Design of FRP-Profiles and All-FRP-Structures

ETHZ Course No. 101-0167-01

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References:

- Bank, L. “Composites for Construction - Structural Design with FRP Materials,” John Wiley & Sons, Inc., 2006. *(Chapters 12 - 15)*
- Fiberline. “Fiberline Design Manual,” www.fiberline.dk, 2003.
- Clarke, JL. (Ed.) “Structural Design of Polymer Composites - EUROCOMP Design Code and Handbook,” E & FN Spon, 1996.
- Shahverdi, M., “Mixed-mode static and fatigue failure criteria for adhesively-bonded FRP joints”. PhD Thesis, EPFL, Switzerland, 2013.

Content of the second exam on 11.12.2024, 15:45 - ca. 18:00!!! at Empa Dübendorf

Topics:

- Flexural strengthening of RC according to SIA166
  Lecture from 23.10.2024, Lecturer Dr. C. Czaderski
- Column confinement of RC
  Lecture from 30.10.2024, Lecturer Prof. Dr. M. Motavalli
- Design of FRP profiles and all FRP structures
  Lecture from 20.11.2024, Lecturer Prof. Dr. M. Shahverdi
- Externally bonded FRP reinforcement for metallic structures
  Lecture from 28.11.2024, Lecturer Dr. H. Heydarinouri
- Conceptual questions on the topics which were presented in the mentioned lectures. Furthermore, some calculations have to be performed.

- Time: 60 Minutes
- No laptops, tablets, smart phones etc.
- Only a calculator
- One A4 – Summary (both sides or two pages one side)

Outline

- **Introduction**
  (Pro’s and con’s of FRP / Examples)
- **Materials**
  (Manufacturing process / Materials / Durability)
- **Design Concept**
  (Concept / Basic assumptions / …)
  - **Bending Beam**
    (Timoshenko theory / Stresses / Deformations / Buckling …)
  - **Axial Members**
    (Serviceability and ultimate limit states)
  - **Connections**
    (Bolted joints / Glued joints)

Introduction

Introduction: Pro's and con's

- **Pro's**
  - **High specific strength:**

Material	CFRP	GFRP	Steel S500
$l_{max} = \frac{\sigma_{max}}{\rho \cdot g}$	**138.4 km**	**27.8 km**	**6.4 km**

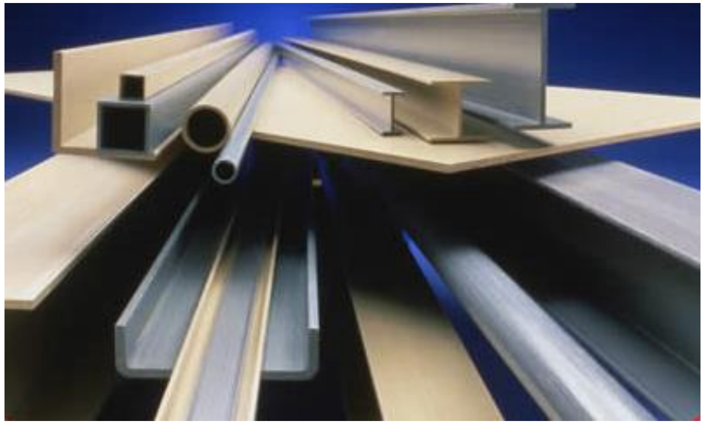
  - **Good in-plane mechanical properties**
  - **High fatigue and environmental resistance**
  - **Adjustable mechanical properties**
  - **Lightweight-> ease of handling, small additional load…**
  - **Quick assembly / erection**
  - **Low maintenance**
  - **Highly cost-effective (2-10 €/kg)**

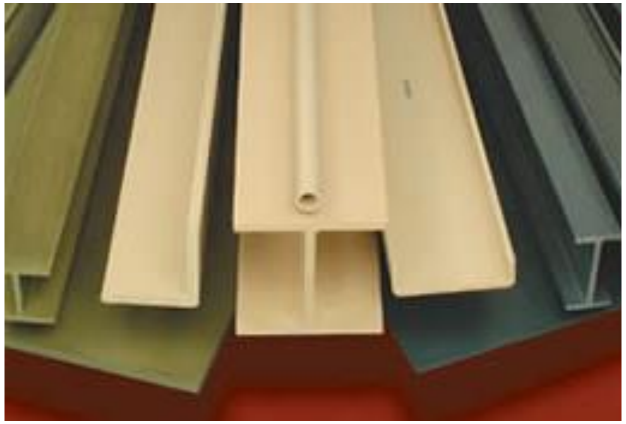
Introduction: Pro’s and con’s

- **Con’s**
  - **Brittle**
  - **High initial costs**
  - **Low to moderate application temperature** (-20 up to 80 °C)
  - **Low fire resistance** (sometimes with unhealthy gases)

Introduction: Common profiles

- **Structural profiles**
  - **Most structural profiles produced in conventional profile shapes similar to metallic materials**
  - **Similarity in geom. and properties, however no <u>standard</u> geom., mechanical and physical properties used by all manufacturers**





Structural profiles

Non-structural profiles

Introduction: Examples

- **Footbridges**

Fiberline Bridge in Kolding, DK

1997
The bridge was installed during 18 hours over 3 nights
Span: 40 m
Cost: 0.5 mio CHF
Only Fiberline standard profiles used

http://fiberline.com/fiberline-bridge-kolding

Pontresina bridge, Switzerland

1997
Span: 2 x 12.5 m
Weight: 3.3 tons (installation by helicopter)

http://fiberline.com/pontresina-bridge-switzerland

Introduction: Examples

- **Footbridges**

Composite pedestrian bridge in Lleida, Spain

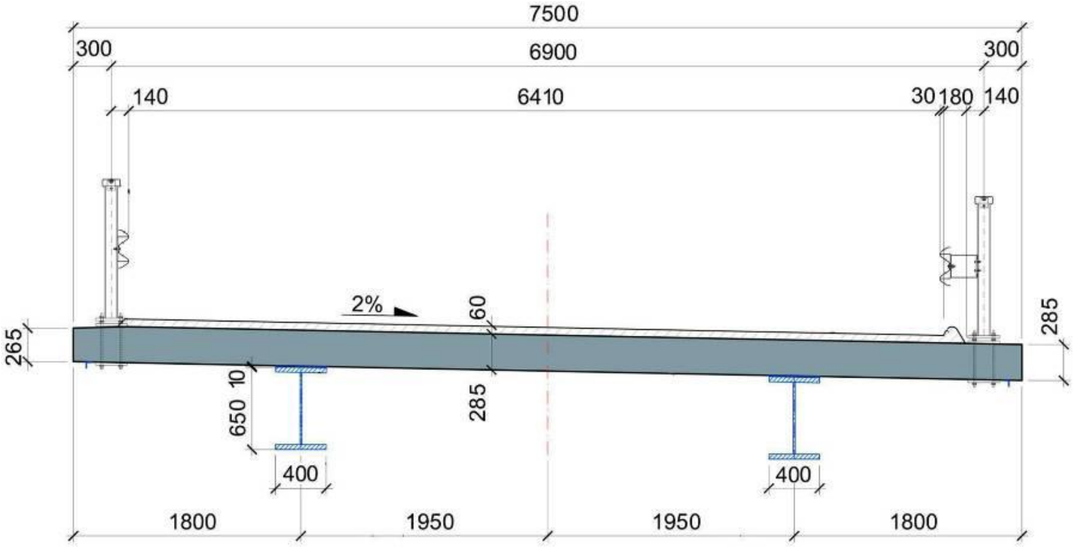
Span: 38 m
Width: 3.0 m

http://fiberline.com/international-award-innovative-grp-footbridge

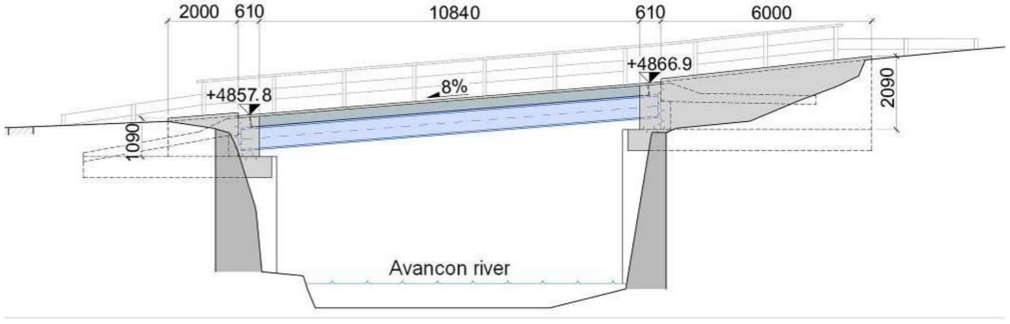
“GRP does not conduct electricity, which is also very important as it means there is no magnetic interference with the electrified railway,” continues Mr. Sobrino.

Introduction: Examples *(***Avançon Bridge, Switzerland, 2012***)*

- **Road bridges**



Cross section of new two-lane bridge (dimensions in [mm])



Longitudinal section of new bridge (dimensions in mm) [Prof. Keller]

Bridge details

Location: Bex, Suisse

Installed on: 12th October, 2012

Dimensions: 12m x 7m (9 tons)

Introduction: Examples

- **Bridgedeck** (Footbridges)

