical durability as near to reality as possible
Design approach

What does “safety” mean?
- Acceptable failure probability under defined conditions

These are:
- Up to 40°C constant in service (not MAT)
- Wet alkaline concrete (no reduction for different exposition classes)

Which are the time dependent properties under these conditions:
- Strength
- Bond strength
Creep curves

Typical creep curve is the primary result

Total displacement:
Elastic strain (1,5%) on apr. 500mm length

Bond slip
Inelastic time dependent creep of the rebar itself

Bond creep dependent on concrete behavior
Of Interest is only the time to failure

time to failure
Durability Concept

References:
- DIN 53768
- EN 705 GFRP Pipes: Regression Analysis
- ACI 440.3R 04: B8:Creep rupture test under sustained load (modified test in saturated concrete)
- CSA S806-02 Annex J: modified test in saturated concrete
Durability  no diameter influence

time to failure tests in wet concrete 60°C
different bar diameters

Lines: mean and 5% percentile for d=16mm according fib
residual strength 1200 MPa
Safety Approach without time dependence

Semiprobabilistic safety approach

\[ f_E, f_R \]

\[ E_m \quad E_k \quad R_k \quad R_m \]

\[ k_E \sigma_E \quad k_R \sigma_R \]

\[ p_r = p (R<E) \]
Safety Approach with time dependence

- **60°C** and **40°C**
- 100 fold time
- Resistance
- Action \( F \)
- \( \gamma_m \)
- \( \gamma_F \)
- \( F_d \)
- \( F_k \)
Design of a Thin Slab 45mm

Concrete C50
Thickness 45mm
Width 280mm
Reinforcement 3 Combar Ø8

I = 1100mm
Structural Design Actions

Actions:
Dead load 0,28m x 0,045m x 25kN/m³ = 0,32kN/m line load 1
Live load 1 0,28m x 5kN/m² = 1,40kN/m line load 2
Live load 2 2,0kN at any point = 2,00kN point load 1

Load cases:
Line load 1 + line load 2
Line load 1 + point load 1 in the middle
Line load 1 + point load near support

⇒ Max Med (incl. gamma) = 0,89kNm
⇒ Max Ved (incl. gamma) = 3,1kN
Structural Design Resistance bending

Difference between steel reinforcement and FRP reinforcement

Design value for long term strength GFRP Combar \( f_{d100a} = 445 \text{N/mm}^2, E = 60000 \text{N/mm}^2 \)

Design value (long term) strength steel B500 \( f_{yk} = 435 \text{N/mm}^2, E = 200000 \text{N/mm}^2 \)

**Concrete gets different loading for same moment**

Bending design, with force and momentum equilibrium with your method (FEM, omega method, stress block ... taking account the stress-strain diagramme of reinforcement)
Structural Design Resistance bending Result

Total height: 0.045m
Axis reinf.: 0.017m
Af ges: 1.51cm²

Concrete fcd 28.33 N/mm²
Design value for long term strength Combar
f_{fd100a} = 445N/mm², E = 60000N/mm²

Mmax = 0.89 kNm
f concrete -28.33N/mm²  eps = -3.5mm/m
f Combar 408N/mm²  eps = 6.77mm/m
Thickness compressive section = 10mm
Structural Design Resistance Shear

Total height: 0,045m
Axis reinf.: 0,017m
As ges: 1,51cm²

\[ V_{Rd,c} = \beta \cdot \frac{1}{424} \cdot \kappa \cdot (100 \cdot \rho_l \cdot E_{fl} \cdot f_{ck})^{1/3} \cdot b_w \cdot d \]

- \( \beta = \frac{3}{(a/d)} \geq 1,0 \); increase factor for the effect of loads close to bearing
- \( \kappa = 1 + \sqrt{200/d} \); scaling factor (d in mm)
- \( \rho_l \) = reinforcement ratio for longitudinal reinforcement
- \( E_{fl} \) = Elastic modulus of longitudinal reinforcement
- \( f_{ck} \) = characteristic compressive cylinder cube strength of concrete at 28 days
- \( b_w \) = width of the web on beams
- \( d \) = effective depth to tension steel

\[ V_{Rd,ct} \approx \frac{2}{3} \text{ of steel RC} \]

\( V_{Rd,c} = 7,5\text{kN} \)

Excel sheet for various design issues available:
http://www.schoeck.co.uk/en_gb/downloads?product=4&type=10&filter=1#
Bending test slab 45mm

Concrete C45
Thickness 45mm
Width 280mm
Reinforcement 3 Combar Ø8

\[ I = 1100\text{mm} \]
Bending test concrete slab 45mm
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Bending test concrete slab 45mm
Bending Test: Force Deflection curve

Bending Test 45mm slab, 3x8mm ComBAR, 1100mm support

- Concrete Failure
- Char. Short Term Strength reinforcement
- Char. Long Term Strength reinforcement
- Design long term Strength reinforcement
- Deflection limit
Design of a beam/girder 520mm

Concrete C25
Thickness 520mm
Width 250mm

Load heavy!
Combar number? Ø?

