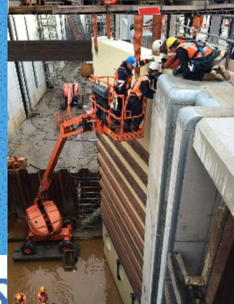
Technology Transfer Group: Infrastructure

Rules and Regulations in FRP Infrastructural applications

Pitea, 23-01-2019



Content Presentation

- Current FRP Infrastructural Market
- EU Design Guidance
  - JRC (joint review committee)
  - Usage of guidance notes from other sectors
- National regulations
  - Netherlands: CUR 96 / Edition 2017
  - Italy: CNR-DT 205/2007
  - Germany: BÜV Empfehlung TKB
- Insight in CUR 96 / Ed. 2017

Current FRP infrastructural market

- Growth in European FRP infrastructural market
- Larger more complex FRP civil constructions
- Rules & Regulations (EU) are under development
- Pro-active National parties

InfraCore inside

RAMSSES

InfraCore company

Royal HaskoningDHV
Enhancing Society Together

Typical infrastructural FRP Structures

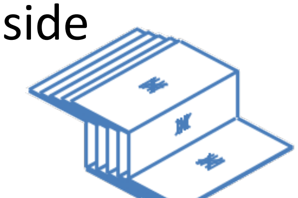
- Trusses
  - Profiles
  - (pultrusion)

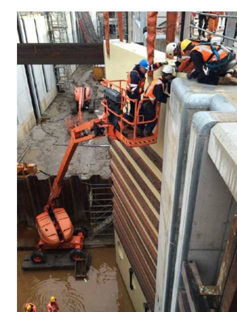
Pontresina bridge by Fiberline

- Monocoque structures
  - Shells
  - Sandwich
  - (infusion)