Würenlos, Switzerland

Loopersteg, Switzerland

Introduction: Examples

- **Buildings**

Eyecatcher Building, Basel, Switzerland 1998

Height: 15 m
Storeys: 5

http://www.fiberline.com/gb/casestories/case1835.asp

Project: Maagtechnic

Introduction: Examples

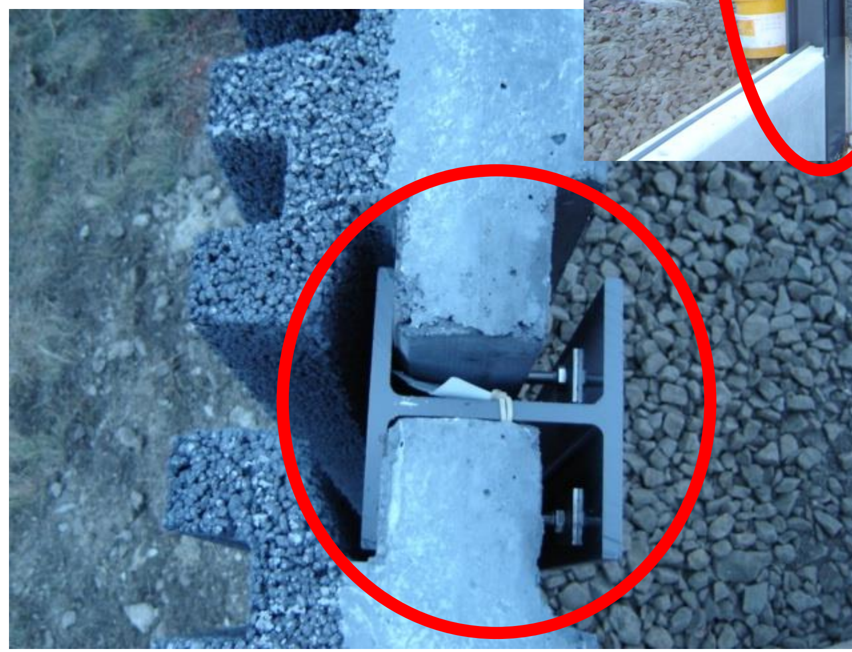
- **Laboratory bridge**

Empa Laboratory Bridge, Switzerland

Span: 19 m
Width: 1.6 m
Load capacity: 15 tons

Introduction: Examples

- **Noise barrier SBB**



Göschenen, Switzerland

Project: Maagtechnic

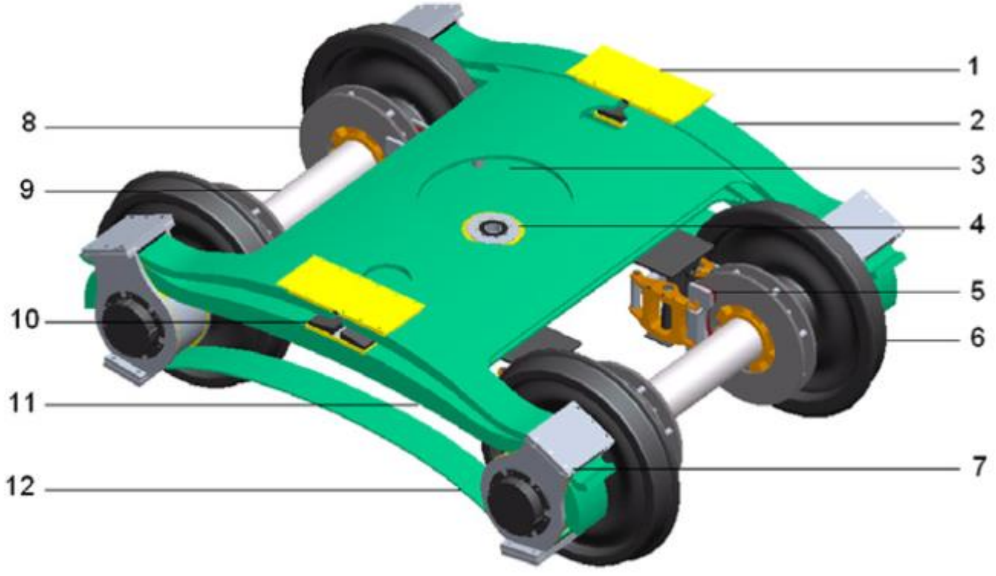
Introduction: Examples

- **Balconies**

Switzerland

Project: Maagtechnic

Introduction: Examples
bogie



Summary of the name and material of each part shown in Fig

Number	Name	Material
1	Side bearer	Polyurethane, nylon and rubber
2	Upper bogie frame	Glass fibre reinforced epoxy
3	Lower bogie transom	Glass fibre reinforced epoxy
4	Central pivot point	Steel, rubber and polyurethane
5	Calliper	Steel, rubber and brake pads
6	Wheel	Steel
7	Axlebox	Steel, rubber and polyurethane
8	Brake disc	Steel
9	Axle	Steel
10	Bogie frame bearer	Rubber, polyurethane
11	Lower bogie frame	Glass fibre reinforced epoxy
12	Axle tie	Glass fibre reinforced epoxy

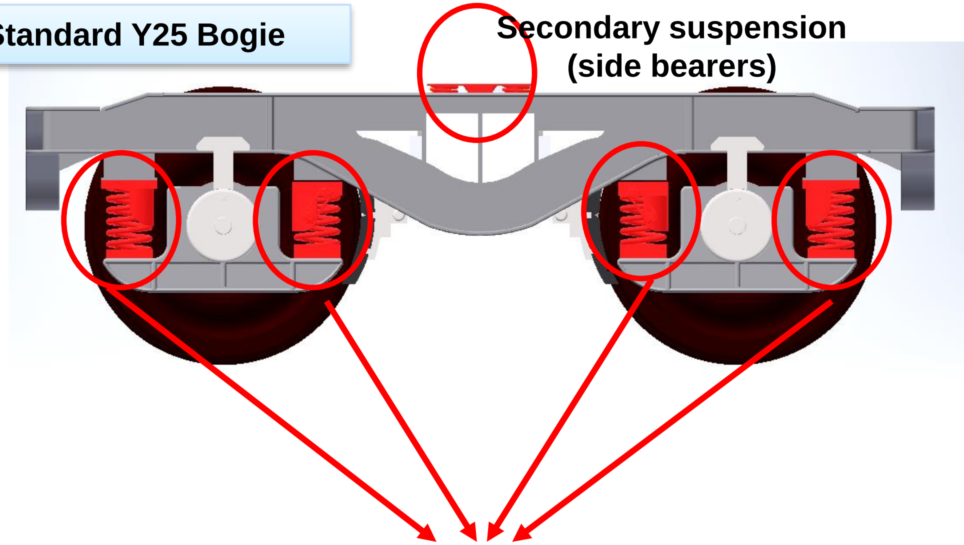
Hou, J. and G. Jeronimidis, A novel bogie design made of glass fibre reinforced plastic. Materials & Design, 2012. 37: p. 1-7.

Introduction: Examples

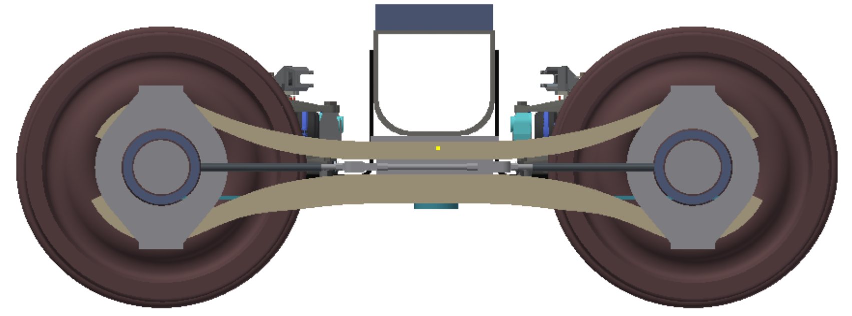
bogie

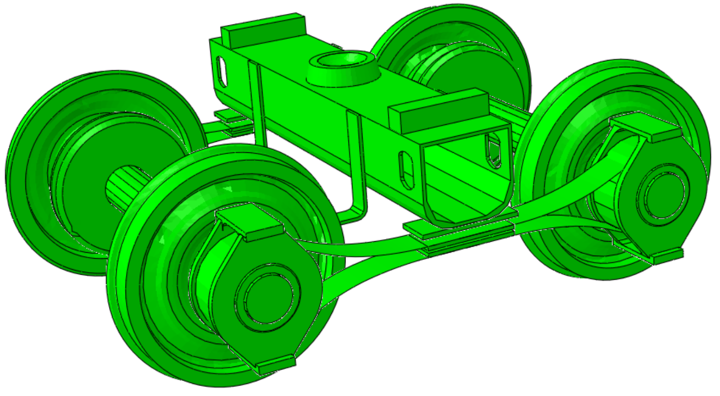
- **Metallic coil spring are replaced by FRP leaf springs, i.e. suspension system is integrated to the FRP frame**

Standard Y25 Bogie



Hybrid GFRP bogie





Introduction: Application

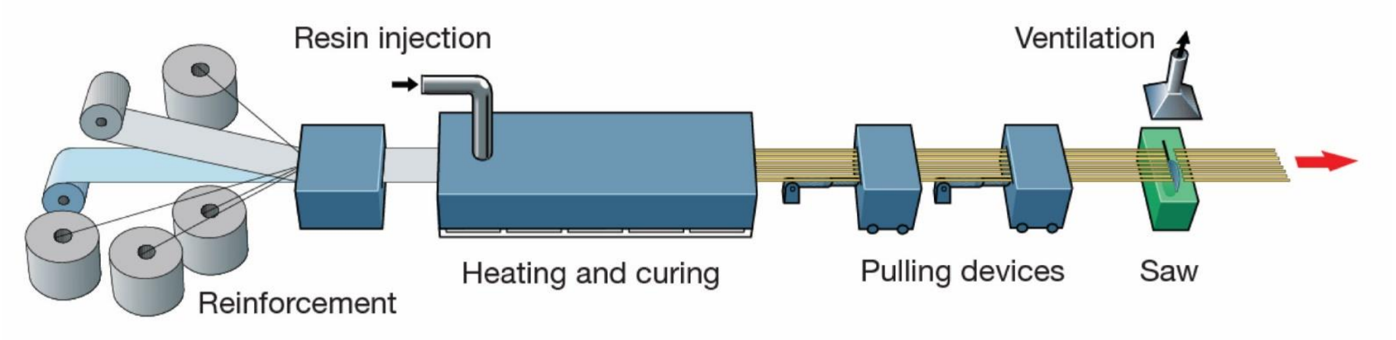
- Applications where GFRP structures are competitive:
  - **Significant corrosion and chemical resistance is required**
    (Food and chemical processing plants, cooling towers, offshore platforms …)
  - **Electromagnetic transparency or electrical insulation is required.**
  - **Light-weight is cost essential**
    (fast deployment …)
  - **Prestige and demonstration objects**
    (e.g. Novartis Campus Entrance Building)

Photo: Prof. Th. Keller, EPFL

Material

Material: Pultrusion process

- **Only pultruded GFRP profiles will be considered in this lecture**



Pultrusion line

- **Production of profiles with constant cross-section along the length**
- **High quality**
- **Continuous longitudinal fiber bundles and filament mats**

Pultrusion process

Take from [https://www.youtube.com/watch?v=aXq1hrzne2k]

Material: Components

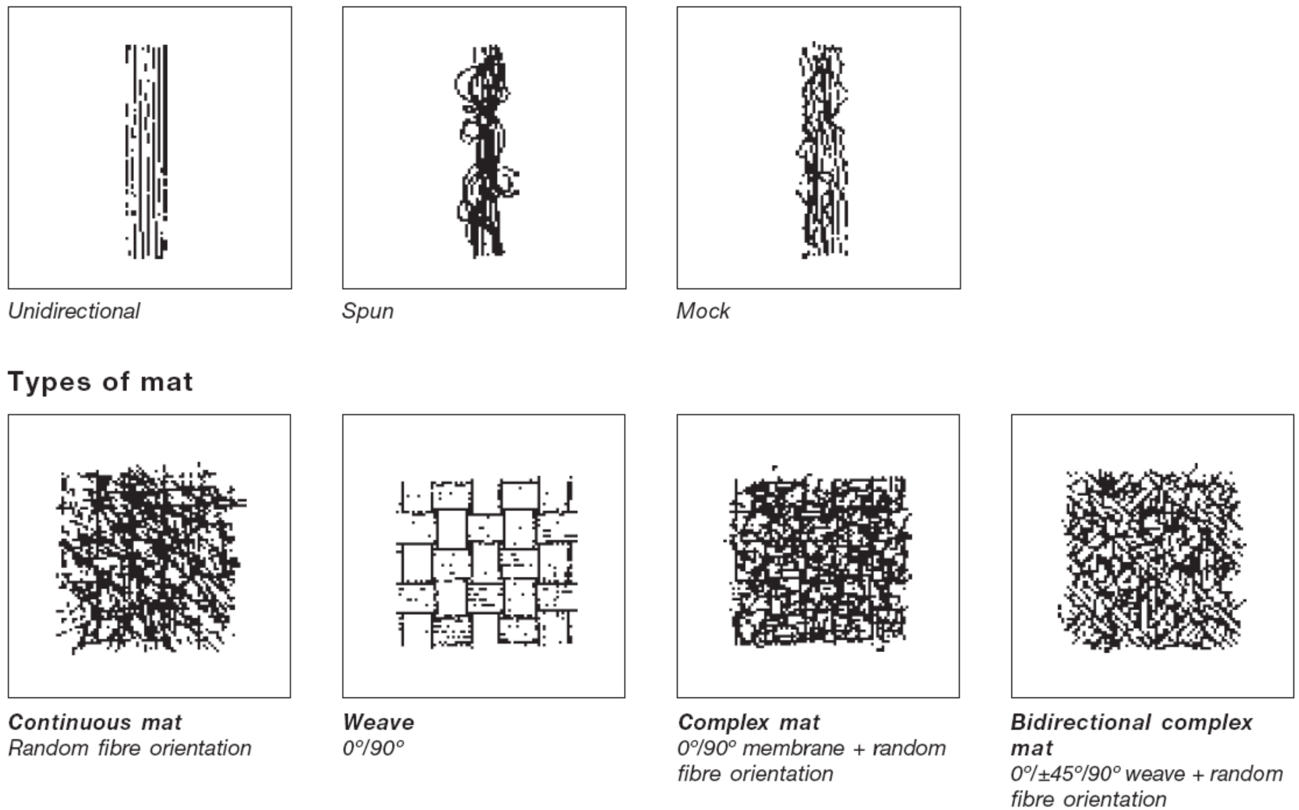
- **Pultruded profiles contain three primary components:**
  - **Reinforcement**
  - **Matrix**

