Libo Yan – Fraunhofer WKI & iBMB TU Braunschweig

Plant-based Natural Fibre Reinforced Polymer Composites in Construction: Properties, Application and Challenge

FNR Online Seminar: Bioverbundwerkstoffe — Leichte, innovative Baustoffe, 22.06.2022

Fraunhofer WKI

iBMB MPA TU BRAUNSCHWEIG
Institut für Baustoffe, Massivbau und Brandschutz
Materialprüfanstalt für das Bauwesen

FNR Fachagentur Nachwachsende Rohstoffe e.V.
Fachagentur Nachwachsende Rohstoffe e. V. (Agency for Renewable Resources)

Gefördert durch:
Bundesministerium für Ernährung und Landwirtschaft
aufgrund eines Beschlusses des Deutschen Bundestages

Agenda

- Introduction of Plant-based Natural Fibre Reinforced Polymer (NFRP) Composites
- Properties of Flax Fibre, Yarn, Fabric and FRP Composites
- Potential Application of Flax FRP Composites in Construction
- Challenge and Outlook

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Introduction of Plant-based Natural Fibre Reinforced Polymer (NFRP) Composites

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Introduction of Plant-based Natural Fibre Reinforced Polymer Composites

Classification of fibre materials and polymer matrix

Classification of polymer matrix based on thermal behavior

- Thermoplastics

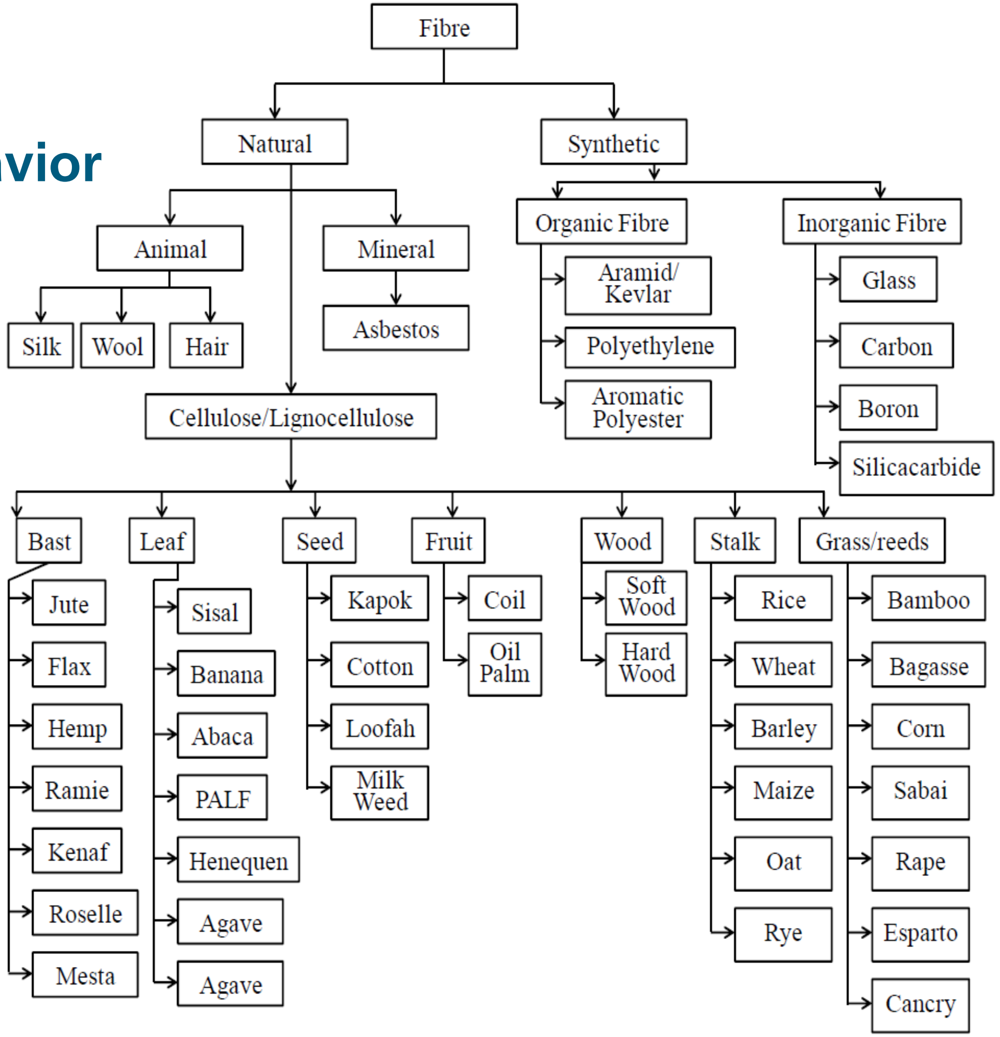
  → design flexibility, ease of moulding but high temperature processing (e.g. polypropylene)

- Thermosets (**for civil engineering application**)

  → Better mechanical properties and thermal stability, room temperature processing (e.g. epoxy)

Classification of natural fibres based on origin

- Plant-based natural fibres (e.g. flax)
- Animal-based natural fibres (e.g. silk)
- Mineral-based natural fibres (e.g. basalt)



Jawaid and Abdul Khalil (2011) *Carbonhydr. Polym.* 86: 1-18

Introduction of Plant-based Natural Fibre Reinforced Polymer Composites

Why are plant-based natural fibres?

- From renewable and agricultural waste resources → support of circular and bio-economy
- Potential to reduce GHG emissions (carbon neutral/low carbon impact)
- Often low toxicity and high bio-degradability
- Less resource-intensive production (water, energy, waste)
- Readily available worldwide
- Non-abrasive, lighter and cheap in comparison with glass fibres or other synthetic fibres
- Specific tensile properties are comparable to those of glass fibres

Introduction of Plant-based Natural Fibre Reinforced Polymer Composites

Why are flax fibres?

Fibre type	Relative density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Specific modulus ($GPa \times cm^3/g$)	Elongation at failure (%)
Abaca	1.5	400–980	6.2–20	9	1.0–10
Alfa	0.89	35	22	25	5.8
Bagasse	1.25	222–290	17–27.1	18	1.1
Bamboo	0.6–1.1	140–800	11–32	25	2.5–3.7
Banana	1.35	500	12	9	1.5–9
Coir	1.15–1.46	95–230	2.8–6	4	15–51.4
Cotton	1.5–1.6	287–800	5.5–12.6	6	3–10
Curaua	1.4	87–1150	11.8–96	39	1.3–4.9
Flax	1.4–1.5	343–2000	27.6–103	45	1.2–3.3
Hemp	1.4–1.5	270–900	23.5–90	40	1–3.5
Henequen	1.2	430–570	10.1–16.3	11	3.7–5.9
Isora	1.2–1.3	500–600	–	–	5–6
Jute	1.3–1.49	320–800	30	30	1–1.8
Kenaf	1.4	223–930	14.5–53	24	1.5–2.7
Piassava	1.4	134–143	1.07–4.59	2	7.8–21.9
Palf	0.8–1.6	180–1627	1.44–82.5	35	1.6–14.5
Ramie	1.0–1.55	400–1000	24.5–128	60	1.2–4.0
Sisal	1.33–1.5	363–700	9.0–38	17	2.0–7.0
Aramid	1.4	3000–3150	63–67	46.4	3.3–3.7
Carbon	1.4	4000	200–240	157	1.4–1.8
E-glass	2.5	1000–3500	70–76	29	0.5
S-glass	2.5	4570	86	34.4	2.8

Yan et al. (2014) *Composites Part B* 56: 296-317

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Properties of Plant-based Flax Fibre, Yarn, Fabric and FRP Composites