Frederikstadt bridge by FireCo

- Specific structures
  - InfraCore Inside
  -

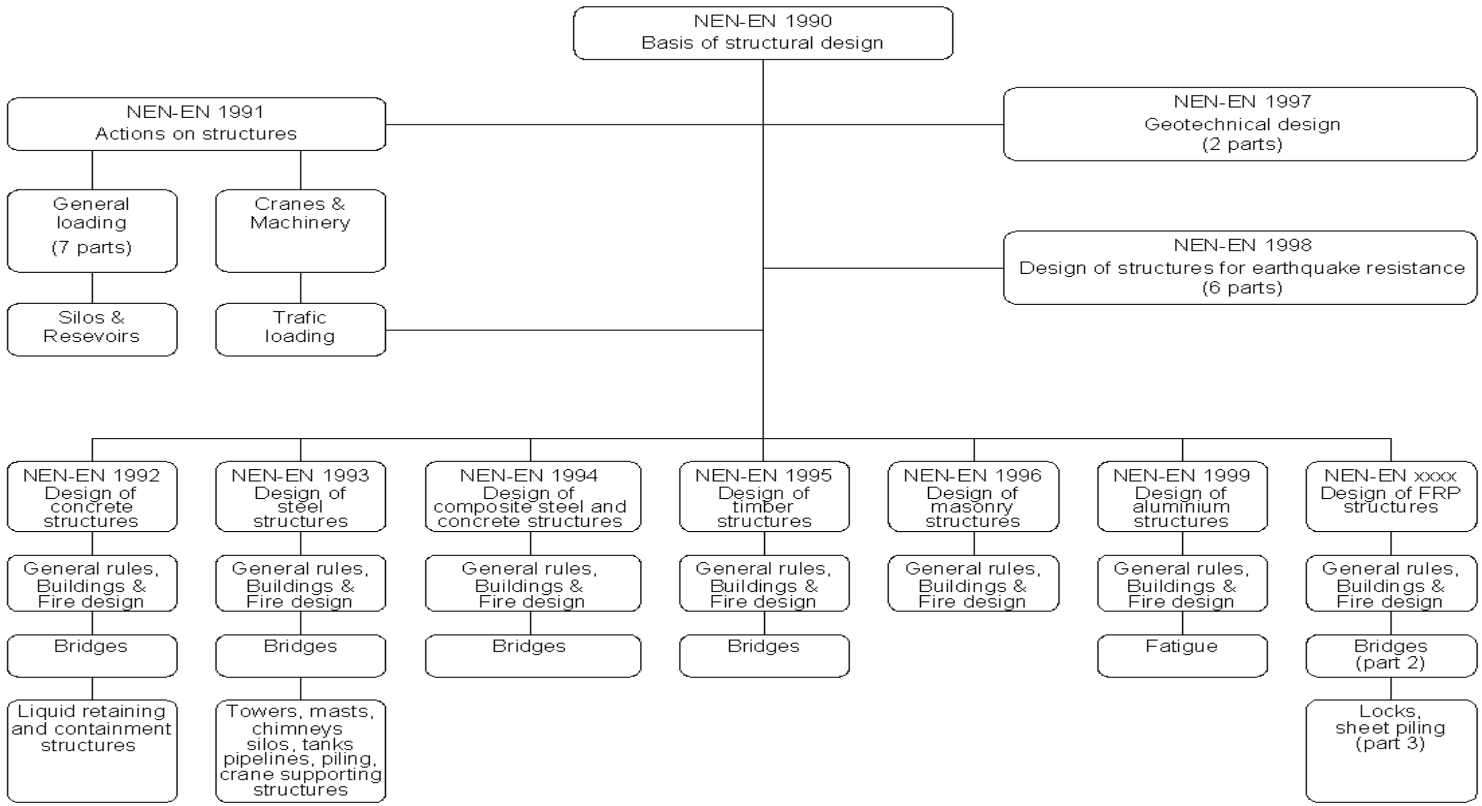




CompositesNL E-LASS

FiberCore europe

EU Design Guidance: Current



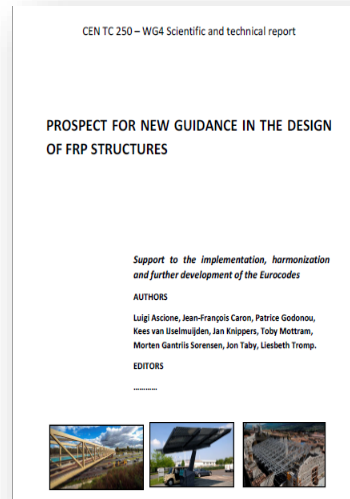
EN-19xx

Design of FRP Structures

EU Design Guidance: *under development*

National Notes in European design guidance

CUR96; 2017
FRP in buildings and
civil engineering structures


CEN TC 250 – WG4 Scientific and technical report

PROSPECT FOR NEW GUIDANCE IN THE DESIGN OF FRP STRUCTURES

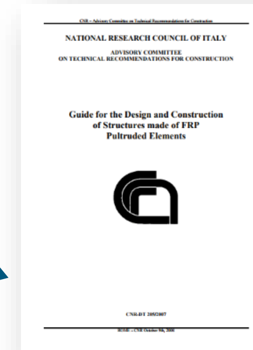
Support to the implementation, harmonization and further development of the Eurocodes

AUTHORS

Luigi Ascione, Jean-François Caron, Patrice Godonou, Kees van IJselmuijden, Jan Knippers, Toby Mottram, Morten Gantriis Sorensen, Jon Taby, Liesbeth Tromp.

EDITORS

JRC
Prospect for the Design
of FRP Structures


NATIONAL RESEARCH COUNCIL OF ITALY

ADVISORY COMMITTEE ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION

Guide for the Design and Construction of Structures made of FRP Pultruded Elements

CNR-DT 205/2007


BÜV-Empfehlung

Tragende Kunststoffbauteile im Bauwesen [TKB]

- Entwurf, Bemessung und Konstruktion -

Stand 08 / 2010

BÜV Empfehlung TKB

EU Design Guidance: *under development*

FRP design guidance for infrastructure makes use of FRP experience in other markets

MIL Handbook 17

- Analysis methods
- Material tests
- Building block approach

GL Offshore Wind Turbines

- Fatigue of FRP
- Material and connections

DNV-OS-C501 Offshore Standard

- FRP in a marine climate
- FRP in fire

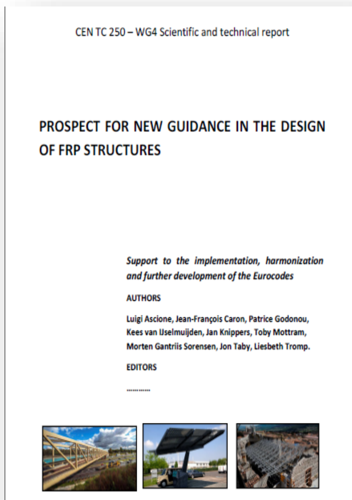
EN 13121 FRP Pressure vessels

- Chemical resistance
- Accelerated ageing test

EU Design Guidance: *under development*

European design guidance for FRP: timeline

2018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…………

JRC
Prospect for the Design of FRP Structures

2020

FRP
Technical Specification

In progress

2022?

FRP
Eurocode

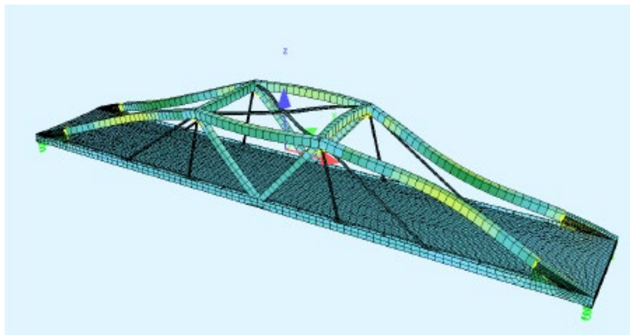
At least 2 years of succesfull usage

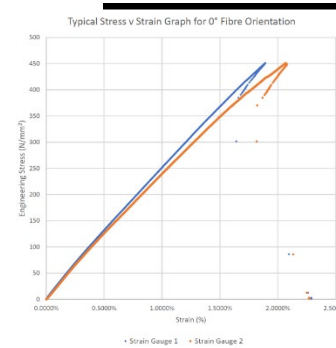
EU Design Guidance: challenges for FRP

- Not 1 material, but wide range of materials
- Fibre orientations
  - Various lay ups
  - Directions with fibers & directions with few or no fibers!
- Influence of quality of resin & production proces
- Reliability of models, many parameters
- In situ composed material => associated suitable quality control system
- Technology development…