    polyester
    epoxy
    phenol

  - **Supplementary constituents**

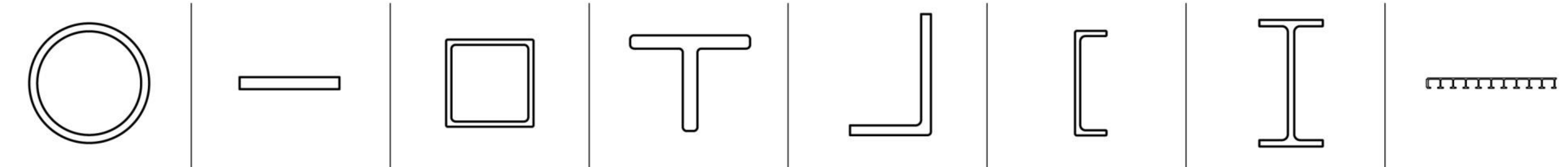
    polymerisation agents
    fillers
    additives

Types of roving



Material: Shapes of pultruded profiles

- **Available Profiles on Stock:**



Name	Tubes	Flat - Profiles	Square Tubes	T - Profile	Angle	U / UL - Profile	I / IL - Profile	Plank
Dimensions [mm]	Ra = 37.5 / 45 T = 5	B = 30 - 1220 H = 6 -12	H = 50 - 240 T = 5 - 12	H = 60 / 90 B = 60 / 72 T = 6 / 10	H = 50 - 150 B = 50 - 150 T = 6 - 12	H = 120 - 360 B = 60 -180 T = 6 - 18	H = 120 - 360 B = 60 -180 T = 6 - 18	B = 500 H = 40

Length up to 12 m (for transportation reasons)!

- Special cross-sections can be designed and ordered
  (several kilometres are necessary → special tools have to be designed)

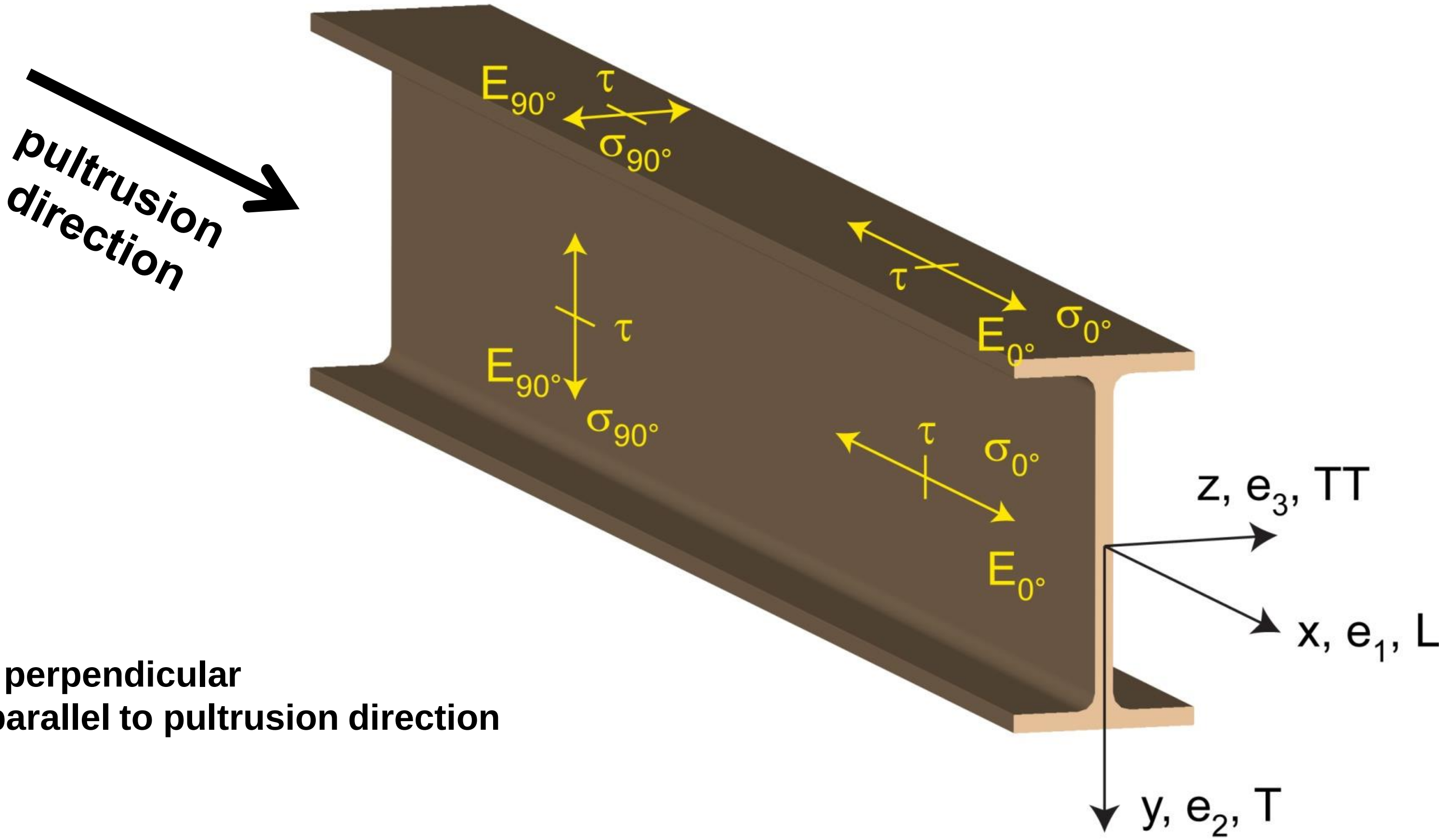
Material: Durability

- **Various environmental and load conditions that affect durability of (G)FRPs in terms of strength, stiffness, fiber/matrix interface integrity, cracking:**
  - **water/sea water**
  - **chemical solutions**
  - **prolonged freezing**
  - **thermal cycling (freeze-thaw)**
  - **elevated temperature exposure**
  - **UV radiation**
  - **creep and relaxation**
  - **fatigue**
  - **fire…**

Design Concept

Design Concept: Basic Assumptions

- **Definitions and directions**



90° → perpendicular
0° → parallel to pultrusion direction

Design Concept

- **Codes**
  - **Every manufacturer has its own profile design → No European Design Code is available!** (only EN13706, about testing and notation)
  - **There exists European guidelines: EUROCOMP 1996 Design Code**
    EUROCOMP 1996 Handbook
  - **Fiberline Design Manual is based on Eurocomp 1996.**
    - Design concept (according to Eurocodes and Swisscodes)
    - Partial safety factors
    - Measured material parameters
    - Rules for bolted connections

Design Concept

- **Concept of Limit State Design** **(According to Euro Codes and Swiss Codes)**

- **Ultimate limit stress**

$$E_d \leq R_d$$

E_d … **Calculated stress (including load factors) … SIA260 / 261**

R_d … **Rated value of the resistance capability**

where $\mathbf{R}_d = \frac{\mathbf{R}_k}{\gamma_m}$

R_k … the resistance capability

γ_m…the reduction coefficient / partial safety factor

Design Concept

- **Partial safety factor** $\gamma_m = \gamma_{m,1} \cdot \gamma_{m,2} \cdot \gamma_{m,3} \cdot \gamma_{m,4}$

Coefficient	Description	Max. γ_m	Min. γ_m	Fiberline
$\gamma_{m,1}$	Derivation of mat. properties	2.25	1.15	1.15
$\gamma_{m,2}$	Degree of postcuring	1.6	1.1	1.1
$\gamma_{m,3}$	Production process	2.0	1.0	1.0
$\gamma_{m,4}$	Operating temperature			

Operating temperature °C	$\gamma_{m,4}$	
	Short-term load	Long-term load
-20 ... +60	1.0	2.5
80	1.25	3.13

Design Concept: Basic Assumptions

- **Material Properties, stength values** (Fiberline Profiles)

$1/\gamma_m$

All values given in **[MPa]**		Typical strength values	Reduced strength values short-term	Reduced strength values long-term
Flexural strength, 0°	$f_{b,0°}$	240	185	75
Flexural strength, 90°	$f_{b,90°}$	100	75	30
Tensile strength, 0°	$f_{t,0°}$	240	185	75
Tensile strength, 90°	$f_{t,90°}$	50	40	15
Compressive strength, 0°	$f_{c,0°}$	240	185	75
Compressive strength, 90°	$f_{c,90°}$	70	55	20
Shear strength (in-plane)	f_{τ}	25	20	8

$\gamma_m = 1.3$

$\gamma_m = 3.2$

Design Concept

- **Serviceability limit states**

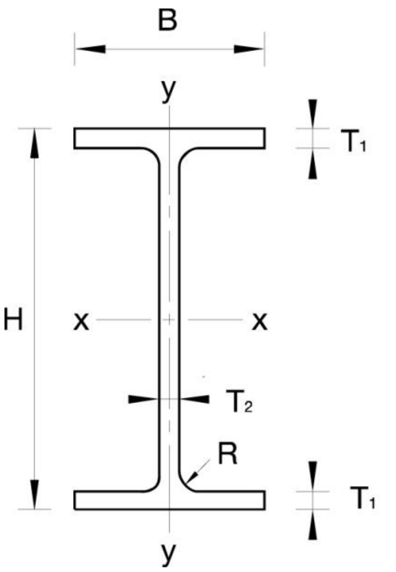
$$E_d \leq C_d$$

E_d … **the crucial action effect due to the load cases considered in the investigated dimensioning situation. Typically maximal deflection response of the structure.**

C_d … **corresponding serviceability limit. SIA 261**

Design Concept: Basic Assumptions

- **Typical data sheet of a profile** (Fiberline I-Profile)