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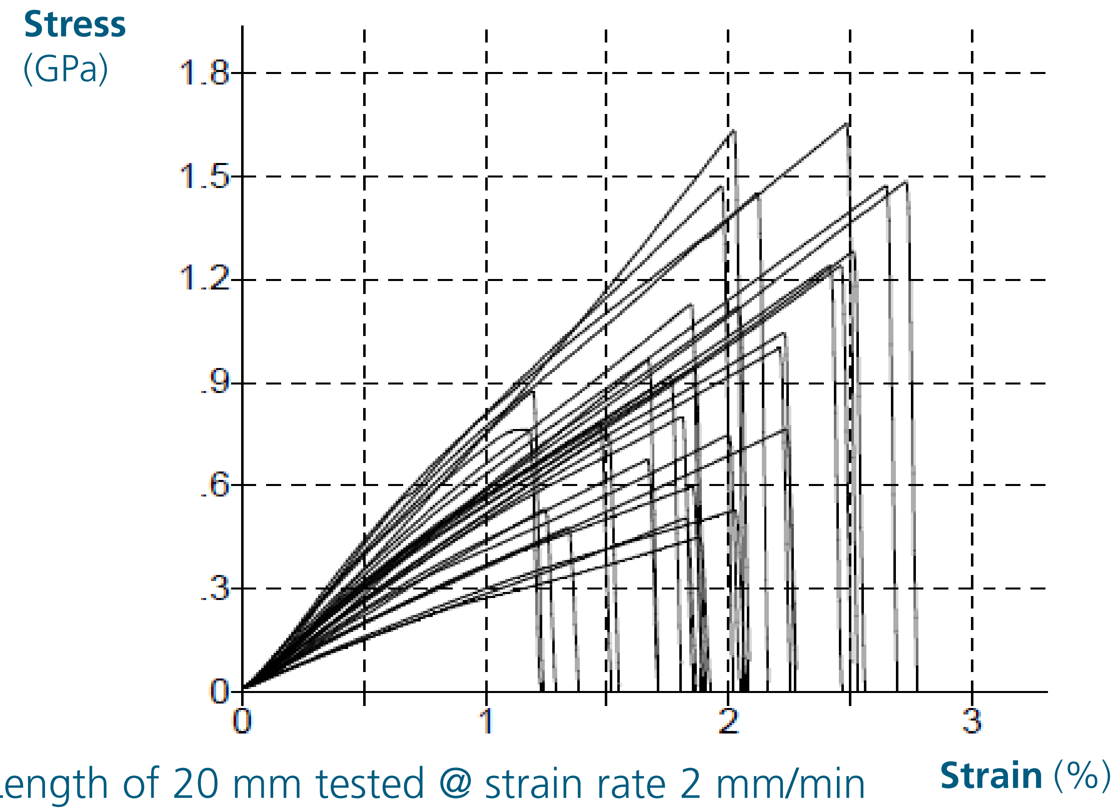
Properties of Plant-based Flax Fibre, Yarn, Fabric and FRP Composites

Tensile properties of single flax fibre

Material: Single/technical flax fibres extracted from the yarn of uni-directional flax fabric



Tensile strength (MPa)		Young´s modulus (GPa)		Strain to failure (%)	
Average ± SD	C.o.V	Average ± SD	C.o.V	Average ± SD	C.o.V
850 ± 280	33%	55 ± 9	16%	1.99 ± 0.48	24%
1012 ± 380	38%	62 ± 19	31%	1.94 ± 0.42	22%
1020 ± 530	52%	63 ± 21	33%	2 ± 0.87	42%

Tensile properties of single flax fibres show high variation

Length of 20 mm tested @ strain rate 2 mm/min

C.o.V: Coefficient of Variation

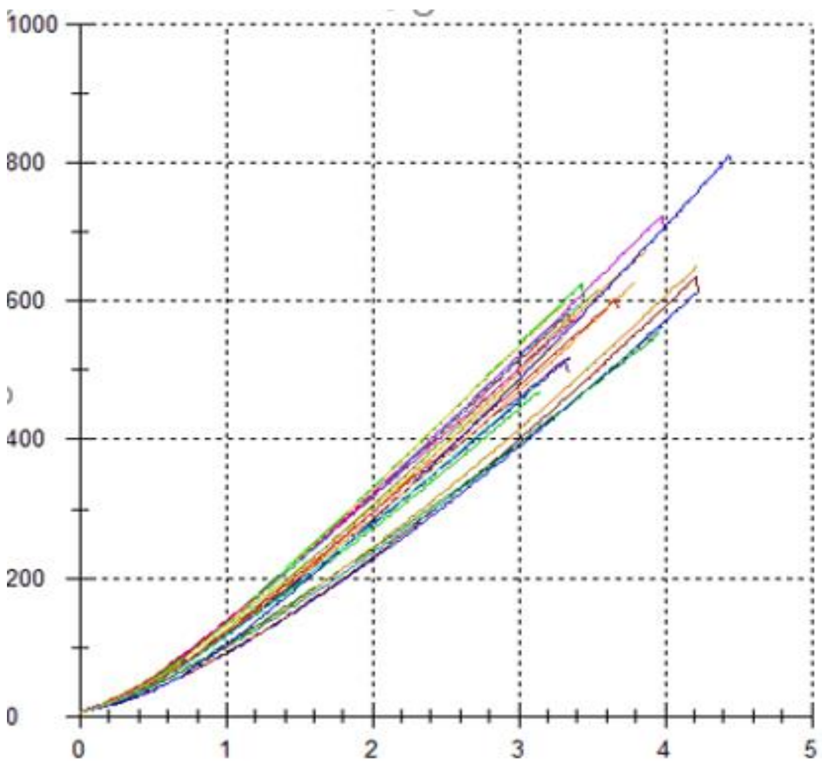
Doctoral work: S. Aldroubi

Properties of Plant-based Flax Fibre, Yarn, Fabric and FRP Composites

Tensile properties of single-strand flax yarn

Material: Twisted flax yarn extracted from unidirectional, non-crimp fabric
Yarn length of 250 mm

Stress (MPa)



Strain (%)

Flax yarn under light microscope

Maximum stress (MPa)		
Average	SD	CoV (%)
599	78	13

Modulus of Elasticity MoE (GPa)		
Average	SD	CoV (%)
19.8	2.2	11

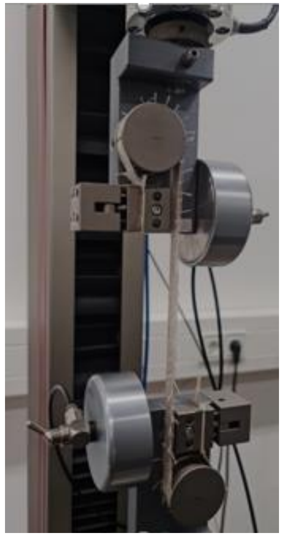
SD: Standard deviation

Doctoral work: S. Aldroubi

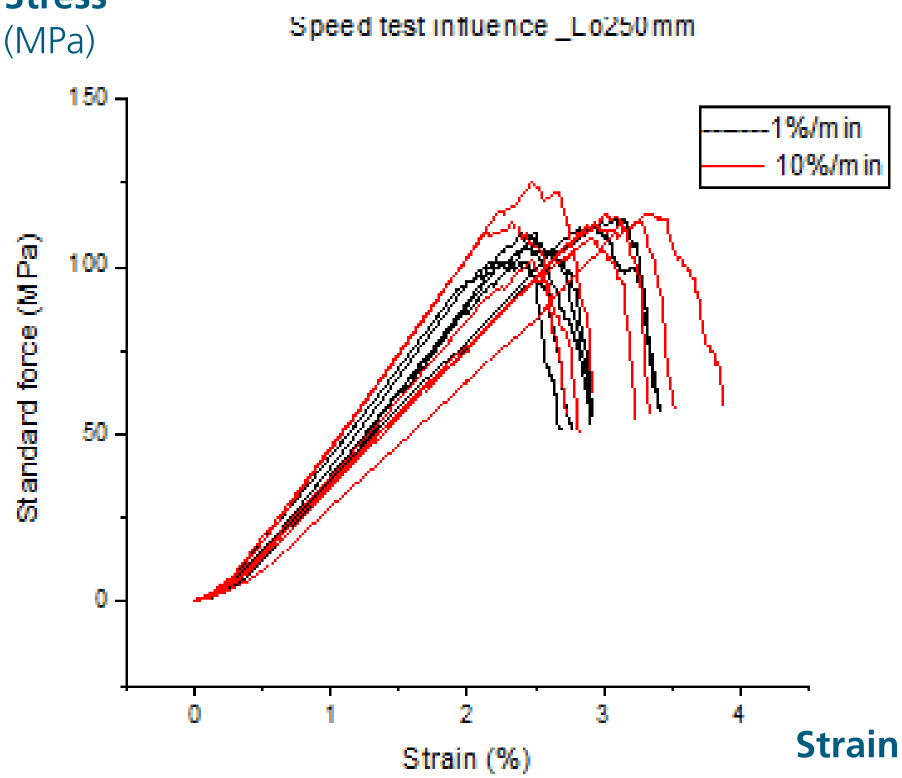
Properties of Plant-based Flax Fibre, Yarn, Fabric and FRP Composites