EU Design Guidance for FRP

A combination of analytical models and <u>Testing</u>

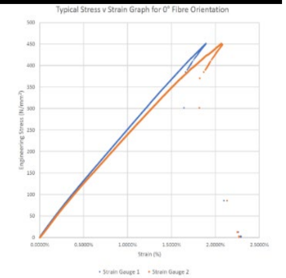




- When no sufficiently reliable theoretical model is available (yet)
  - representative test results from other projects can be used!
- As part of quality control
  - Tensile/bending test (general quality)
  - ILSS (fibre resin compatibility)
  - Glass transition temperature (cure, resin and durability)

EU Design Guidance for FRP

A combination of analytical models and <u>Testing</u>



As part of the design

- Determine characteristic mechanical properties
  - Materials
  - Connections
  - Complex phenomena: creep, fire, fatigue after impact, …

As part of Quality Control & Health Monitoring

  - Deflections
  - Eigenfrequency

InfraCore inside

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EU Design Guidance for FRP

A combination of analytical models and <u>Testing</u>

Full-scale test Lotharingen bridge, Utrecht. Lightweight Structures and Damsteegt

If the structure is continuously exposed to a service temperature of more than 40 °C combined with water (humidity) the effect of this should be determined by means of tests under these combined conditions.

COMMENT
The combination of elevated temperature and water (humidity) may lead to a more severe degradation of properties than for the individual effects when combined.

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FiberCore europe

EU Design Guidance for FRP

A combination of analytical models and <u>**Testing**</u>

Full scale test:

30 M fatigue cycles 60 tons <u>after serious impact</u>

Eurocode InfraCore traffic deck 3m x 7m

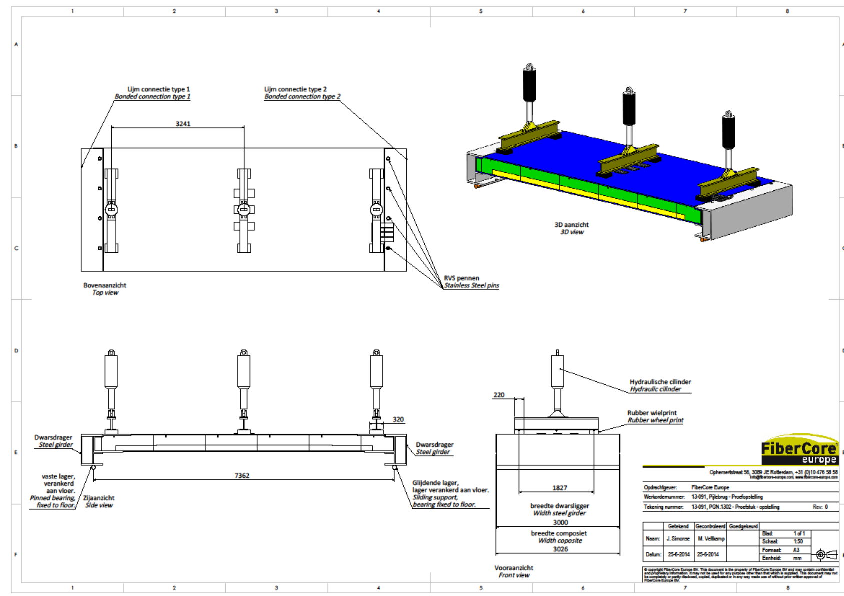
No structural damage growth

Bridge installed

with 50 years of

Future Lifetime,

without repair



PROVEN TECHNOLOGY

Witnessed by DNV-GL (at WMC & TNO)

EU Design Guidance for FRP

A combination of analytical models and <u>Testing</u>

CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

only in Dutch (English translation in 2019)

- **Partial factors**
  - Material factors
  - Conversion factors
- **Material properties**
- **ULS / SLS**
  - Modeling of FRP
  - Design rules
- **Quality control**
  - Protocols
  - Testing
  - Imperfections

ULS: Ultimate Limit State

SLS: Serviceability Limit State

CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

- Guarantee reliability & Safety (Realistically conservative)
- Generic for market
- Allow for economic design
  - sufficient quality control
- Give direct guidance (Maturing market)
  - Design rules AND Testing: allow for techn. developments
  - Annex J: points of attention to inform inexperienced clients, owners, contractors
  - Comments throughout, to explain relevance of the rule
  - Chapter for details, realization, maintenance & testing
  - Extra component partial material safety factor

MANY CHALLENGES HAVE BEEN TACKLED

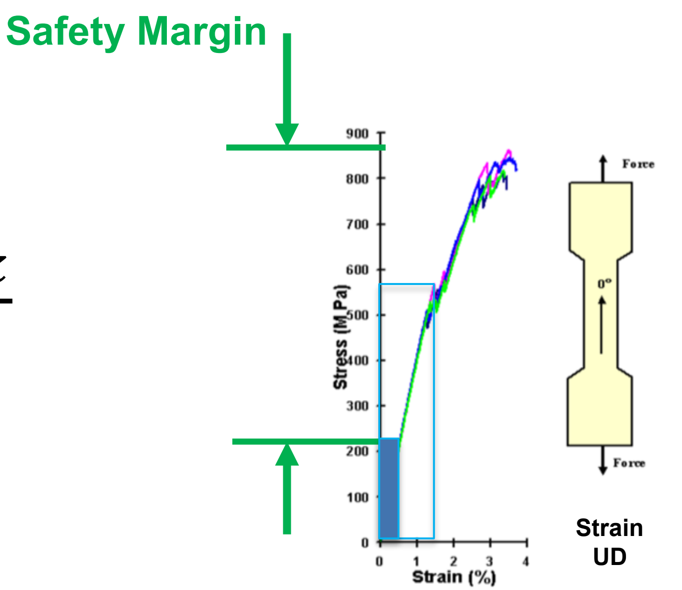
CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