I-profile	H	B	T $_1$	T $_2$	R	A	A $_{k,y}$	A $_{k,x}$	g	I $_{xx}$	W $_{xx}$	I $_{yy}$	W $_{yy}$	E $_{0°}$	E $_{0°}$·I $_{xx}$
HxBxT 1)	mm	mm	mm	mm	mm	mm ^{2}	mm ^{2}	mm ^{2}	kg/m	mm ^{4}	mm ^{3}	mm ^{4}	mm ^{3}	MPa	Nmm ^{2}
factor	1	1	1	1	1	10 ^{3}	10 ^{3}	10 ^{3}	1	10 ^{6}	10 ^{3}	10 ^{6}	10 ^{3}	10 ^{3}	10 ^{9}
I 120x60x6	120	60	6	6	7.5	1.42	0.68	0.58	2.55	3.10	51.7	0.22	7.30	23	71.30
I 160x80x8	160	80	8	8	8	2.49	1.22	1.02	4.48	9.66	121	0.69	17.3	28	270.5
I 200x100x10	200	100	10	10	10	3.89	1.90	1.60	6.99	23.6	236	1.69	33.7	28	660.8
I 240x120x12	240	120	12	12	12	5.60	2.74	2.30	10.1	48.9	408	3.50	58.3	28	1369
I 300x150x15	300	150	15	15	15	8.74	4.28	3.60	15.7	119	796	8.54	114	28	3332
I 360x180x18	360	180	18	18	18	12.6	6.16	5.18	22.7	248	1376	17.7	197	28	6944

Bending Beam

Bending Beam: Design of …

- Calculate **bending moments Md and shear forces Qd** acting on the profile, using the appropriate load factors (SIA 260 / 261)

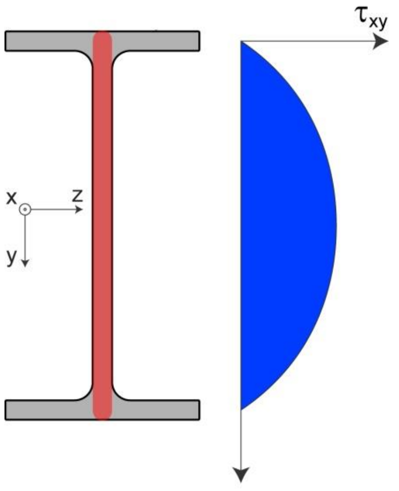
- **Ultimate limit state**
  - **Bending:**

$$\sigma_{\max} = \frac{M_{d,y,\max}}{W_y} \left(+ \frac{M_{d,z,\max}}{W_z} \right) \leq \frac{f_{b,0°}}{\gamma_m}$$

  - **Shear:**

$$\tau_{\max} = \frac{Q_{d,y,\max}}{A_{k,y}} \leq \frac{f_{\tau}}{\gamma_m}$$

A_k … relevant shear area



Bending Beam: Design of …

- **Serviceability limit state**
  - **Deflection limit:** $\frac{w_{\max}}{L} < \frac{1}{\alpha}$

    α … typically selected between 200 and 400 given by SIA 261 or the building owner

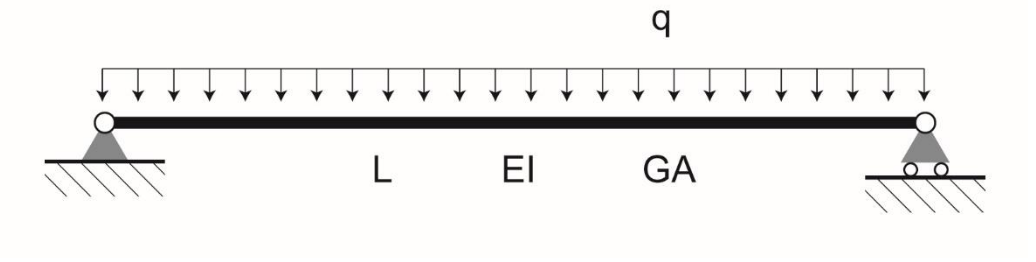
    $w_{\max}$ … calculated including shear deformations

  - **Vibrations**

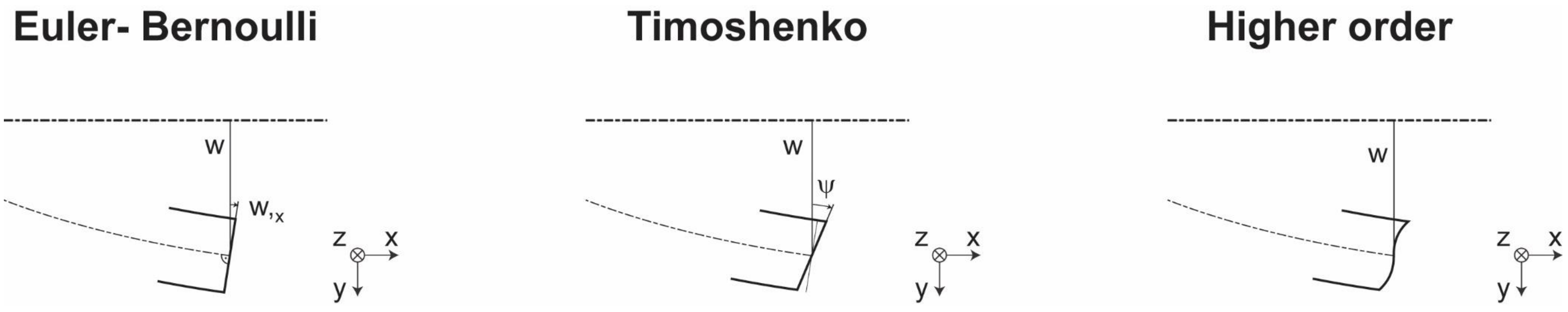
    Light-weighted and ‘soft’ structures are susceptible to vibrations (traffic, wind, the movement of people …)!!

Bending Beam: Timoshenko Theory

- **Pultruded profiles have a low shear modulus → shear deformation must be taken into account!**
- **Several bending theories have been published for beams:**
  - **Euler-Bernoulli theory (1702)**
  - **Timoshenko theory (1968)**
  - **Higher order beam theory**
- **A simply supported beam with a symmetric cross-section is discussed**



Bending Beam: Timoshenko Theory



Cross-sections plane and perpendicular	Cross-sections plane but **NOT** perpendicular	Cross-sections do **NOT** remain plane
1 degree of freedom	2 degrees of freedom	3+ degrees of freedom
w	**w** and **ψ**	**w**, **ψ** and …

Bending Beam: Euler vs. Timoshenko Theory

Kinematic relationships

$$u_x = -y \cdot w(x),_x$$
$$u_y = w(x)$$

$$u_x = -y \cdot \psi(x)$$
$$u_y = w(x)$$

$$\varepsilon_x = \frac{\partial u_x}{\partial x} = -y \cdot w(x),_{xx}$$
$$2\varepsilon_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} = 0$$

$$\varepsilon_x = \frac{\partial u_x}{\partial x} = -y \cdot \psi(x),_x$$
$$2\varepsilon_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} = -\psi(x) + w(x),_x$$

Hook's law

$$\sigma_x = \mathrm{E}_{0^\circ} \cdot \varepsilon_x \quad \text{and} \quad \tau_{xy} = \mathrm{G} \cdot 2\varepsilon_{xy}$$

$$M_z = \iint_{QS} -y \cdot \sigma_x \cdot dydz = w,_{xx} \cdot \mathrm{E}_{0^\circ} \cdot \mathrm{I_z}$$

$$M_z = \iint_{QS} -y \cdot \sigma_x \cdot dydz = \psi,_x \cdot \mathrm{E}_{0^\circ} \mathrm{I_z}$$
$$Q_y = \kappa \iint_{QS} \tau \cdot dydz = \left(w,_x - \psi\right) \cdot \kappa \cdot GA$$

Bending Beam: Euler vs. Timoshenko Theory

Equilibrium

In a first approximation, the deflections are calculated by direct integration of:

$$w,_{xx} = \frac{M(x)}{\mathrm{E}_{0°} \cdot \mathrm{I}_z}$$

Equilibrium on an infinitesimal beam element:

$$q(x) = -Q,_x = -\left(w,_{xx} - \psi,_x\right) \cdot \kappa \cdot GA$$

$$M,_x - Q = \psi,_{xx} \cdot \mathrm{E}_{0°}\mathrm{I}_z + \left(w,_x - \psi\right) \cdot \kappa \cdot GA = 0$$

Coupled second order differential equation

Solution for the simply supported beam (distributed load)

$$M(x) = \frac{1}{2}qLx - \frac{1}{2}qx^2 \quad , \quad w(0) = 0 \text{ and } w(L) = 0$$

$$w,_{xx} = \frac{1}{\mathrm{E}_{0°} \cdot \mathrm{I}_z}\left(\frac{1}{2}qLx - \frac{1}{2}qx^2\right)$$

$$w(x) = \frac{qx}{24 \cdot \mathrm{E}_{0°} \cdot \mathrm{I}_z} \cdot \left(L^3 - 2Lx^2 + x^3\right)$$

$$w(0) = 0 \text{ and } w(L) = 0$$

$$M(0) = 0 \rightarrow \psi,_x(0) = 0 \text{ and } M(L) = 0 \rightarrow \psi,_x(L) = 0$$

Functions:

$$w(x) = A_1x^4 + A_2x^3 + A_3x^2 + A_4x + A_5$$

$$\psi(x) = B_1x^3 + B_2x^2 + B_3x + B_4$$

Bending Beam: Euler vs. Timoshenko Theory

Put in $\psi,_{xx} \cdot \mathrm{E}_{0°}\mathrm{I}_z + (w,_x - \psi) \cdot \kappa \cdot GA = 0$ and solve for the coefficients →

$$B_1 = -4A_1 \quad , \quad B_3 = -2A_3 - \frac{24A_1 \cdot \mathrm{E}_{0°}\mathrm{I}_z}{\kappa \cdot \mathrm{GA}}$$

$$B_2 = -3A_2 \quad , \quad B_4 = -\frac{6A_2 \cdot \mathrm{E}_{0°}\mathrm{I}_z}{\kappa \cdot \mathrm{GA}} - A_4$$

Use the boundary conditions and the second differential eq. to calculate $A_1 - A_5$:

$$w(x) = \frac{qx(L-x)}{2 \cdot \kappa \cdot \mathrm{GA}} + \frac{qx(L-x)(L^2 + Lx - x^2)}{24 \cdot \mathrm{E}_{0°}\mathrm{I}_z}$$

Deflection at midspan

$$w\left(L/2\right) = \frac{5 \cdot qL^4}{384 \cdot \mathrm{E}_{0°}\mathrm{I}_z}$$

$$w\left(L/2\right) = \frac{5 \cdot qL^4}{384 \cdot \mathrm{E}_{0°}\mathrm{I}_z} + \frac{q \cdot L^2}{8 \cdot \kappa \cdot \mathrm{GA}}$$