Tensile properties of flax fabric (unidirectional)

Material: Non-crimp unidirectional flax fabric
300gsm_ 105Tex → 30 yarns per cm width.
Free fabric length: 250 mm, Test speed: 1%/min and 10%/min



Stress (MPa)



Strain (%)

Strain rate (%/min)	1%/min (n =7)	10%/min (n=5)
MoE (GPa)	9.4 ± 0.8	8.0 ± 0.5
CoV (%)	8.5	6.0
Fmax (MPa)	211 ± 10	221 ± 7
CoV (%)	4.6	3.2
Strain at Fmax (%)	2.6 ± 0.3	3.1 ± 0.2
CoV (%)	13	5,9

Doctoral work: S. Aldroubi

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Properties of Plant-based Flax Fibre, Yarn, Fabric and FRP Composites

Comparison of single fibre, yarn and fabric in tensile properties

Fibre: 1000 MPa and 60 GPa (CoV: 16%-52%)

Tensile strength (MPa)		Young´s modulus (GPa)		Strain to failure (%)	
Average ± SD	C.o.V	Average ± SD	C.o.V	Average ± SD	C.o.V
850 ± 280	33%	55 ± 9	16%	1.99 ± 0.48	24%
1012 ± 380	38%	62 ± 19	31%	1.94 ± 0.42	22%
1020 ± 530	52%	63 ± 21	33%	2 ± 0.87	42%

Yarn: 600 MPa and 20 GPa (CoV: 11%-13%)

Maximum stress (MPa)		
Average	SD	CoV (%)
599	78	13

Modulus of Elasticity MoE (GPa)		
Average	SD	CoV (%)
19.8	2.2	11

Fabric: 210-220 MPa and 8.0-9.4 GPa (CoV: 3.2%-8.5%)

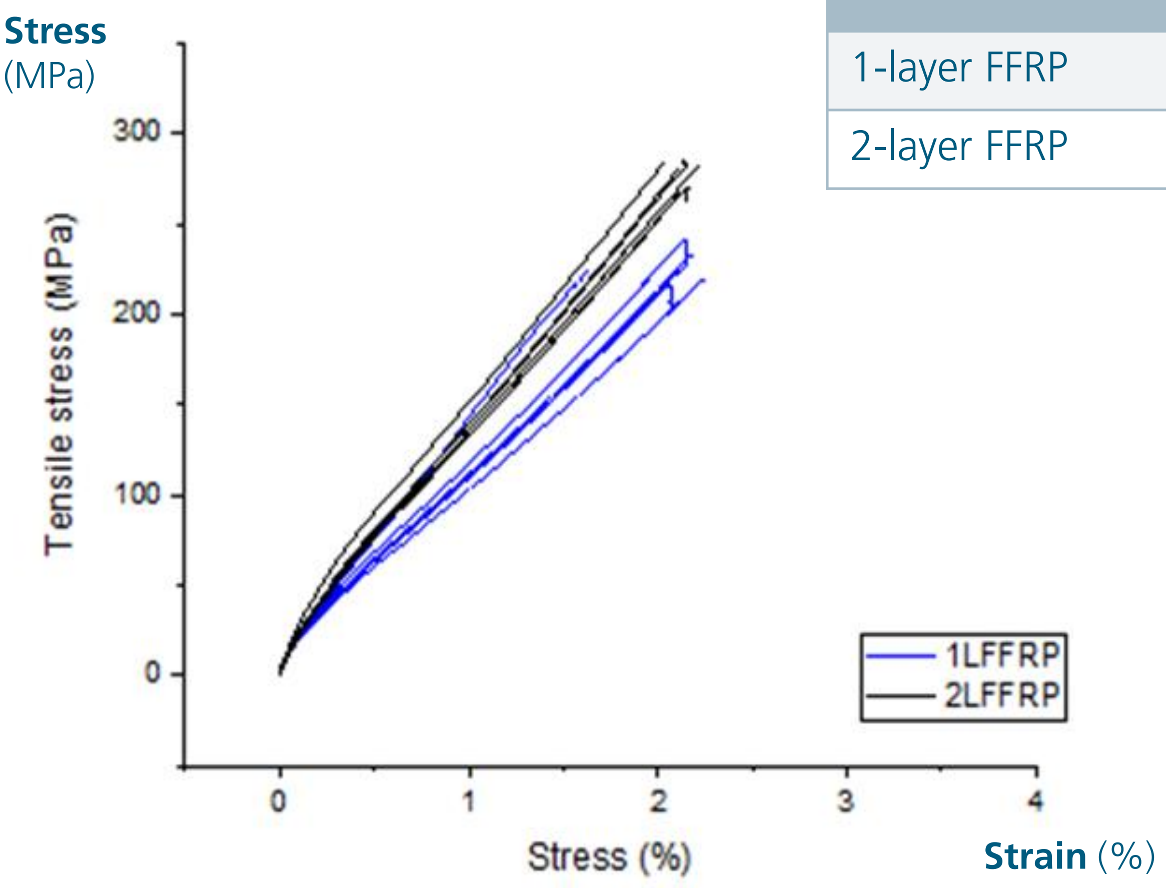
Strain rate (%/min)	1%/min (n =7)	10%/min (n=5)
MoE (GPa)	9.4 ± 0.8	8.0 ± 0.5
CoV (%)	8.5	6.0
Fmax (MPa)	211 ± 10	221 ± 7
CoV (%)	4.6	3.2

- From fibre to yarn and to fabric, tensile strength and tensile modulus reduce remarkably
- From fibre to yarn and to fabric, the variation in tensile strength and modulus also reduce remarkably

Doctoral work: S. Aldroubi

Properties of Plant-based Flax Fibre, Yarn, Fabric and FRP Composites

Tensile properties of unidirectional flax fabric/epoxy composites



	MoE (GPa)	Strength (MPa)	Strain (%)
1-layer FFRP	12.4 ± 0.9 (7.3%)	228 ± 9 (4.0%)	2.08 ± 0.20 (9.6%)
2-layer FFRP	15.9 ± 0.6 (3.7%)	278 ± 8 (2.9%)	2.13 ± 0.06 (2.8%)

Doctoral work: S. Aldroubi

Potential Application of Flax FRP Composites in Construction

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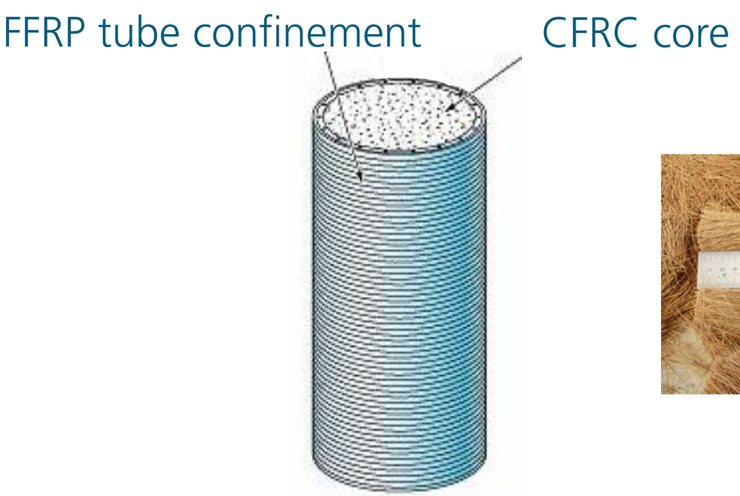
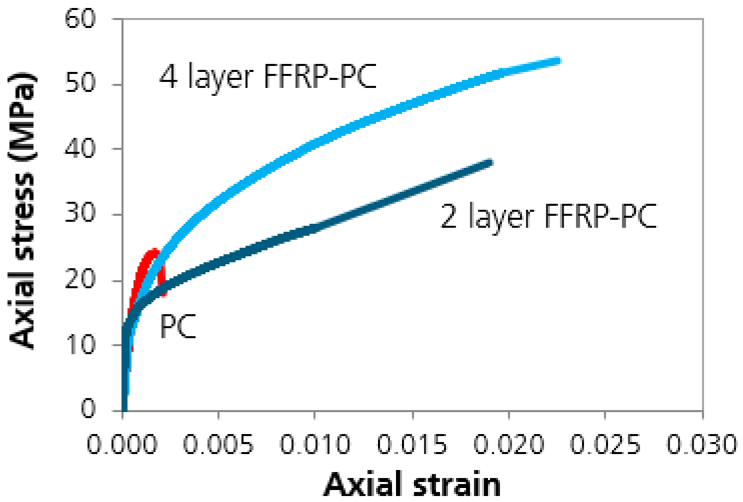
Application of Flax FRP Composites in Construction