Timber Beams
Insulation
Structural Design Actions

Actions:
Dead load char. = 23 kN/m line load
Live load char. = 21 kN/m line load
Dead load design = 31.05 kN/m
Live load design = 31.5 kN/m

Loads:
max $M_d = (31.05 + 31.5) \times 3.75^2 / 8 = 110.0$ kNm
max $V_d = (31.05 + 31.5) \times 3.75 / 2 = 117.3$ kN
Design of a beam/girder, bending

\[ \varepsilon_{\text{Beton, Druck}} = -3.4876 \, \text{mm/m} \]
\[ \varepsilon_{\text{Beton, Zug}} = 8.5182 \, \text{mm/m} \]
\[ \varepsilon_{\text{GFK, Zug}} = 7.41 \, \text{mm/m} \]
Design of a beam/girder, shear

$$V_{Rd,c} = \beta \cdot \frac{1}{424 \cdot \gamma_c} \cdot \kappa \cdot \left(100 \cdot \rho_l \cdot E_f \cdot f_{ck}\right)^{1/3} \cdot b_w \cdot d$$

Vrd,c = 33,3 kN << 117,3kN

Not enough capacity => stirrups needed
Design of a beam/girder, shear

Not enough capacity => stirrups needed

\[
\begin{array}{|c|c|}
\hline
M & 130,0 \text{ kNm} \\
\hline
V & 130 \text{ kN} \\
\hline
h & 520 \text{ mm} \\
\hline
b_w & 250 \text{ mm} \\
\hline
\end{array}
\]

concrete: C25/30 \( \gamma_c = 1,5 \)

\[
\begin{array}{|c|c|}
\hline
f_{ck} & 25 \text{ N/mm}^2 \\
\hline
f_{cm} & 33 \text{ N/mm}^2 \\
\hline
\end{array}
\]

longitudinal reinforcement:

\[
\begin{array}{|c|c|}
\hline
5 & 16 \text{ mm} \\
\hline
E_n & 60,000 \text{ N/mm}^2 \\
\hline
\end{array}
\]

d = 400 \text{ mm}  \\
\( \rho_l = 0,0101 \)  \\
z = 360 \text{ mm}  \\
A_n = 1,005 \text{ mm}^2  \\
A = h - c_v - d_B - 1/2 \cdot d_{Stb} \\
\]

shear reinforcement:

\[
\begin{array}{|c|c|}
\hline
4 & 12 \text{ mm} \\
\hline
E_{tw} & 50,000 \text{ N/mm}^2 \\
\hline
s_{tw} & 200 \text{ mm} \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|}
\hline
A_{tw} (stir) & 423 \text{ mm}^2 \\
\rho_{tw} (stir) & 0,0085 \\
a_{tw} (stir) & 2,113,7 \text{ mm}^2/m \\
f_{stw} (Bü) & 160 \text{ N/mm}^2 \\
\hline
\end{array}
\]

Afl - only in tensile zone!
Design of a beam/girder, shear

\[ V_{Rd} = V_{Rd,c} + V_{Rd,f} \]

\[ V_{Rd,f} = a_{tw} \cdot f_{fd,w} \cdot z \cdot \cot (\theta) \]

- \( V_{Rd,c} \): shear resistance of members without shear reinforcement
- \( a_{tw} \): cross-section area of shear reinforcement = \( A_{tw} / s_w \)
- \( f_{fd,w} \): design value tensile strength of shear reinforcement
- \( \varepsilon_{fd,w} \): design value maximum strain of shear reinforcement

\[ \varepsilon_{fd,w} = 2,3 \left( \frac{2 \cdot E I^* \left[ \frac{MNm^2}{50} \right]}{M} \right) \leq 7,0 \% \]

\[ E I^* \]: simplified bending stiffness
\[ E I^* = E_{Eg} \cdot A_{Eg} \cdot (0.8 \cdot d)^2 \]

\[ \theta \]: angle of inclination of strut
\[ \theta = \arctan \left( \sqrt{\frac{M / V \cdot a_{fw} \cdot E_{fw}}{A_{Eg} \cdot E_{Eg}}} \right) \]
\[ \geq 20^\circ \]
\[ \leq 50^\circ \]