Bending Beam: Euler vs. Timoshenko Theory

- **General expression for the total beam deflection as a sum of the deflection due to bending and shear:**

$$w(x) = \frac{f_1(x)}{E_{0^\circ} I_z} + \frac{f_2(x)}{\kappa \cdot GA}$$

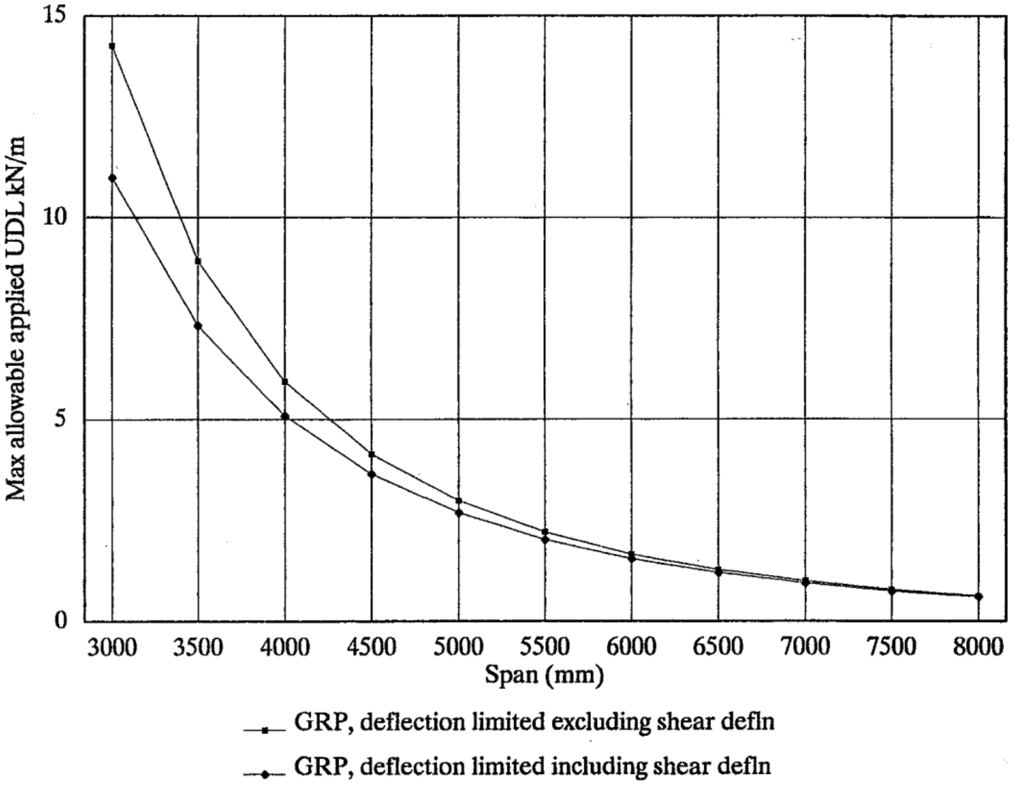
Beam	$f_1(w_{\max})$	$f_2(w_{\max})$	$x(w_{\max})$
Simply supported			
Uniformly distr. load (q)	$\frac{5 \cdot qL^4}{384}$	$\frac{qL^2}{8}$	$\frac{L}{2}$
Concentrated load (P)	$\frac{PL^3}{48}$	$\frac{PL}{4}$	$\frac{L}{2}$
Cantilever beam			
Uniformly distr. load (q)	$\frac{qL^4}{8}$	$\frac{qL^2}{2}$	L
Concentrated load (P)	$\frac{PL^3}{3}$	PL	L

Bending Beam: Euler vs. Timoshenko Theory

- **Example:** influence of the shear deformation

Profile: 300 x 150 mm I-beam

Load: uniformly distributed



General rule of thumb for slender Beams:

for GFRP beams with span/depth > 25

shear deformation can be ignored

Bending Beam: Example

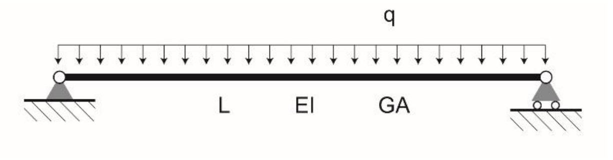
- Choose an appropriate Profile for the following specifications

L = 3.0 m

$q_{d,uls}$ = 13 kN/m

$q_{d,ser}$ = 10 kN/m

w_{max}/L = 1/300 → w_{max}=0.01 m



1. Deflections and loading

$$w_{max} = \frac{5 \cdot q_{d,ser} L^4}{384 \cdot \mathrm{E}_{0°} \mathrm{I}_z} + \frac{q_{d,ser} \cdot L^2}{8 \cdot \kappa \cdot \mathrm{GA}}$$

$$\sigma_{max} = \frac{q_{d,uls} L^2}{8} \cdot \frac{h}{2 \cdot \mathrm{I}_z}$$

$$\tau_{max} = \frac{q_{d,uls} L}{2} \cdot \frac{1}{\mathrm{A}_{k,y}}$$

Bending Beam: Example

2. Find a profile with sufficient bending stiffness (SLS).

Shear deformations are neglected in a first step:

$$\mathrm{E}_{0°}\mathrm{I}_z \geq \frac{5 \cdot q_{d,ser} L^4}{384 \cdot w_{\max}} = 1.054 \cdot 10^6 \ \mathrm{Nm}^2$$

→ from specification table: choose **I** 240x120x12 → $\mathrm{E}_{0°}\mathrm{I}_z = 1.369 \cdot 10^6 \ \mathrm{Nm}^2$

3. Check the bending and shear stresses (ULS)

$$\sigma_{\max} = \frac{q_{d,uls} L^2}{8} \cdot \frac{h}{2 \cdot \mathrm{I}_z} = 35.8 \ \mathrm{MPa} \quad \leq f_{b,0°,d} = 185 \ \mathrm{MPa}$$ **(short term)**

$$\tau_{\max} = \frac{q_{d,uls} L}{2} \cdot \frac{1}{\mathrm{A}_{k,y}} = 7.1 \ \mathrm{MPa} \quad \leq f_{\tau,d} = 20 \ \mathrm{MPa}$$ **(short term)**

Do not forget to check also the long term!

Bending Beam: Example

4. Check deflection (including shear deformation)

$$w_{\max} = \frac{5 \cdot q_{d,ser} L^4}{384 \cdot E_{0^\circ} I_z} + \frac{q_{d,ser} \cdot L^2}{8 \cdot \kappa \cdot GA} = 9.3 \cdot 10^{-3}\,\mathrm{m} \qquad \leq w_{\max} = 0.01\,\mathrm{m}$$

(7.7 mm) (1.6 mm) (κ=0.42)

$$w_{\max} = \frac{5 \cdot q_{d,ser} L^4}{384 \cdot E_{0^\circ} I_z} + \frac{q_{d,ser} \cdot L^2}{8 \cdot GA_{web}} = 9.1 \cdot 10^{-3}\,\mathrm{m}$$

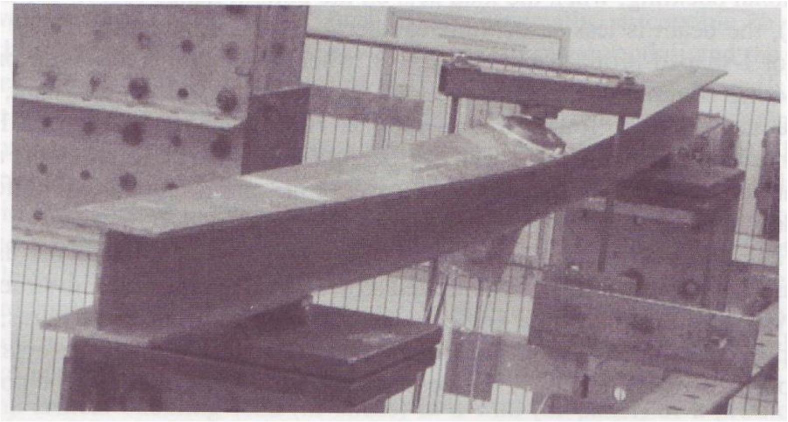
Simplification: use area oft the web (conventionally manufactured GFRP I and □-profiles)

5. Remarks:

- The design of **GFRP**-profiles is mostly driven by serviceability criteria.
- Start the design iteration procedure using the maximal deflection criterion.

Bending Beam: Stability problems

- **Lateral-torsional buckling**



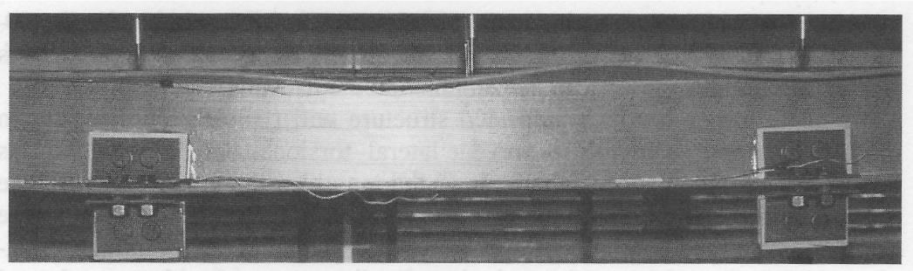
- Flange (compressive) displace laterally to the transverse load direction.
- Torsional stiffness is too low (especially for open section profiles)
- Theoretical calculations or design measures.
  → *see e.g. L.P. Kollár 2003, Mechanics of composite structures.*

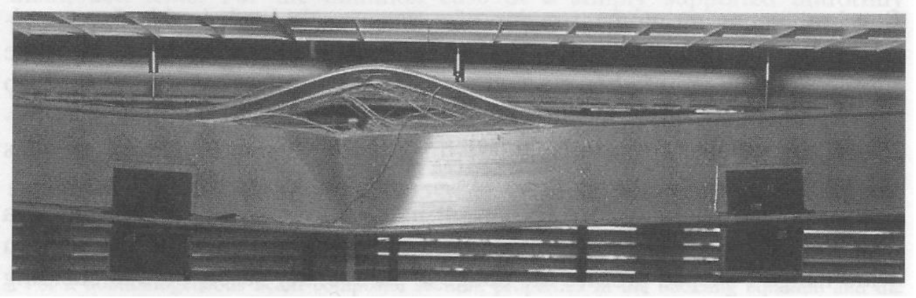
- **Example:**

Compressive flanges are kept in place by connection to the bridge deck.

Bending Beam: Stability problems

- **Local buckling of walls due to in-plane compression**





- Flange (compressive) displaces in the direction of the transverse load.
- Low bending stiffness perpendicular to the pultrusion direction.
- Weak fiber mats.

- **Local buckling of walls due to in-plane shear**
- **Web crushing and web buckling in transverse direction**

Axial Members

Axial Members: Tension

- **Ultimate limit state under axial tension Nd**

$$\frac{\mathrm{Nd}}{\mathrm{A}} \leq \frac{f_{t,0°}}{\gamma_m}$$

A can be either gross or net area

- **Serviceability limit state**

$$\delta_x = \frac{\mathrm{N} \cdot \mathrm{L}}{\mathrm{E}_{0°} \cdot \mathrm{A}}$$

A = gross area

- **Remark:** The critical aspect of axial members in tension are neither the serviceability nor the ultimate limit state. Critical is the **load transfer** to the GFRP profile!