(1) As confining material of concrete column



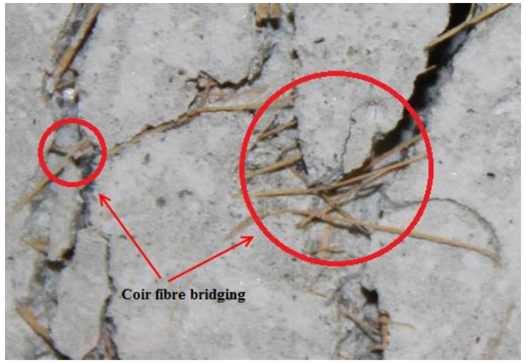
Coir fibres

Flax FRP tube (FFRP) encased coir fibre reinforced concrete (CFRC)



Compressive stress-strain curves of plain concrete, 2 and 4-layer FFRP tube plain concrete

Plain concrete (PC) and CFRC cores after removed FFRP tubes

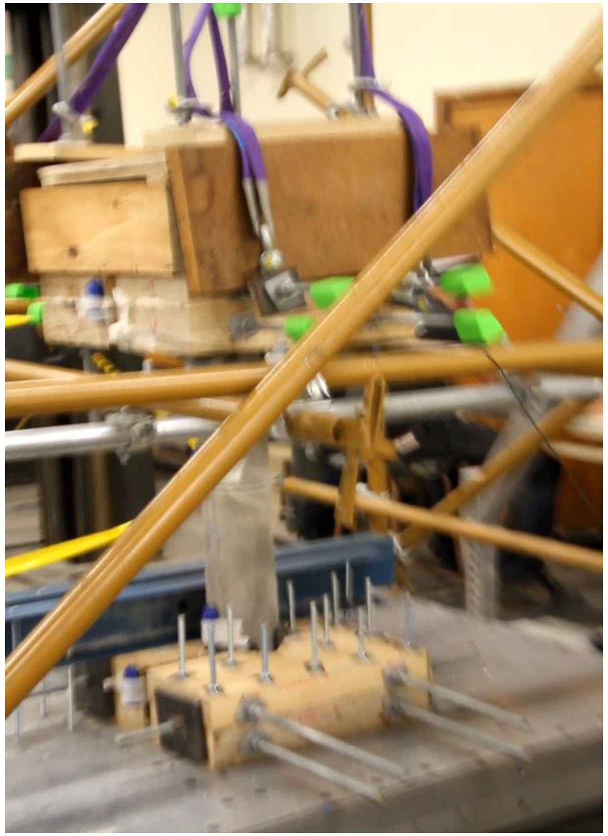


Coir fibre bridging: reduce concrete cracks & modify failure concrete to be ductile

Application of Flax FRP Composites in Construction

As confining materials of normal aggregate concrete

To simulate a bridge pier made of FFRP-CFRC column



Shake table test of an FFRP-CFRC column

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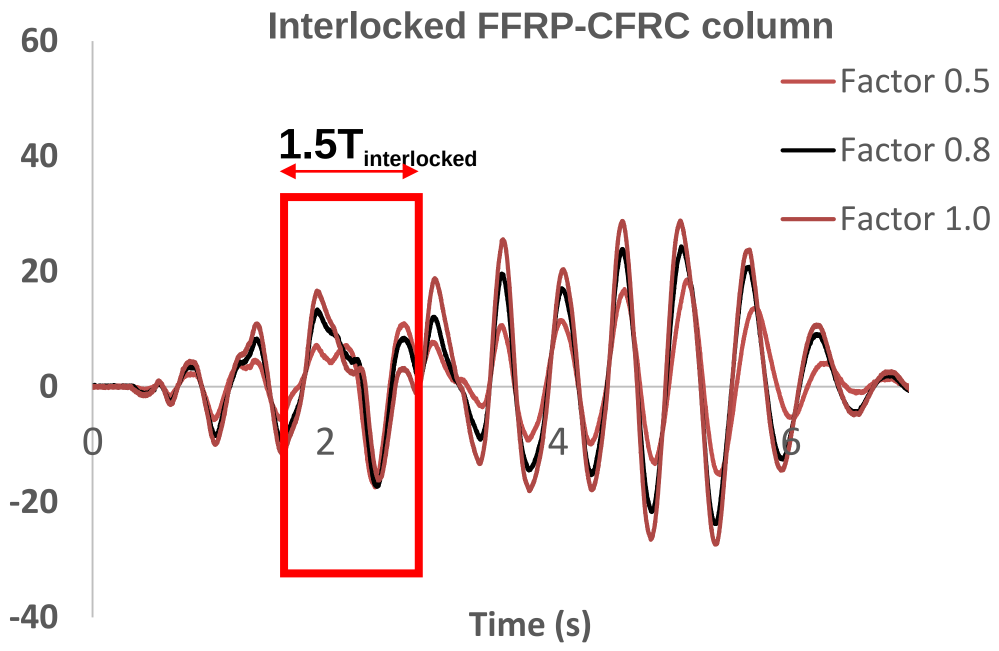

Imported earthquake ground motions

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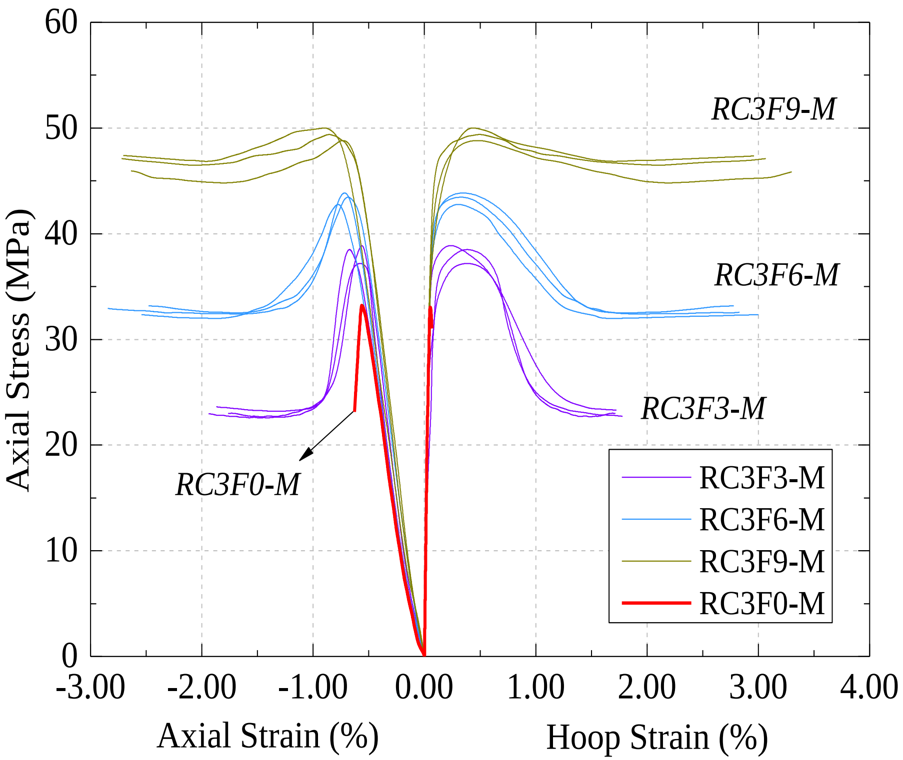
Potential Application of Flax FRP Composites in Construction

As confining material of recycled aggregate concrete (RAC)

Recycled aggregate mix

FFRP tubes: large (300 x 600), medium (150 x 300) and small (75 x 150): unit of mm



FFRP-RAC with RAC strength of 32.8 MPa

(a)

(b)