Design Value vs Characteristic Value

Design value

$$R_d = \frac{\eta_c \cdot R_k}{\gamma_M}$$



γ_M = material safety factor (for **scatter of material properties**, …)

η_c = conversion factor (for **ageing and climate**)

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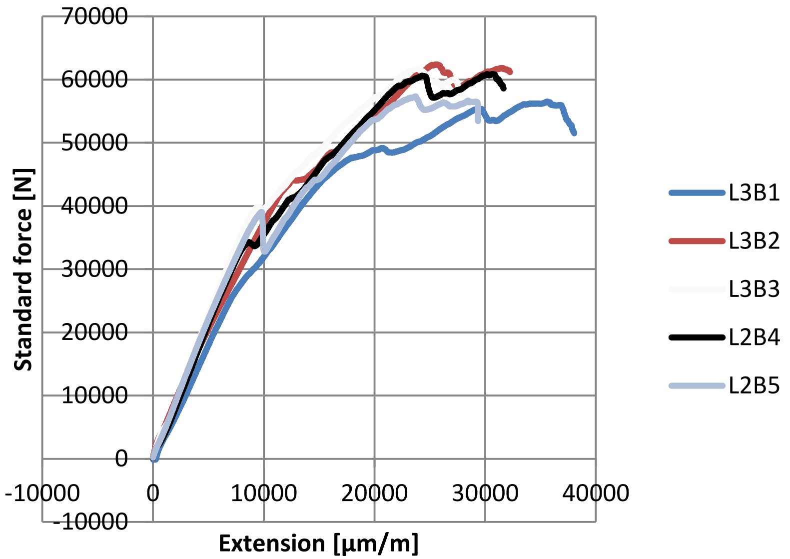
FRP in buildings and civil engineering structures

Scatter of material properties ~ coefficient of variation



$$V_x = \frac{s_x}{m_x}$$

V_x= coefficient of variation

s_x= standard deviation

m_x= average value

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FRP in buildings and civil engineering structures

Partial material factor (CUR96; JRC)

- γ_{M1} takes into account uncertainties in obtaining the material properties
- 1.15 : properties derived from tests
- 1.35 : properties derived from theory
- (Future: 1.0 when fully mature quality control systems and analytical models)

$$\gamma_M = \gamma_{M1} \cdot \gamma_{M2}$$

- γ_{M2} takes into account uncertainties due to the nature of the constituent parts and the production method (i.e scatter in material properties)

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FRP in buildings and civil engineering structures

Partial material factor"γ_M2" ~ Vx and failure mode

Conditions	Ultimate Limit State		
	Strength	Local Stability	Global Stability
Production Process and properties of FRP with $V_x \leq 0,10$	1.2	1.4	1.35
Production Process and properties of FRP with $V_x \leq 0,17$	1.5	2.0	1.50

Vx: coefficient of variation

≤ 0,10: pulltrusion, vacuum infusion, …

≤ 0,17: hand lamination

Producer has to demonstrate that the production process meets this requirement

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FRP in buildings and civil engineering structures

Conversion factors: simplified method to include climatic influence, long term effects

- Temperature
- Moisture
- Creep
  - Depending on laminate lay up
  - When critical for design to be verified by tests
- Fatigue
  - ONLY for reduction of stiffness
  - Strength effect
  - Life time based on fatigue stress cycles (Miner sommation).

$$\eta_c = \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} \cdot \eta_{cf}$$

CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

<u>Conversion factors: simplified method to include climatic influence, long term effects</u>

$$\eta_c = \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} \cdot \eta_{cf}$$

- Temperature η_{ct}
  - **ULS: 0.9;**
  - **SLS : 1.0** for $T_d \leq T_g - 40$ °C;
    0.9 for $T_g - 40$ °C $< T_d \leq T_g - 20$ °C.
- Moisture η_{cm}
  - **1.0 (dry) - 0.9 (dry/wet) - 0.7 (wet)**
- Creep deformations η_{cv}
  - Typical values η_{cv}= **0.4 - 0.8 *(lay up dependent)***
  - To be verified by tests when critical for design
  - NB: for strength verification under permanent loads a creep rupture limit applies.
- Fatigue η_{cf}
  - **0.9** (only for stiffness reduction)