Axial Members: Compression

- **Ultimate limit state under axial compression Nd**

$$Nd \leq \frac{F_c}{1+\frac{F_c}{N_{Euler}}}$$

$$F_C = \frac{A \cdot f_{c,0°}}{\gamma_m}$$ **…** maximal compressive load

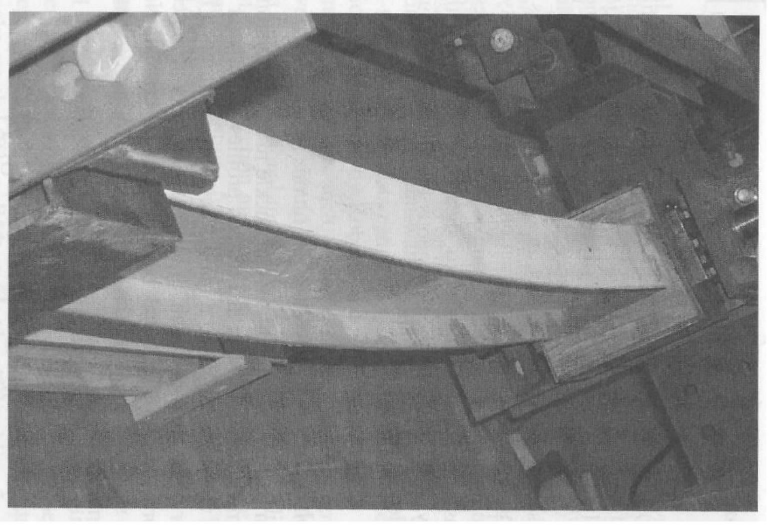
$$N_{Euler} = \frac{\pi^2 \cdot E_{0°} \cdot I}{\gamma_{m,E} \cdot L_k^2}$$ … Euler load

L_k … Buckling length for columns

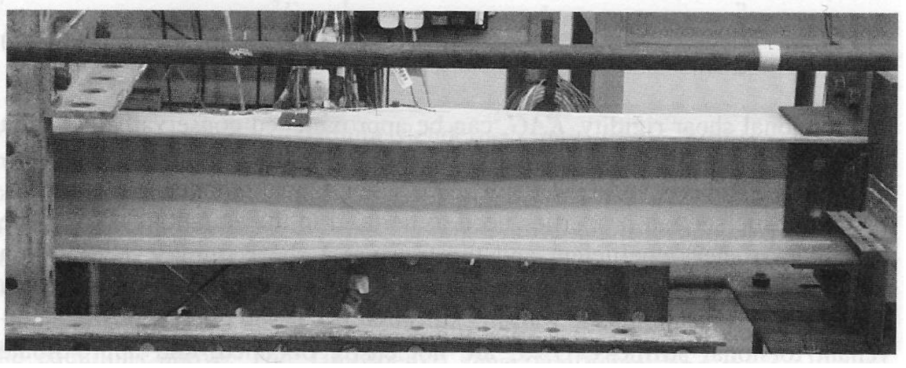
$\gamma_{m,E}$ … coefficient for Young's modulus **= 1.3**

Axial Members: Compression

- The influence of shear deformation should be considered, but in the most cases, the influence will be small (less than 5%)**.**
- **Local buckling** should be considered for short columns.
- For more information on the various buckling modes and effects
→ see *L.P. Kollár 2003, Mechanics of composite structures*



Global buckling

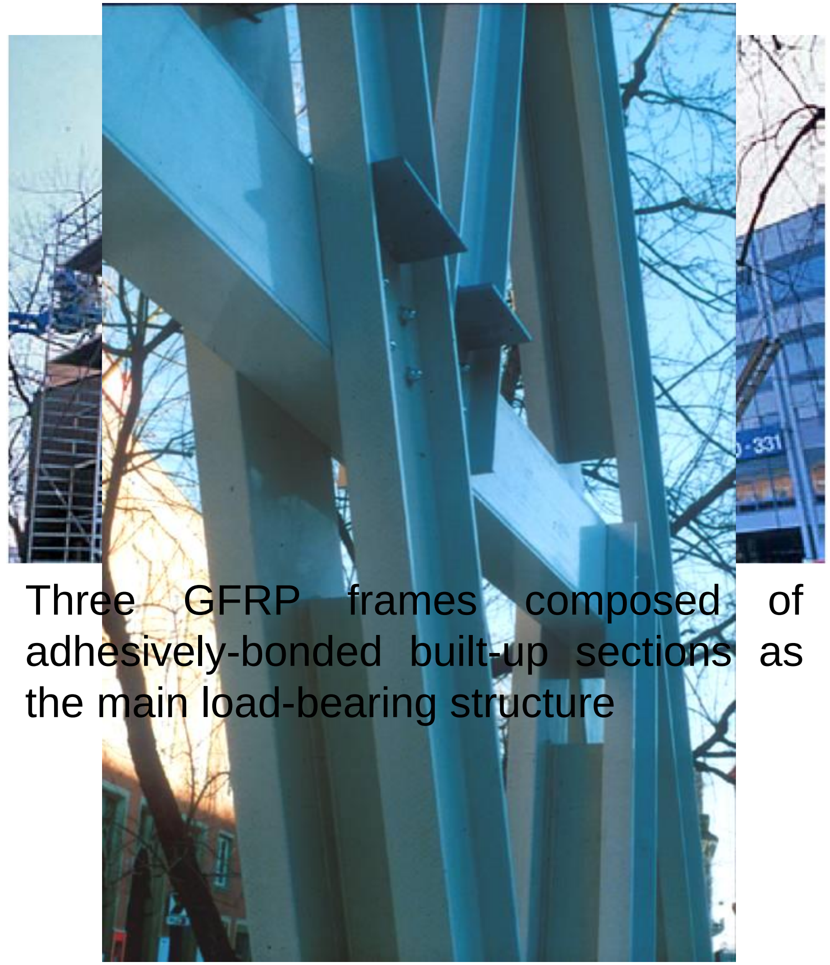


Local buckling

Connections

Joints in FRP composite structures

Eyecatcher Building: a mobile lightweight five-story GFRP building, Switzerland, 1998



Three GFRP frames composed of adhesively-bonded built-up sections as the main load-bearing structure

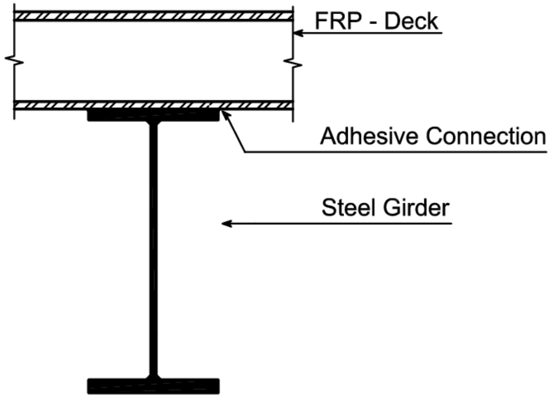
Adhesively-bonded sections built up from pultruded profiles

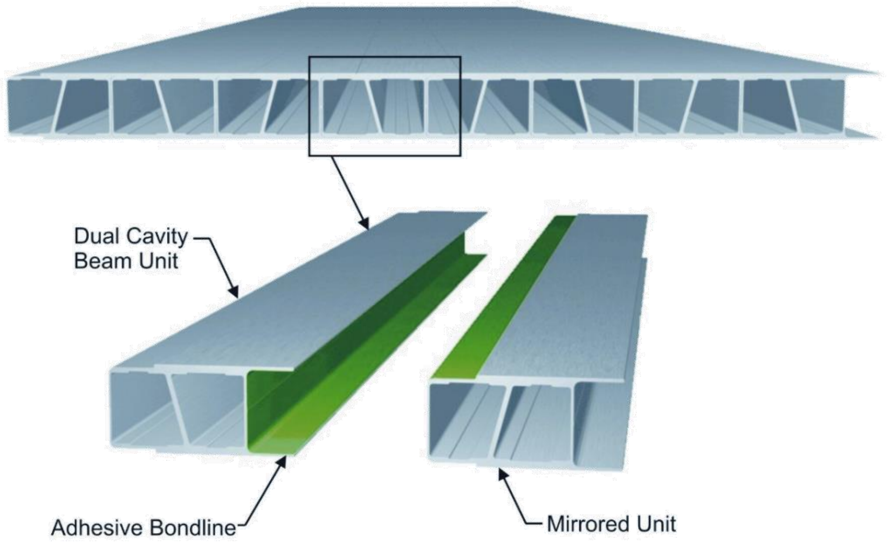
Bolted joints

Joints in FRP composite structures

FRP bridge deck panels

[Thesis Dr. Gürtler, CCLab 2004]





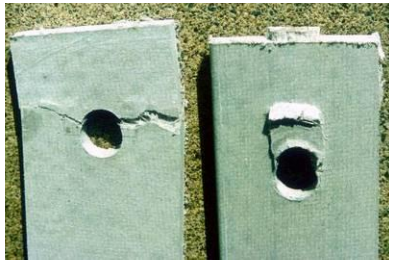
Schematic of *DuraSpan*™ Deck Panel

Overview of the experimental set-up

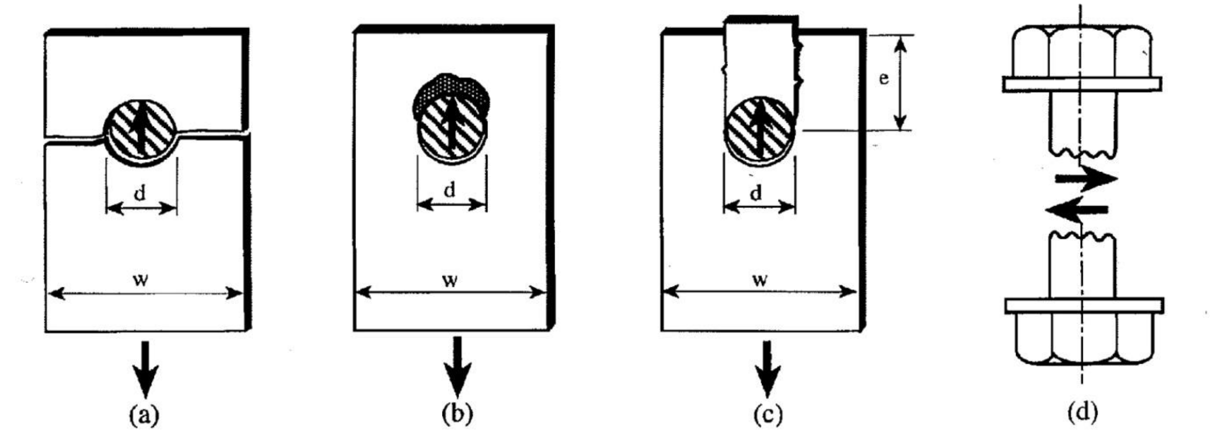
Failure of adhesive bond

Connections: Bolted joints

- Bolts = Stress concentration in the profile and the bolt.
- It is necessary to ensure that the bolts and the profile can withstand this concentrated local stress compression.
- It is necessary to ensure that the region surrounding a group of bolts will not be torn out of the profile.
- Basic failure modes in bolted shear connections:



Prof. Keller, EPFL



net-section failure

bearing failure

shear-out failure

bolt shear failure

Connections: Bolted joints

- The design procedure is comparable to the one for steel connections, but since there exist no standard GFRP material → each manufacturer has its own design rules for bolted joints.