Failure mode: (a) FFRP-RAC and (b) crushed RAC core after removed FFRP tube

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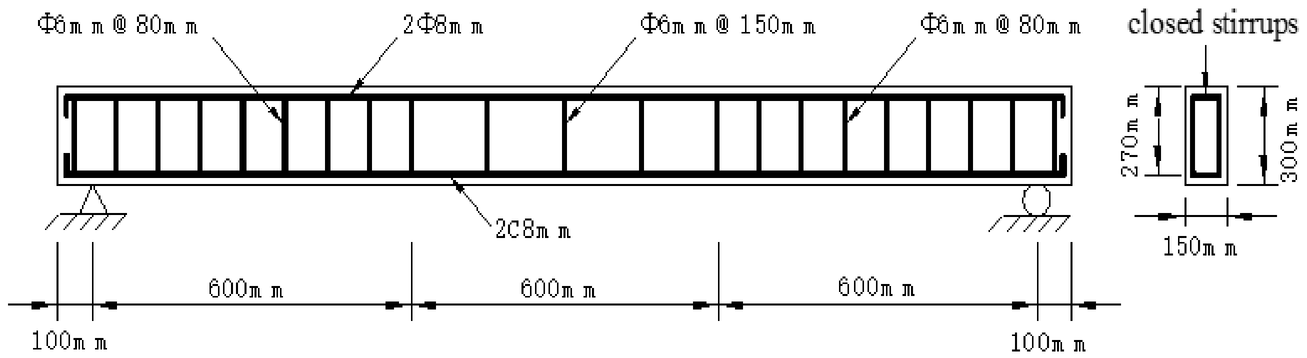
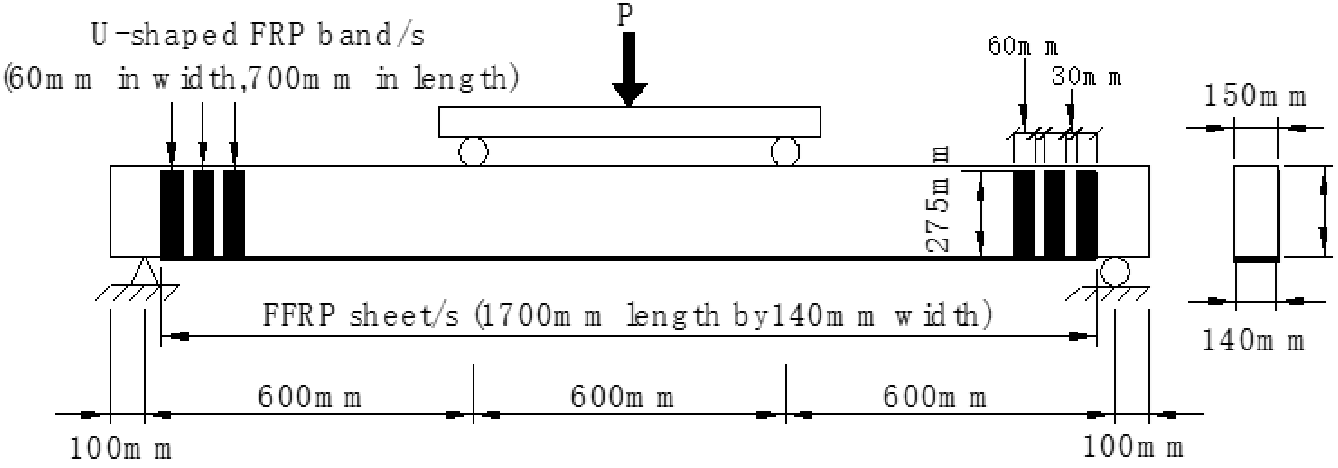
Potential Application of Flax FRP Composites in Construction

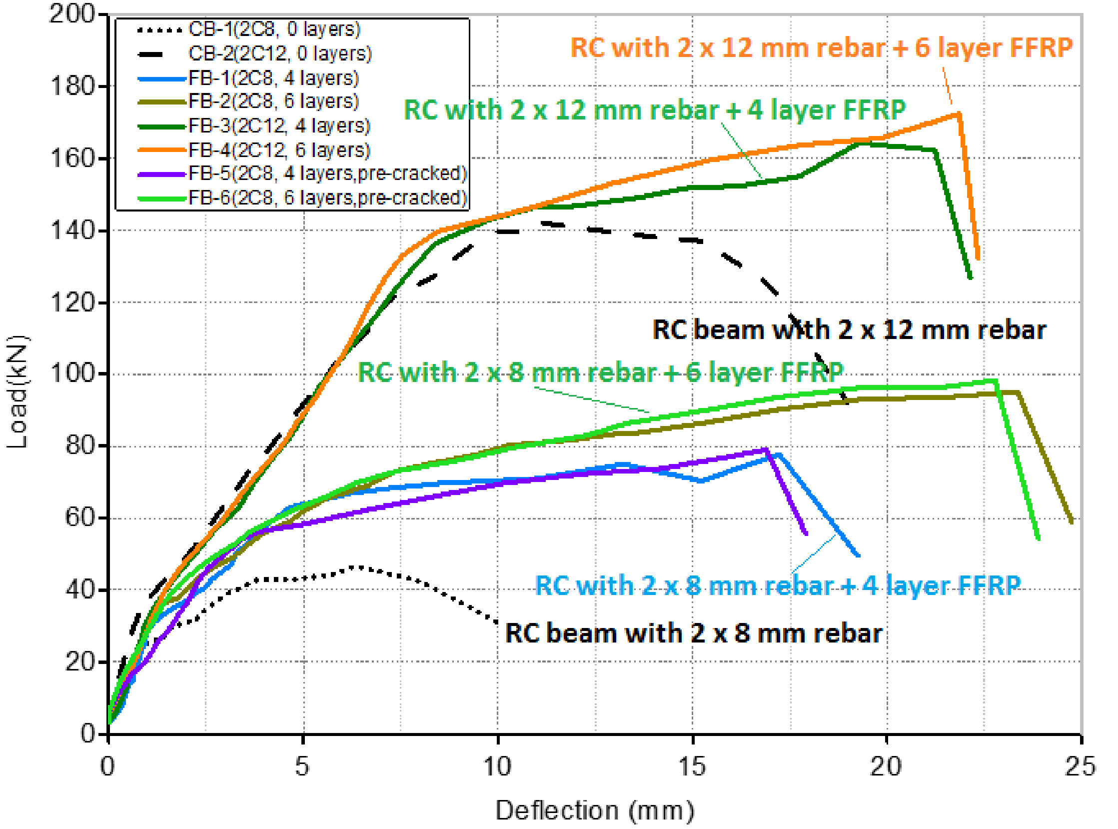
(2) As external strengthening material of reinforced concrete structures



Steel reinforced concrete (RC) beam



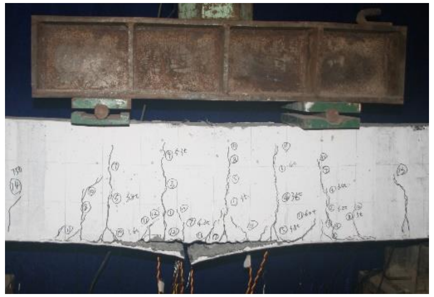
Flax FRP strengthened RC beam

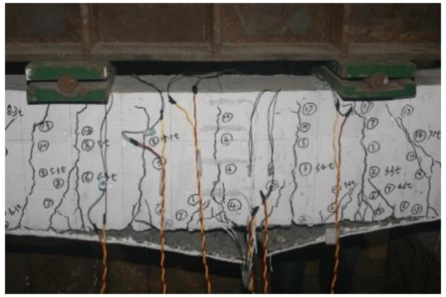


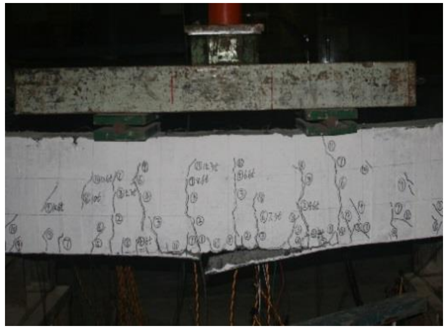
Flexure load vs. deflection of RC beams, 4-layer FFRP-strengthened RC and 6-layer FFRP-strengthened RC beams

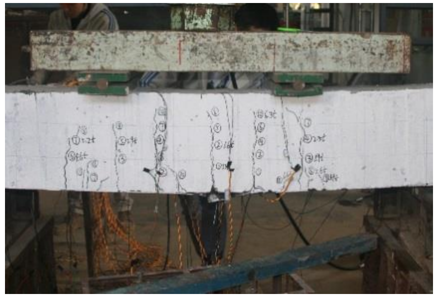
Potential Application of Flax FRP Composites in Construction