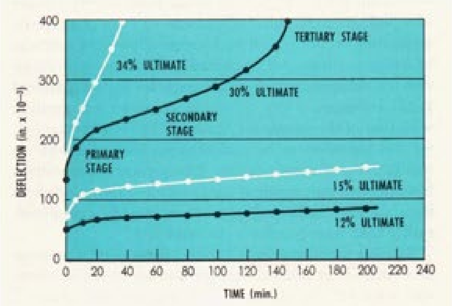


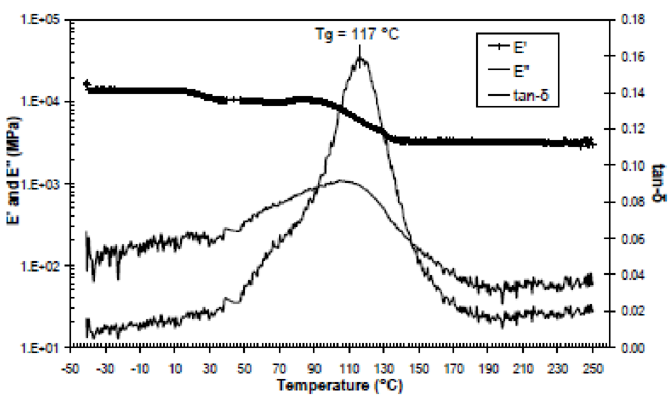
Figure 1. Creep curves for different stress levels for polyester resin, chopped mat laminates in water at 48° C. (17)

CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

Glass transition temperature Tg

- Tg = Temperature for which the stiffness of the resin reduces. (transition to *rubber phase)*
- Tg is an important parameter for durability :
  - Tg requirements in resin selection
  - Tg verification as part of quality control
  - High **actual** Tg: lower reduction factors in design!



Source: research EPFL Switzerland

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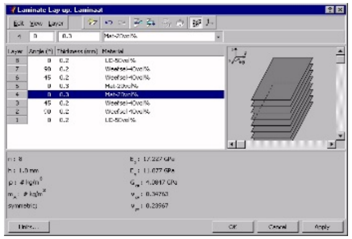
FRP in buildings and civil engineering structures

Chapter 3 Materials: Ply properties (building blocks)

- Fiber and resin properties



- Ply properties:
  - Tabels
  - Formulas (Halpin-Tsai – Manera)
- Laminate properties:
  - Classical laminate theory
  - => software is available

Tabel 3 Nominale waarden voor de stijfheidseigenschappen van een UD-lamel.

V_f	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
40 %	30,8	8,9	2,8	0,30
45 %	34,3	10,0	3,1	0,29
50 %	37,7	11,3	3,5	0,29
55 %	41,1	12,8	3,9	0,28
60 %	44,6	14,6	4,5	0,27
65 %	48,0	16,7	5,1	0,27
70 %	51,4	19,3	6,0	0,26
Reductiefactor UD-stijfheidswaarden (behalve ν_{12}): 0,97				

Tabel 4 Nominale waarden voor de stijfheidseigenschappen van (gebalanceerde) weefsel-lamellen.

V_f	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
25 %	13,4	13,4	2,1	0,21
30 %	15,5	15,5	2,3	0,20
35 %	17,6	17,6	2,5	0,20
40 %	19,8	19,8	2,8	0,19
45 %	22,1	22,1	3,1	0,19
50 %	24,5	24,5	3,5	0,19
55 %	27,0	27,0	3,9	0,18
Reductiefactor weefsel(gebalanceerd)-stijfheidswaarden (behalve n12): 0,93				

Toelichting:
Een andere mogelijkheid om de eigenschappen van een weefsel-lamel te bepalen is om het lamel te beschouwen als een symmetrisch 0/90-laminaat van UD-lamellen en volgens de klassieke laminatentheorie te berekenen, waarop dan weer de reductiefactor wordt toegepast.

Tabel 5: Nominale waarden voor de stijfheidseigenschappen van een mat-lamel.

V_f	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
10 %	6,2	6,2	2,3	0,33
12,5 %	6,9	6,9	2,6	0,33
15 %	7,6	7,6	2,9	0,33
17,5 %	8,3	8,3	3,1	0,33
20 %	9,1	9,1	3,4	0,33
25 %	10,6	10,6	4,0	0,33
30 %	12,2	12,2	4,6	0,33
Reductiefactor mat-stijfheidswaarden (behalve n12) : 0,91				

6.8.3 Nominale waarden sterkte-eigenschappen
Voor de drie in 4.1 genoemde typen lamellen mogen de onderstaande nominale waarden voor de sterkte-eigenschappen worden aangehouden, rekening houdend met het gestelde in 6.8.1.