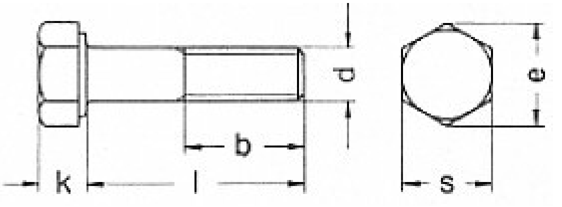
- **IMPORTANT REMARKS:**

  - **The direction of pultrusion and the direction of the force is RELEVANT!!!** (anisotropic material)

  - **Use stainless or galvanised steel**

  - **Do not cut threads in the composite material!**

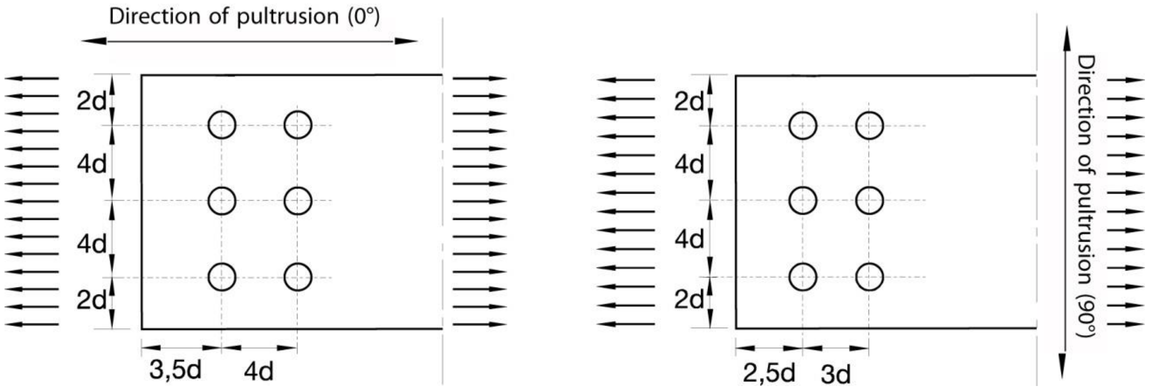
  - **Use screws with shafts**



Connections: Bolted joints *(Fiberline recommendations)*

- **Calculation of load bearing capacity of bolts**
  - Shear in longitudinal direction (0°)
  - Shear in transverse direction (90°)
  - Tensile force

- **Minimum distances**

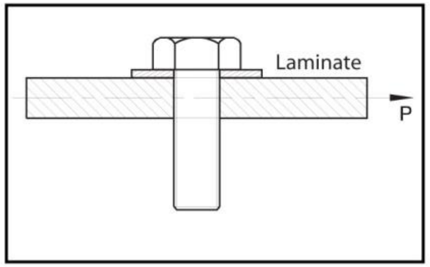


***Connections: Bolted joints** (Fiberline recommendations)*

- **Joint capacity tables, available for shear and tension**

Pin-bearing strength (P) in kN for direction of force 0° (longitudinal direction of profile)

Bolt	Load-bearing capacity per cut (kN)		Thickness of laminate in mm															
	1 cut	2 cuts	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
M 6	2,7	5,4	3,5	4,2	4,8	5,5	6,2	6,9	7,6	8,3	9,0	9,7	10,4	11,1	11,8	12,5	13,2	13,8
M 8	4,8	9,5	4,6	5,5	6,5	7,4	8,3	9,2	10,2	11,1	12,0	12,9	13,8	14,8	15,7	16,6	17,5	18,5
M 10	7,4	14,9	5,8	6,9	8,1	9,2	10,4	11,5	12,7	13,8	15,0	16,2	17,3	18,5	19,6	20,8	21,9	23,1
M 12	10,7	21,4	6,9	8,3	9,7	11,1	12,5	13,8	15,2	16,6	18,0	19,4	20,8	22,2	23,5	24,9	26,3	27,7
M 14	14,6	29,2	8,1	9,7	11,3	12,9	14,5	16,2	17,8	19,4	21,0	22,6	24,2	25,8	27,5	29,1	30,7	32,3
M 16	19,0	38,1	9,2	11,1	12,9	14,8	16,6	18,5	20,3	22,2	24,0	25,8	27,7	29,5	31,4	33,2	35,1	36,9
M 20	30	59	11,5	13,8	16,2	18,5	20,8	23,1	25,4	27,7	30,0	32,3	34,6	36,9	39,2	41,5	43,8	46,2
M 22	36	72	12,7	15,2	17,8	20,3	22,8	25,4	27,9	30,5	33,0	35,5	38,1	40,6	43,2	45,7	48,2	50,8
M 24	43	86	13,8	16,6	19,4	22,2	24,9	27,7	30,5	33,2	36,0	38,8	41,5	44,3	47,1	49,8	52,6	55,4
M 27	54	109	15,6	18,7	21,8	24,9	28,0	31,2	34,3	37,4	40,5	43,6	46,7	49,8	53,0	56,1	59,2	62,3
M 30	67	134	17,3	20,8	24,2	27,7	31,2	34,6	38,1	41,5	45,0	48,5	51,9	55,4	58,8	62,3	65,8	69,2
M 36	96	193	20,8	24,9	29,1	33,2	37,4	41,5	45,7	49,8	54,0	58,2	62,3	66,5	70,6	74,8	78,9	83,1
M 42	131	262	24,2	29,1	33,9	38,8	43,6	48,5	53,3	58,2	63,0	67,8	72,7	77,5	82,4	87,2	92,1	96,9
M 48	171	343	27,7	33,2	38,8	44,3	49,8	55,4	60,9	66,5	72,0	77,5	83,1	88,6	94,2	99,7	105,2	110,8



Design value of ultimate limit state
Safety class: normal
Bolt quality: A4
Washers under head and nut: $D = D_{bolt} \cdot 2$
Hole drilled in profile for bolt: $D = D_{bolt} + 1\text{mm}$

Shear in longitudinal direction 0°

$$P_{B,d} = \frac{d \cdot t \cdot 150 \text{ MPa}}{\gamma_m (=1.3)}$$

Shear in transverse direction 90°

$$P_{B,d} = \frac{d \cdot t \cdot 70 \text{ MPa}}{\gamma_m (=1.3)}$$

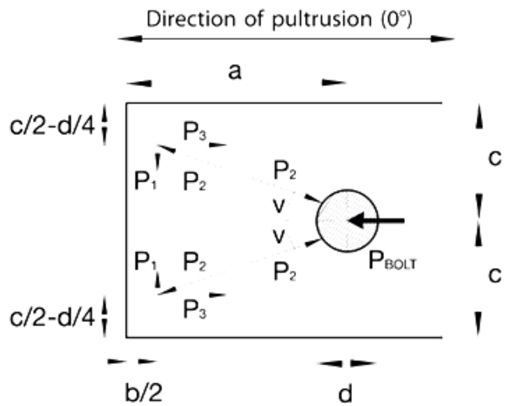
Connections: Bolted joints (Fiberline recommendations)

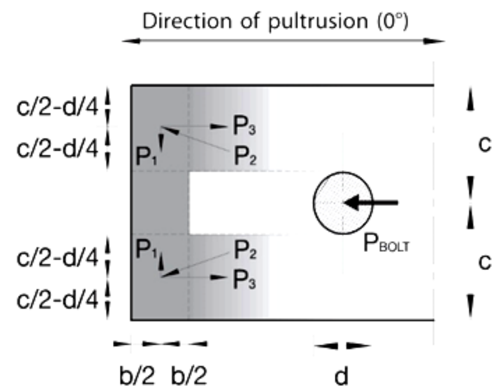
- **Bolted connection in shear:** e.g. shear in longitudinal direction

Simplified model

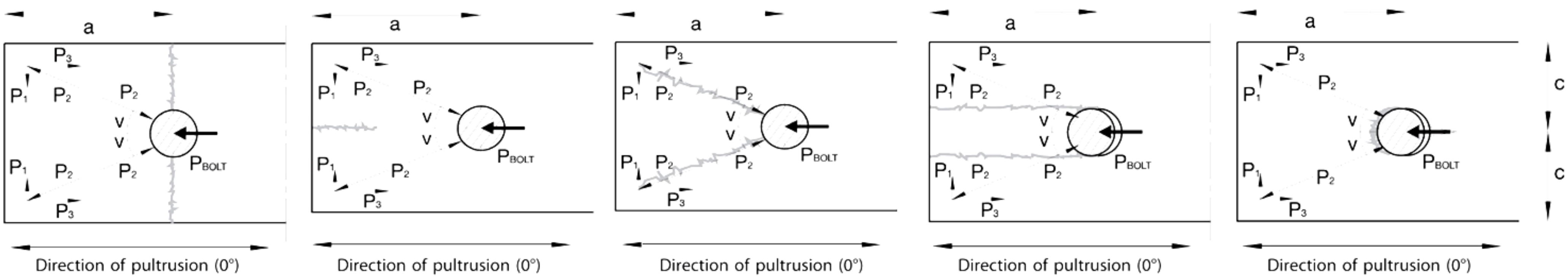
The values are based on

$a = 3{,}5 \cdot d$	$f_{t,0°}$	=	240 MPa
$b = 1{,}0 \cdot d$	$f_{c,0°}$	=	240 MPa
$c = 2{,}0 \cdot d$	$f_{t,90°}$	=	50 MPa
	$f_{c,90°}$	=	70 MPa
	f_v	=	25 MPa





Investigated failure modes



$g_m \cdot P_{Bolt} \leq d \cdot t \cdot 720$ MPa

$g_m \cdot P_{Bolt} \leq d \cdot t \cdot 240$ MPa

$g_m \cdot P_{Bolt} \leq d \cdot t \cdot 240$ MPa

$g_m \cdot P_{Bolt} \leq d \cdot t \cdot 150$ MPa

$g_m \cdot P_{Bolt} \leq d \cdot t \cdot 240$ MPa

Connections: Bolted joints (Fiberline recommendations)

- **Bolted connections in tension**
- **Static conditions**
  - **Bolt:** Tearing of bolt in threaded cross-section

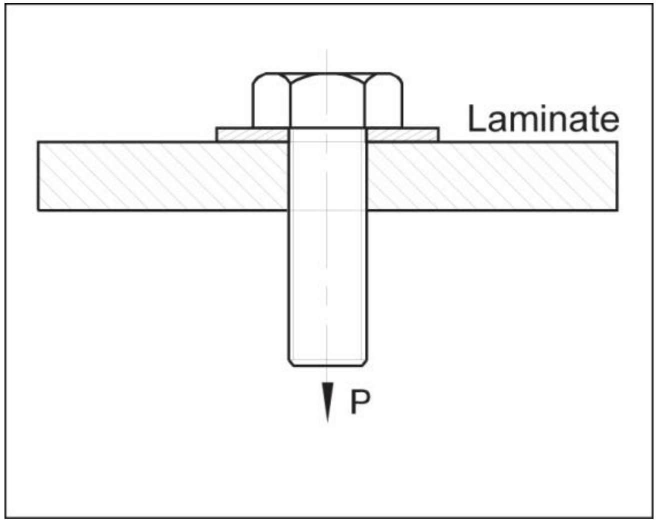
$$P_d \leq \frac{A_s \cdot f_{yk}}{\gamma_m}$$

  - **Laminate:** Shear fracture at rim of washer

$$P_d \leq \frac{2 \cdot d \cdot \pi \cdot t \cdot f_\tau}{\gamma_m}$$

- **Geometry and strength:**

d	...	Diameter of the bolt
A_s	...	Stress area of the bolt
t	...	Thickness of laminate
2d	...	Diameter of washer
f_{yk}	…	Tensile strength of bolt
f_τ	…	Shear strength of laminate