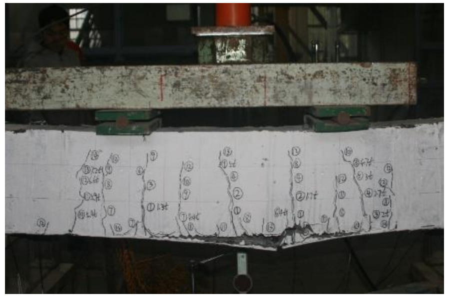
As external strengthening material of reinforced concrete structures

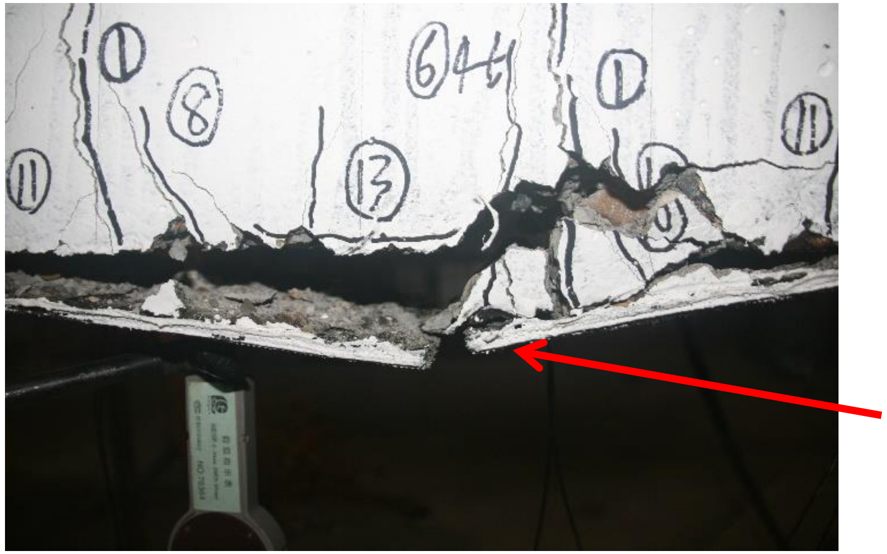










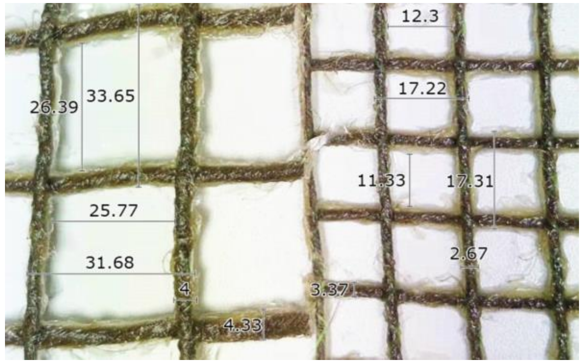


FFRP rupture

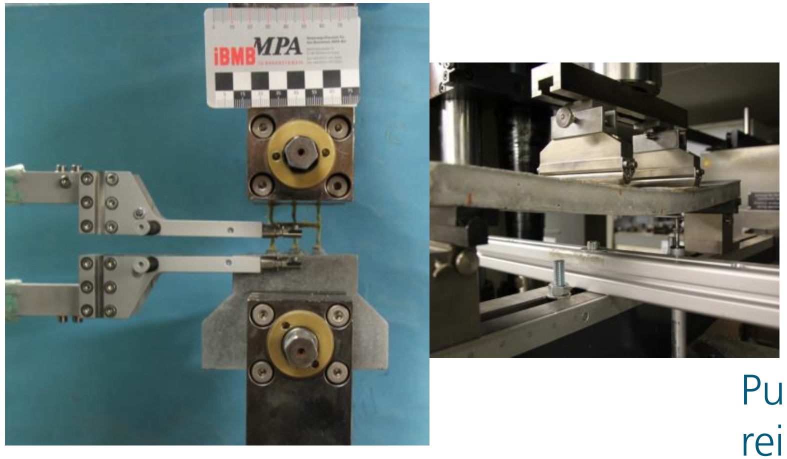
In flax FRP-strengthend RC beams, no delamination of FFRP plates from concrete was observed, showing a good compatibility between RC and the FFRP, and full use of FFRP strength and stiffness.

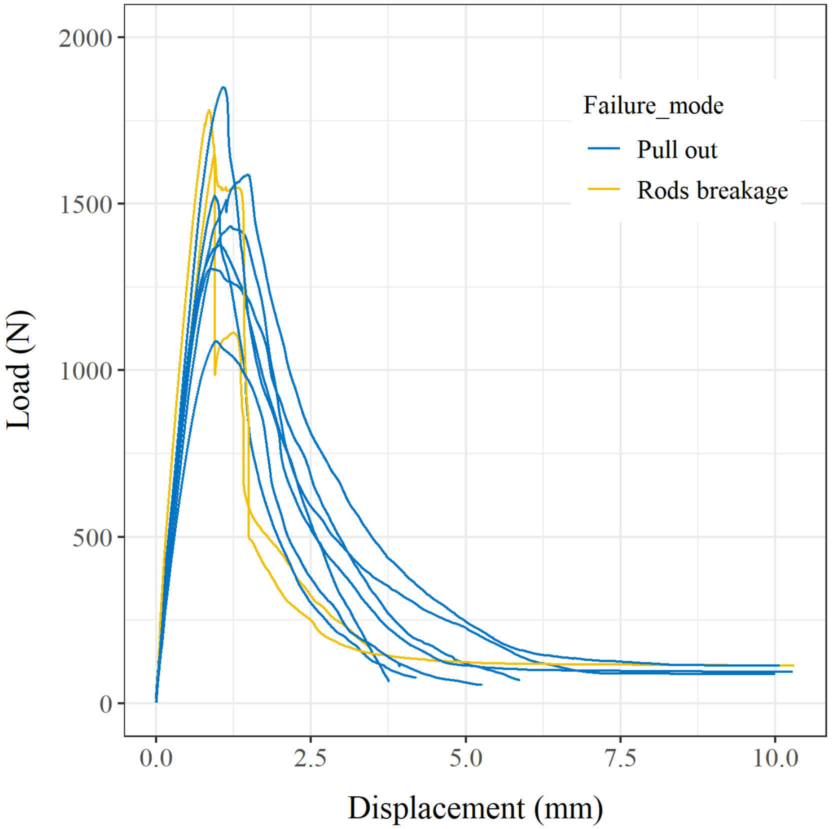
Potential Application of Flax FRP Composites in Construction

(3) As internal reinforcement of concrete – Textile reinforced mortar and recycled aggregate concrete

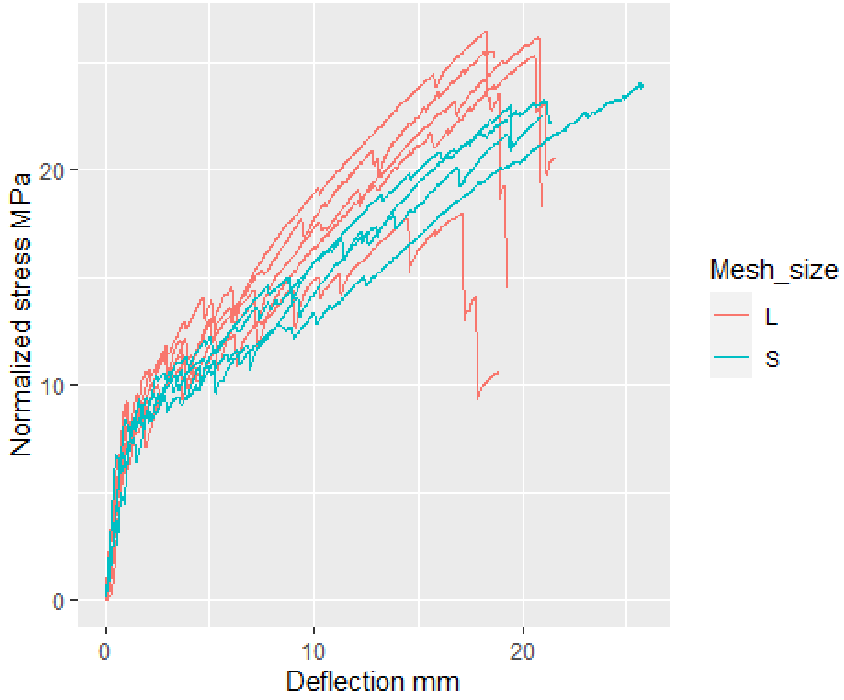


Epoxy coated flax yarn mesh: large and small mesh size





Pull-out load vs. displacement curve of FFRP-reinforced RAC



Normalized stress-deflection curve (by longitudinal fibre volume fraction) of FFRP reinforced mortar