\[ \begin{align*}
\varepsilon_{fd,w} & = 2,7 \% \\
f_{fd,w} & = 136 \text{ N/mm}^2 \\
f_{fd,w} \text{ (stirrups)} & = 163 \text{ N/mm}^2 \\
\theta & = 50,0^\circ \\
\tan \theta & = 1,19 \\
\cot \theta & = 0,84
\end{align*} \]

\[ \begin{align*}
V_{Rd,f} \text{ (stirr.)} & = 86,6 \text{ kN} \\
V_{Rd,f} \text{ (DHB)} & = 0,0 \text{ kN}
\end{align*} \]

\[ V_{Rd} = 117,4 \text{ kN} \]

\[ V_{Rd,max} = \frac{1,1 \cdot b_w \cdot z \cdot f_{cm}^{2/3}}{\gamma_c \cdot (\cot (\theta) + \tan (\theta))} \]

\( f_{cm} \): mean value concrete cylinder compr. Strength
Combar Reference Projects: Industry

no induction currents and corresponding heating up of reinforcement near rectifiers
structural reinforcement
1000 m²

Qatar Aluminum Factory
Qatar, 2008
Ras az Khair Aluminum Factory
KSA, 2011
Combar Reference Projects: Research facilities

IBM
Zurich, CH
2010
Combar Reference Projects: Research facilities

precision lab
Max-Plank-Institute for Solid State Research, Stuttgart
2010 - 2011

unimpaired operation of research equipment
Combar Reference Projects: Structures without steel

Bahnhofcity Vienna 2009
basement walls and drilled piles without steel to avoid inductance from neighboring subway tunnel

Huttengasse Vienna 2012
Combar Reference Projects: Ecological housing

Non-metallic reinforcement in foundation and ceiling slabs to avoid disturbances to the earth’s magnetic field.
Combar Reference Projects: Slender pre-cast elements

Redevelopment of former freight station in Freiburg as office building

45mm concrete steps (Ø 8mm Combar)
Combar Standard Application: Hoesch Additive Floor®

substitution for stainless steel mats

Parking garage Nahe River
Bad Kreuznach 2006
Parking garage T-Mobile Bonn, 2007
extension parking garage P1
Festo AG, Esslingen, 2007
Parking garage Lidl
Freiburg, 2008
Parking garage VEGA
Schiltach, 2008
P&R parking garage Rütgersstr.
City of Buchholz, 2010
parking garage Edeka, Zuffenhausen, 2010
Combar Reference Projects: rail beds and tracks

light rail line 26 Vienna, A 2009
Combar Reference Projects: rail beds and tracks

floor slab
BVB Depot
Basel
2009
Combar Reference Projects: Civil engineering

Gdansk September, 2012

- 4 weeks
- Design
- Detailing (every bar is placed)
- Production
- Delivery
- Surveillance
- Assembly
- Installation
Combar Reference Projects: Civil engineering

Trockau 2015: bridge caps

Bridge built 2001 no deviations from standards like concrete cover or concrete quality. Exposed to deicing salts

But caps with signs of severe chloride induced corrosion
Combar Reference Projects: Civil engineering

Trockau September 2015: bridge caps

Longitudinal bars in FRP
Perpendicular bars with more concrete cover still in steel
Combar Reference Projects: Civil engineering

DESY Lot 3 Hamburg
2009
Combar Reference Projects: Civil engineering

Emscherkanal
Bottrop
2010
FRP reinforcement

„Where steel reaches its limits“
Fatigue behaviour Combar

- Exclusion of anchoring failures
- Additional stresses introduced through bond have to be included
  - beam tests Ø8, 16, 25 mm bars at $\sigma_{\text{max}} = 300 \text{ N/mm}^2$, $2\sigma_a = 70 \text{ N/mm}^2$:
    - $\Rightarrow > 2 \text{ Mio. load cycles}$
  - beam tests Ø16 mm bars at $\sigma_{\text{max}} = 180 - 200 \text{ N/mm}^2$, $2\sigma_a = 150 \text{ to } 180 \text{ N/mm}^2$:
    - $\Rightarrow > 2 \text{ Mio. load cycles}$

In contrast to steel, the stress amplitude is a function of the upper stress level. The lower the stress, the higher the allowable stress amplitude.
Why 40°C?
Temperature in 60mm thick concrete member

Through radiation and convection up to 65°C can be reached in thin concrete elements at air temperatures of 30°C.

So which is the needed resistance for this actions?
Evaluating the rated „mean“ temperature

10,000h at 60°C is equal to 1,000,000h at 40°C
100,000h at 40°C is equal to 1,000,000h at 23°C
Evaluating the „rated“ mean temperature

Summing up a whole year with this approach leads to a rated mean temperature in concrete members of max. 38°C (thickness 60-200mm, 5 directions, grey, 12 climate regions)