Connections: Bonded joints

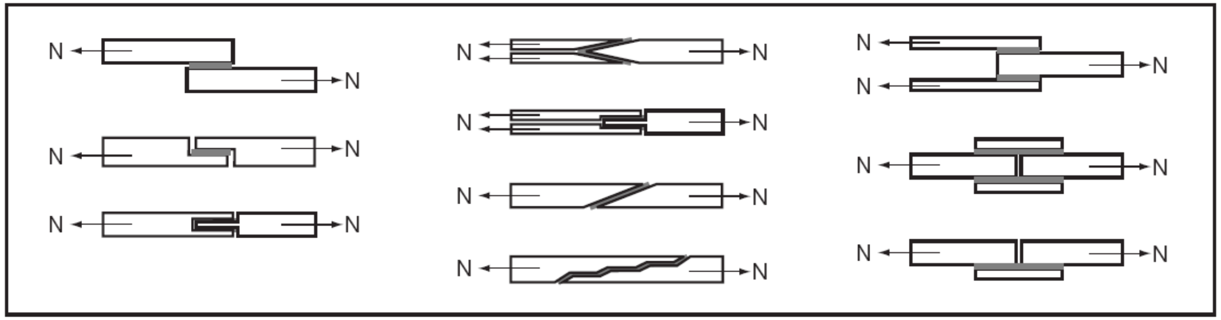
- **Using an adhesive agent for joining profiles can have advantages:**
  - Easy to use / easy to make aesthetic joints
  - Typically more rigid than bolted joints
  - Glued joints subjected to dynamic loads are good
- **But be careful …**
  - Adhesive agents have properties that depend on time, temperature, humidity …
  - Failure in glued joints takes place suddenly (brittle behaviour)
  - The load-bearing capacity is not proportional to the area which is glued
- **The design of bonded joints may be based on:**
  - **Analytical** models for plate-to-plate connections (see Eurocomp 1996 Design Code)
  - Design **guidelines** supplemented by testing
  - **Finite element** analysis

Connections: Bonded joints

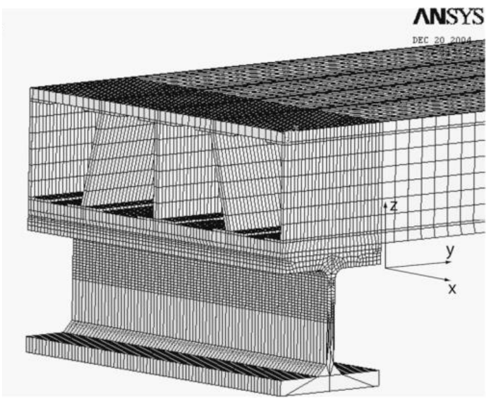
- **A bonded joint has the following three primary failure modes:**
  - adhesive failure
  - cohesive failure of adhesive
  - cohesive failure of adherend
- **The design of any bonded joint shall satisfy the following conditions:**
  - allowable shear stress in the adhesive is not exceeded.
  - allowable tensile (peel) stress in the adhesive is not exceeded.
  - allowable through-thickness tensile stress of the adhesive is not exceeded.
  - allowable in-plane shear stress of the adherend should not be exceeded.
- **The calculation of the stresses has to be done very carefully! Often calculations are supplemented by testing.**

Connections: Bonded joints

- **Different types of bonded joint configurations**



- **Research on bonded joints for structural applications**



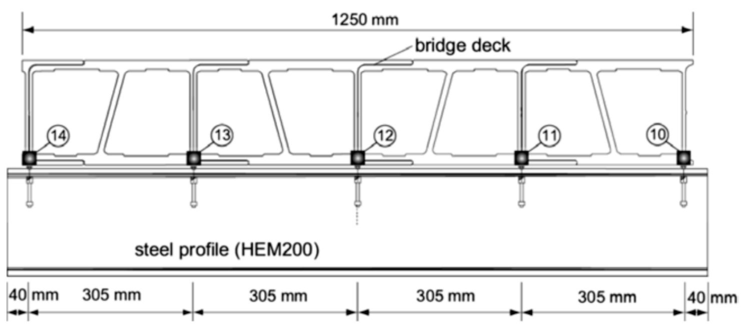
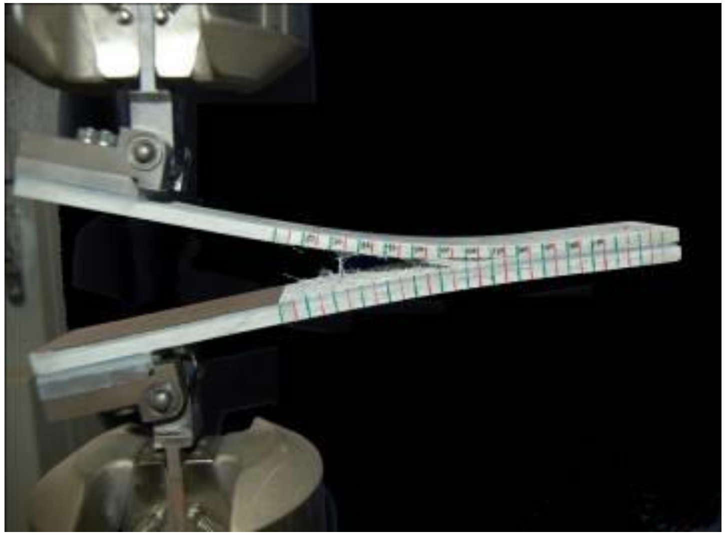
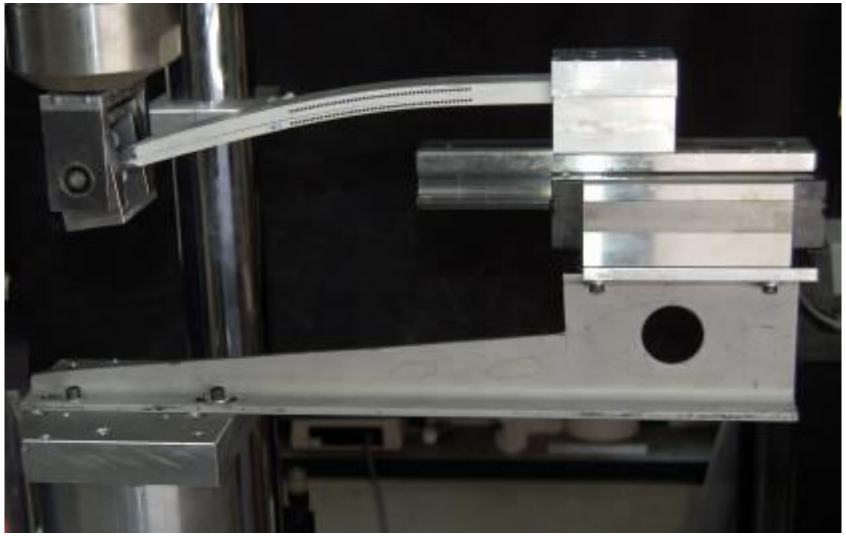
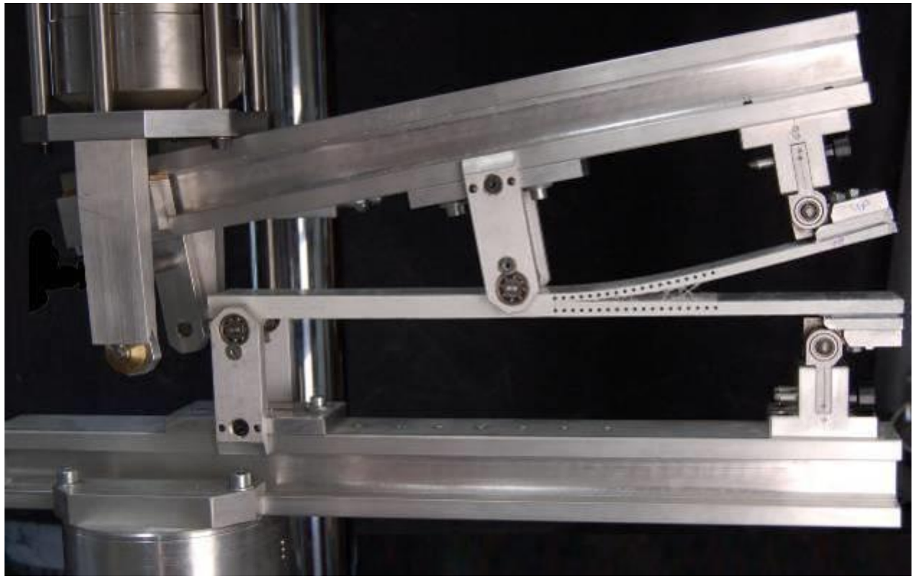


Fig. 17. Failure sequence of double lap joint (DN 100.2/5), frame intervals 1/2000 s.

Connections: Bonded joints, *fracture modes*







Displacement control,

1 mm/min, 5 Hz

Ambient conditions

Shahverdi, M., “Mixed-mode static and fatigue failure criteria for adhesively-bonded FRP joints”. PhD Thesis, EPFL, Switzerland, 2013.

Connections: Introduction

Table 5.2 Typical features of different connections between FRP members. ... from Eurocomp 1996 Design Manual (supplemented)

Advantages	Disadvantages
Mechanical connections	
• Requires no special surface preparation • Can be disassembled • Ease of inspection • Quasi ductile behaviour	• Low strength to stress concentrations • Special practices required in assembly; results in time consuming assembly • Fluid and weather tightness normally requires special gaskets or sealants • Corrosion of metallic fasteners
Bonded connections	
• High joint strength can be achieved • Low part count • Fluid and weather tightness • Potential corrosion problems are minimized • Smooth external surfaces • Stiffness	• Cannot be disassembled • Requires special surface preparation • Difficulty of inspection • Temperature and high humidity can affect joint strength • BRITTLE
Combined connections	
• Bolts provide support and pressure during assembly and curing • Growth of bondline defects is hindered by bolts	• Structurally bolts act as backup elements - in an intact joint, bolts carry no load

Connections: Introduction

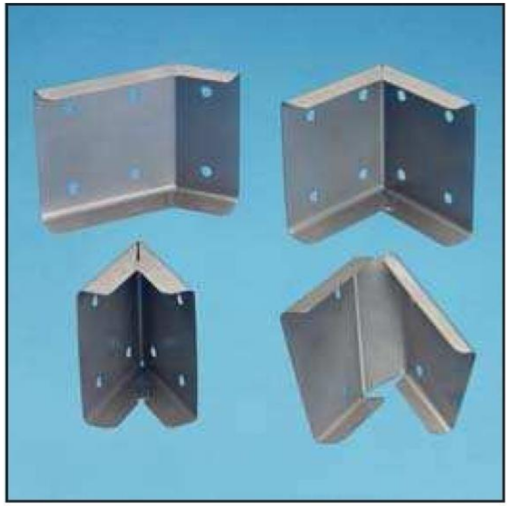
Table 5.1 Characteristics of different joint categories. (from Eurocomp Design Code 1996)

	Mechanical	*Bonded*	*Combined*
Stress concentration at joint	high	medium	medium
Strength/weight ratio	low	medium	medium
Seal (water tightness)	no	yes	yes
Thermal insulation	no	yes	no
Electrical insulation	no	yes	no
Aesthetics (smooth joints)	bad	good	bad
Fatigue endurance	bad	good	good
Sensitive to peel loading	no	yes	no
Disassembly	possible	impossible	impossible
Inspection	easy	difficult	difficult
Heat or pressure required	no	yes/no[1]	yes/no[1]
Tooling costs	low	high	low
Time to develop full strength	immediate	long	long

[1] no if cold curing two-part adhesives are used in an appropriate environment

Connections: Other joints

- **Brackets for assembly** (Fiberline)



Brackets for efficient assembly of profile structures.

Example of joint with a Fiberline bracket. EP patent No. 0819200

- **Custom pultruded connections**

GFRP: Some final remarks

- **Perpendicular to the direction of pultrusion, the material is WEAK and SOFT!**
  → avoid such loadings if possible

- **In order to use pultruded GFRP-profiles economically, the design must be done in a clever way!**
  e.g.: for bridges, the railings should be used as part of the load-bearing structure

- **GFRP structures are very light** → vibration problems may occur

- **Where large stiffness is needed (where static height and deflections must remain very small)** → GFRP does not always lead to lighter structures than with steel.

Thank you for attention

any question?