Doctoral work: W.Z. Ma

Fraunhofer WKI

Potential Application of Flax FRP Composites in Construction

As internal reinforcement of concrete – Textile reinforced mortar and recycled aggregate concrete

FlaXship at 16th German Concrete Canoe Competition (2017)

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FlaXship developed by civil engineering students @ iBMB, TU Braunschweig

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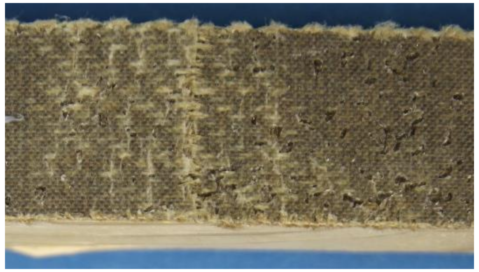
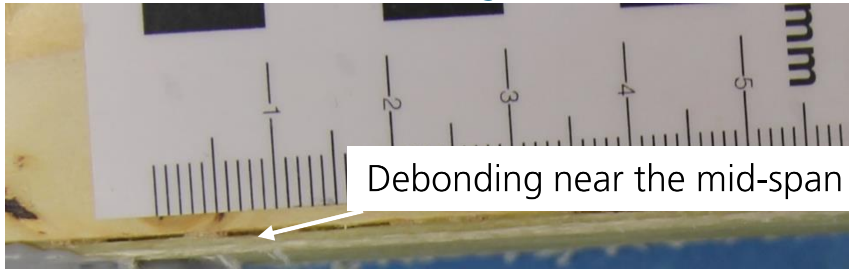
Potential Application of Flax FRP Composites in Construction

(4) As external strengthening material of timber as hybrid timber system

FRP rupture (Flax layer)

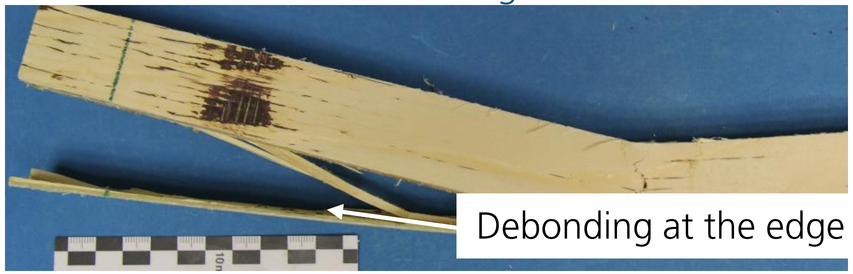


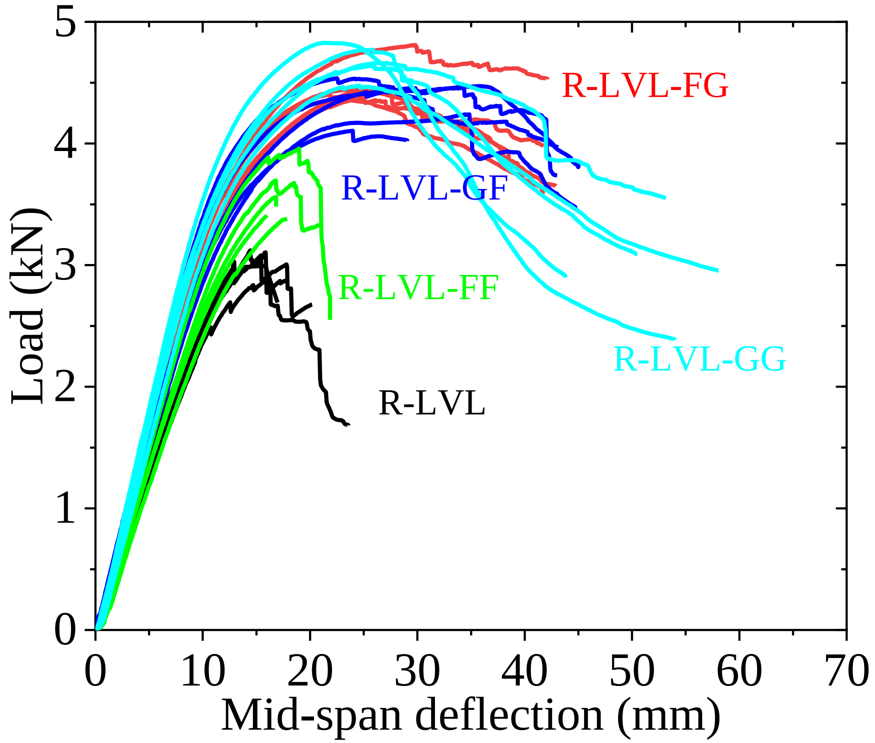
Debonding-1



FRP rupture (Glass layer)

Debonding-2





Laminated veneer lumber (LVL)
F: Flax FRP
G: Glass FRP

Load vs. deflection of pure LVL, FFRP-reinforced LVL, GFRP-reinforced LVL and flax and glass hybrid FRP-reinforced LVL beams

Doctoral work: S.L. Huang

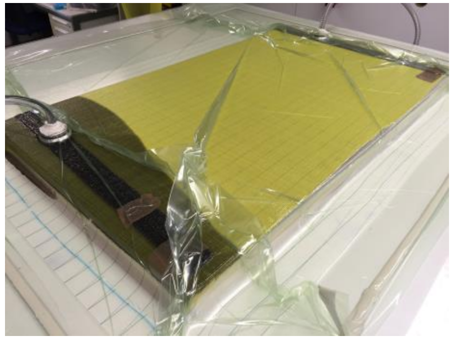
Potential Application of Flax FRP Composites in Construction

(5) As skin material with light core for sandwich structures

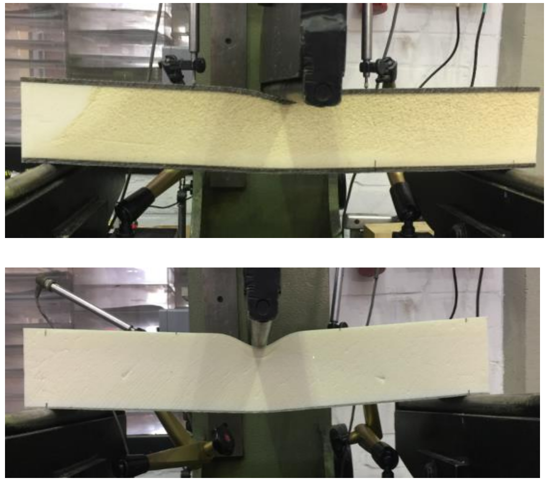
Extruded polystyrene (XPS) foam core

Balsa wood core

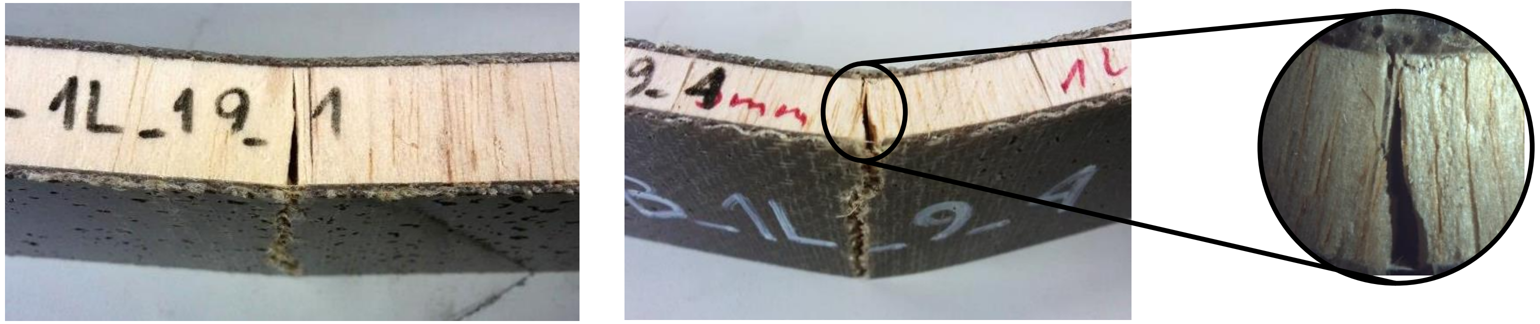
Flax fabric skin and wood core



Resin infusion process



Indentation failure: 4-layer FFRP (top) and 2-layer GFRP (bottom) skinned 80 mm XPS panel