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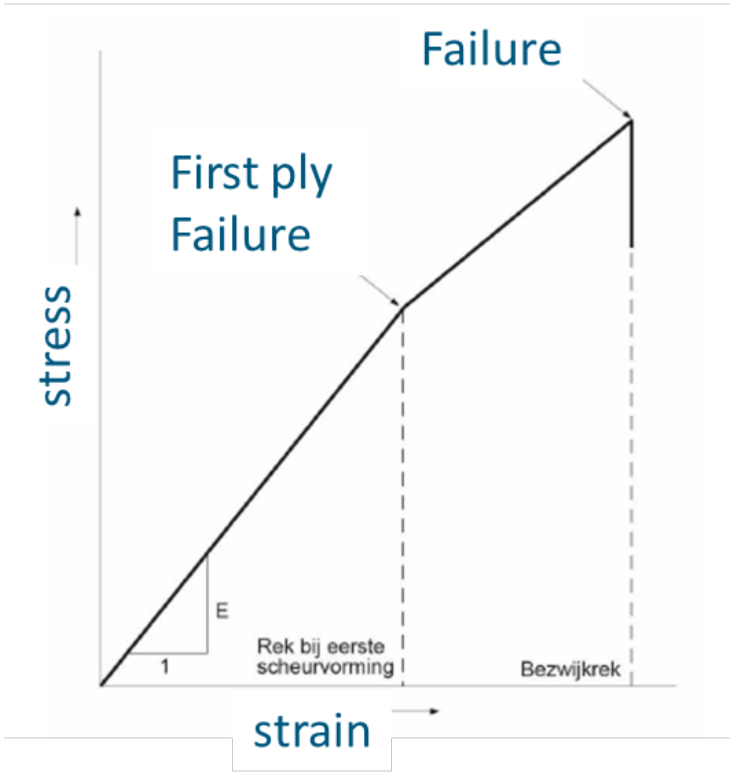
Design verification on 3 levels

- Profiles: cross section level
- Plates and shells:
  - Ply level
  - Laminate level



- **Failure criterion: Ultimate failure**

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FRP in buildings and civil engineering structures

Chapter 6: Profiles

- Verification on cross sectional level (capacity of profile)
- Common for pultrusion profiles

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{Y,Ed}}{M_{Y,Rd}} + \frac{M_{Z,Ed}}{M_{Z,Rd}} + \frac{V_{Y,Ed}}{V_{Y,Rd}} + \frac{V_{Z,Ed}}{V_{Z,Rd}} + \frac{T_{Ed}}{T_{Rd}} \leq 1{,}0$$

Waarin:

N_{Ed}, $M_{Y,Ed}$ en $M_{Z,Ed}$, $V_{Y,Ed}$, $V_{Z,Ed}$ en T_{Ed} Design values of occurring section forces

N_{Rd}, $M_{Y,Rd}$ en $M_{Z,Rd}$, $V_{Y,Rd}$, $V_{Z,Rd}$ en T_{Rd} Design values of section capacity or resistance

- X_{Rd}: smallest capacity including holes and imperfections.
- Also for profiles the verification on laminate or ply level is allowed.

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FRP in buildings and civil engineering structures

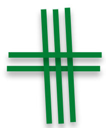
Chapter 6: Plates and Shells

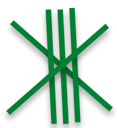
- Ply level: Tsai Hill

tension

$$\left(\frac{\sigma_{1,t,S}}{\sigma_{1,t,R}}\right)^2-\left(\frac{\sigma_{1,t,S}\cdot\sigma_{2,t,S}}{\sigma_{1,t,R}^2}\right)^2+\left(\frac{\sigma_{2,t,S}}{\sigma_{2,t,R}}\right)^2+\left(\frac{\tau_{12,S}}{\tau_{12,R}}\right)^2=\left(\frac{1}{\gamma_m\cdot\gamma_f\cdot\gamma_c}\right)^2$$

druk :

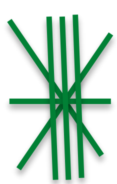




compression

$$\left(\frac{\sigma_{1,c,S}}{\sigma_{1,c,R}}\right)^2-\left(\frac{\sigma_{1,c,S}\cdot\sigma_{2,c,S}}{\sigma_{1,c,R}^2}\right)^2+\left(\frac{\sigma_{2,c,S}}{\sigma_{2,c,R}}\right)^2+\left(\frac{\tau_{12,S}}{\tau_{12,R}}\right)^2=\left(\frac{1}{\gamma_m\cdot\gamma_f\cdot\gamma_c}\right)^2$$

- Laminate level: Simplified Strain Criterion
  - 1.2% strain limit for FRP when min. 12.5% fibre reinforcement in all main directions (0/90/45/-45).



For UNI AXIAL loads:

$$\varepsilon_{x,Ed}\leq\frac{\eta_c\cdot 1{,}2\%}{\gamma_M}$$

$$\varepsilon_{y,Ed}\leq\frac{\eta_c\cdot 1{,}2\%}{\gamma_M}$$

$$\gamma_{xy,Ed}\leq\frac{\eta_c\cdot 1{,}6\%}{\gamma_M}$$

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FRP in buildings and civil engineering structures

Chapter 6: Fatigue

- Fatigue: stiffness reduction => conversion factor
- Fatigue strength: S-N curve
- Fatigue life: $$\log(N) = m \cdot \log\left(\frac{\gamma_{Mf} \cdot \gamma_M \cdot \sigma_{max}}{\eta_c \cdot B}\right)$$
  - N= number of cycles
  - m = regression parameter (slope)
- Variable amplitude loads may be considered as a combination of constant amplitude loads using Rainflow counting.
- Miner's rule: $$D = \sum_i^M \frac{n_i}{N_i} \leq 1,$$

CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

Chapter 6: Fatigue – Reference values

Table 11.16 - Reference values for regression parameters a and *B* for UD laminate.

UD non-crimp fabric	Glass/epoxy UD non-crimp fabric	Glass/polyester UD non-crimp fabric	Carbon/epoxy UD non-crimp fabric
	a, B	a, B	a, B
R = -1	-10, 600*(V_f/0.55)	-9, 700*(V_f/0.55)	-15,900*(V_f/0.55)
R = 0.1	-10, 1100*(V_f/0.55)	-7, 1300*(V_f/0.55)	-30, 1200*(V_f/0.55)
R = 10	-18, 750*(V_f/0.55)	-	-

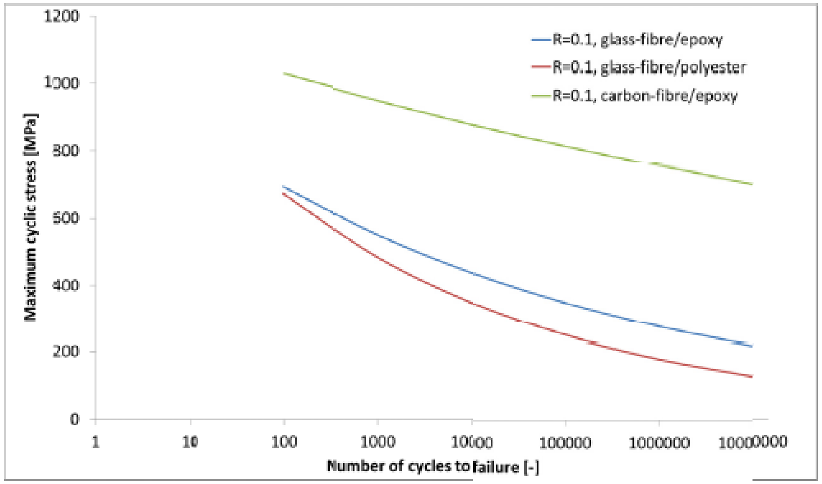

Figure 11.1 - *S-N* curves for a number of materials, V_f 55%, *R*= 0.1.

$$\log(N) = m \cdot \log\left(\frac{\gamma_{Mf} \cdot \gamma_M \cdot \sigma_{\max}}{\eta_c \cdot B}\right)$$

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CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

Chapter 7: Serviceability Limit State design

- SLS deals with the **functionality** and **durability** of the structure

- Deformation due to variable load
  => a measure for the response

- Deformation due to permanent load (creep)
  => water ponding, sagging

- Design guidance is generic
  => Client specifications are necessary!

- SLS requirements (deflection or comfort) are determining for FRP design => materials, costs , environmental impact

CompositesNL

E-LASS

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CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

Chapter 10 / Annexes Quality checks

- Material checks
- Qualified personnel
  - FRP Supervisor at relevant activities
  - Executing personnel
    - Training / instruction protocols to be provided
- QA- factory protocols
  - aspects to be addressed in QA protocols
  - Future: look at Class work shop certificates

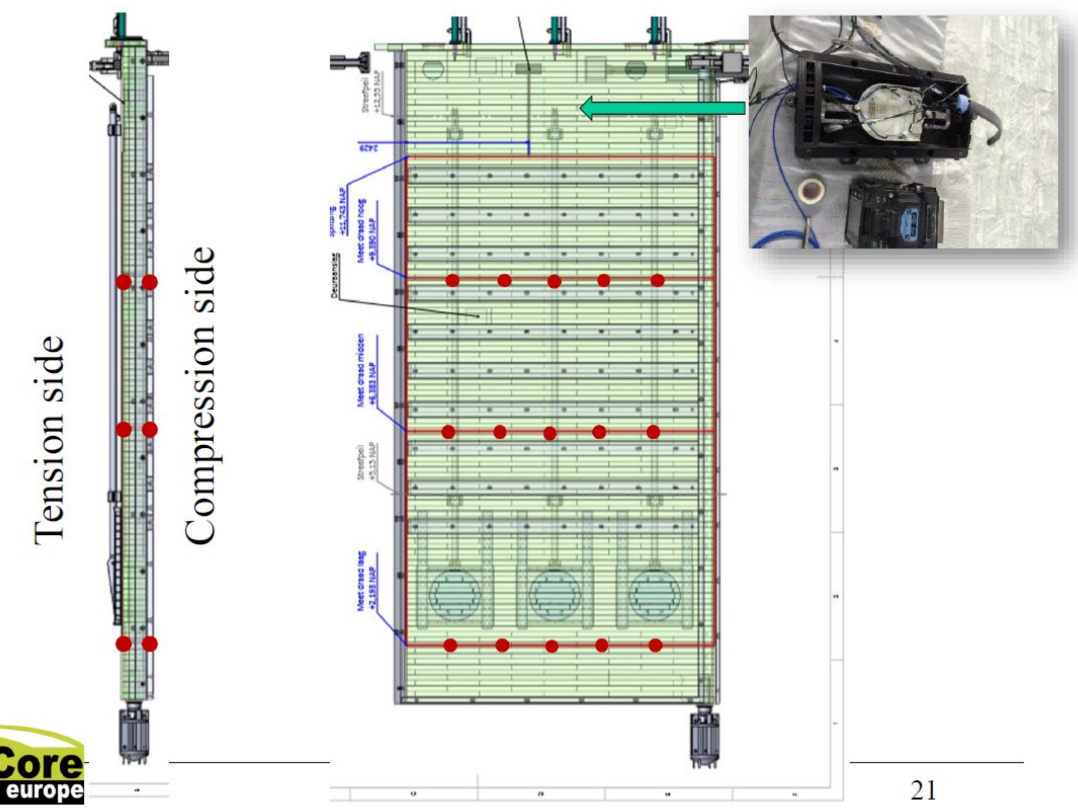
- project specific:
  - FAT tests (project specific)
  - SAT tests (measurement of deflection and response as built: e.g. reference for health monitoring)
  - Optional: monitoring by structural health monitoring technology

CUR recommendation 96 Edition 2017

FRP in buildings and civil engineering structures

Chapter 10 / Annexes Quality checks

Embedding of sensor lines



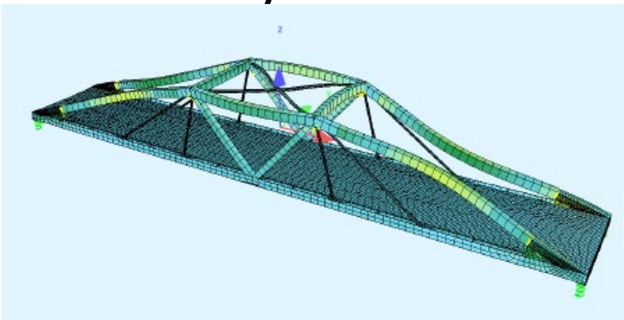
CUR recommendation 96 Edition 2017

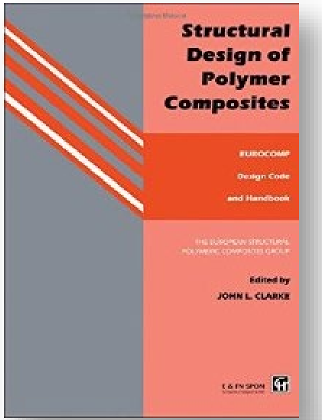
FRP in buildings and civil engineering structures

<u>Annex J: points of attention to educate inexperienced clients, owners, contractors</u>

Design rules, Testing & Attention for FRP critical aspects!

FRP: ready for use!



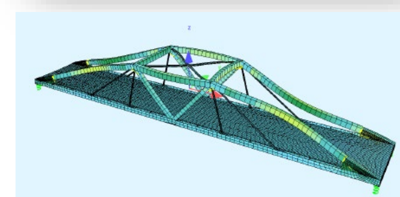


Acknowledgment: co-author

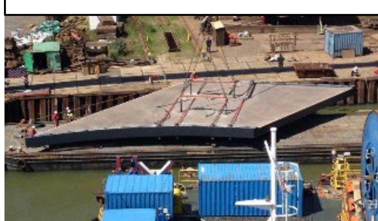
Liesbeth Tromp

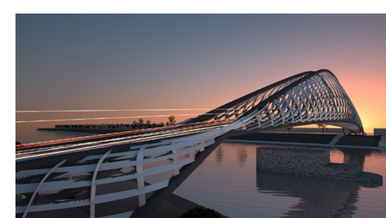
- Lead engineer FRP @ Royal HaskoningDHV
- Infrastructure and architecture

- Technical Coordinator & co-author CUR96 FRP structures
- Representative of Netherlands in TC250-WG4 (Eurocode FRP committee)
- 1997 – MSc Aerospace Engineering, TU Delft
- > 20 years of experience in FRP & lightweight engineering
- Guest lecturer TU Delft (Civil Engineering, Architecture)
- Post Academic FRP course for professionals
- With TU Delft: ProfEd online course FRP for infrastructure



More info on CUR96:
✉ liesbeth.tromp@RHDHV.com
✆ +31-68 353 03 20





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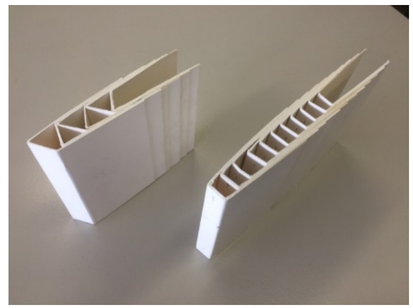
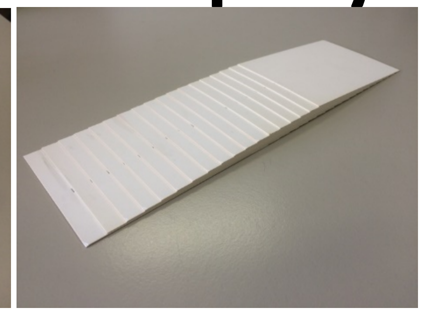
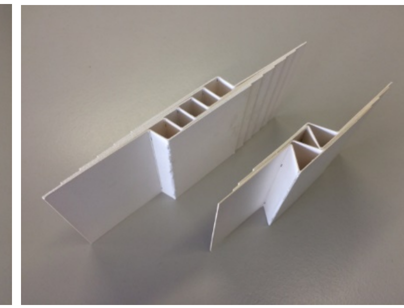

- Postal address: Oostdijk 25, 3077 CP Rotterdam/NL
- Office address: Marconistraat 16, 3029 AK Rotterdam /NL
- Email: info@infracore-company.com
- Internet: www.infracore-company.com
- Phone: 0031-624628868