Pure core failure: vertical core break under the application point of the load. The crack goes from the bottom until the top skin layer

Challenge and Outlook

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Challenge

Challenge of using plant-based natural FRP composites in construction

Hard to standardize natural fibres with stablized properties

- **Large variability in properties among various plant-based natural fibres**

Fibre type	Relative density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Specific modulus (GPa × cm^3/g)	Elongation at failure (%)
Abaca	1.5	400–980	6.2–20	9	1.0–10
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Coir	1.15–1.46	95–230	2.8–6	4	15–51.4
Cotton	1.5–1.6	287–800	5.5–12.6	6	3–10
Curaua	1.4	87–1150	11.8–96	39	1.3–4.9
Flax	1.4–1.5	343–2000	27.6–103	45	1.2–3.3
Hemp	1.4–1.5	270–900	23.5–90	40	1–3.5
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Ramie	1.0–1.55	400–1000	24.5–128	60	1.2–4.0
Sisal	1.33–1.5	363–700	9.0–38	17	2.0–7.0
Aramid	1.4	3000–3150	63–67	46.4	3.3–3.7
Carbon	1.4	4000	200–240	157	1.4–1.8
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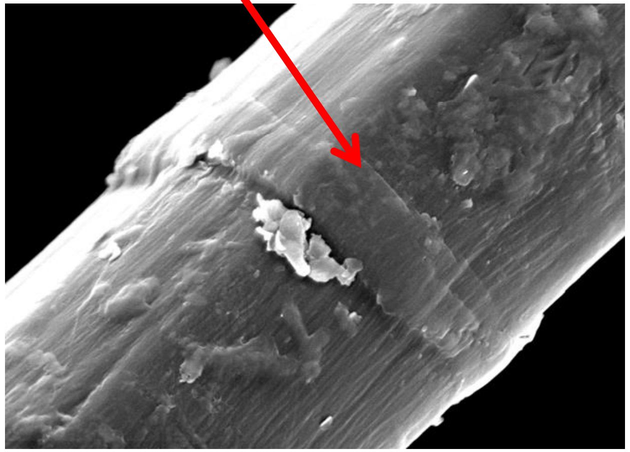
Yan et al. (2014) *Composites Part B* 56: 296-317

Challenge

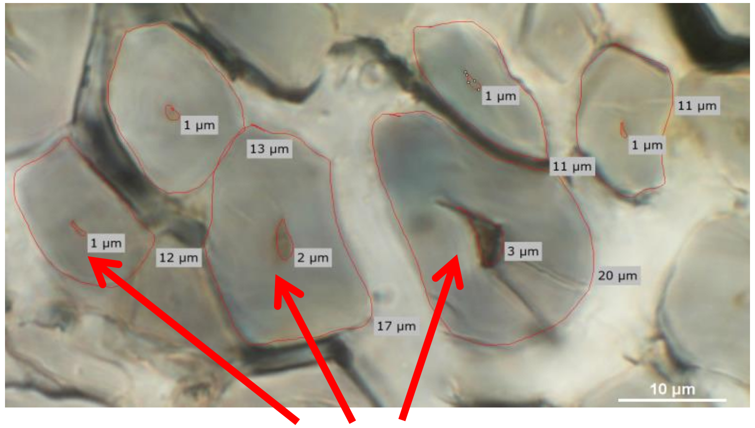
Challenge of using plant-based natural FRP composites in construction

- **Large variability in physical and mechanical properties of the same NF**

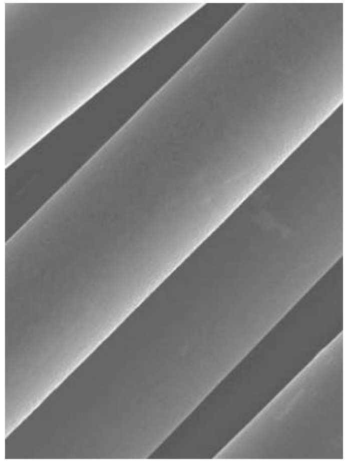
Defect: Kink band



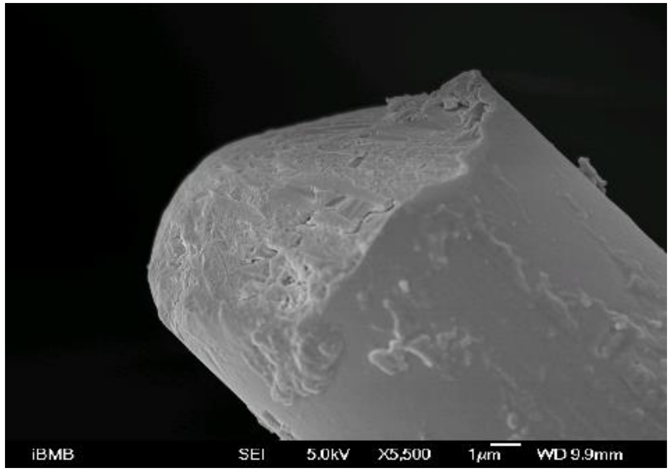
SEM of a flax fibre



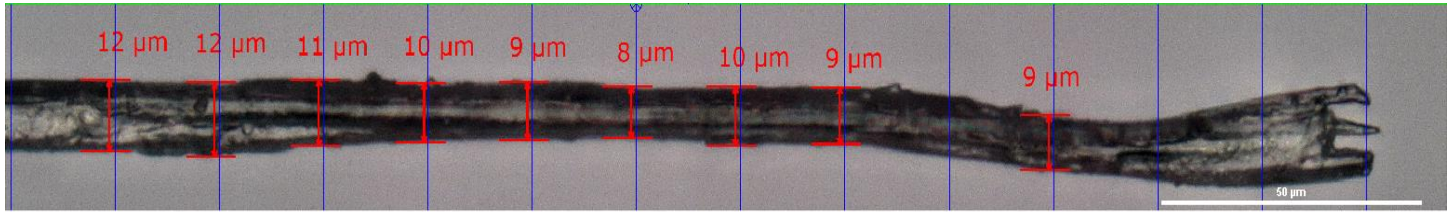
Flax fibres in a fibre bundle with different cross shapes



SEM of glass fibres



SEM of cross-section of a glass fibre



Non-continuous diameters along a flax fibre

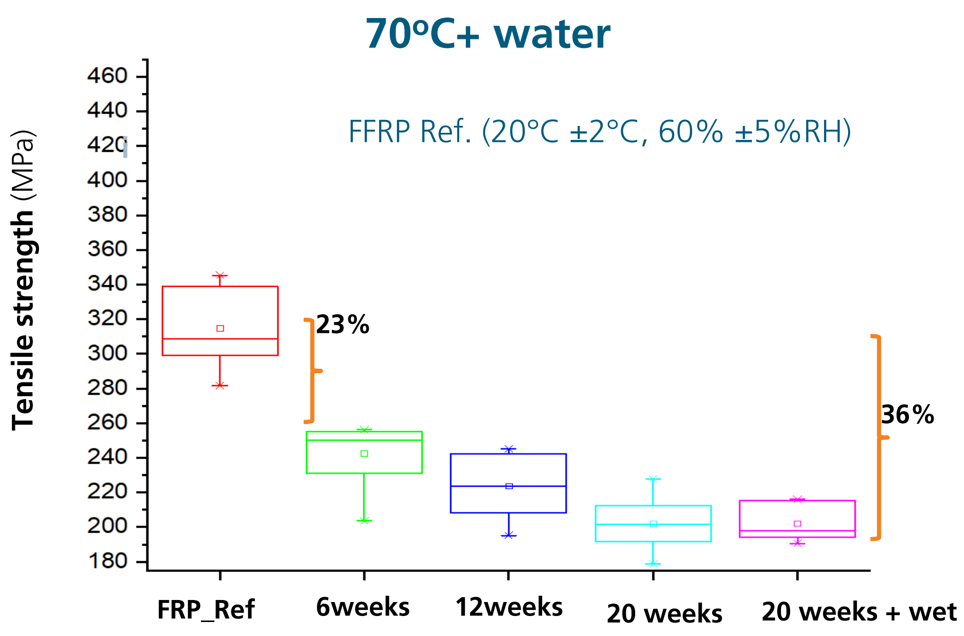
Doctoral work: S. Aldroubi

Fraunhofer WKI

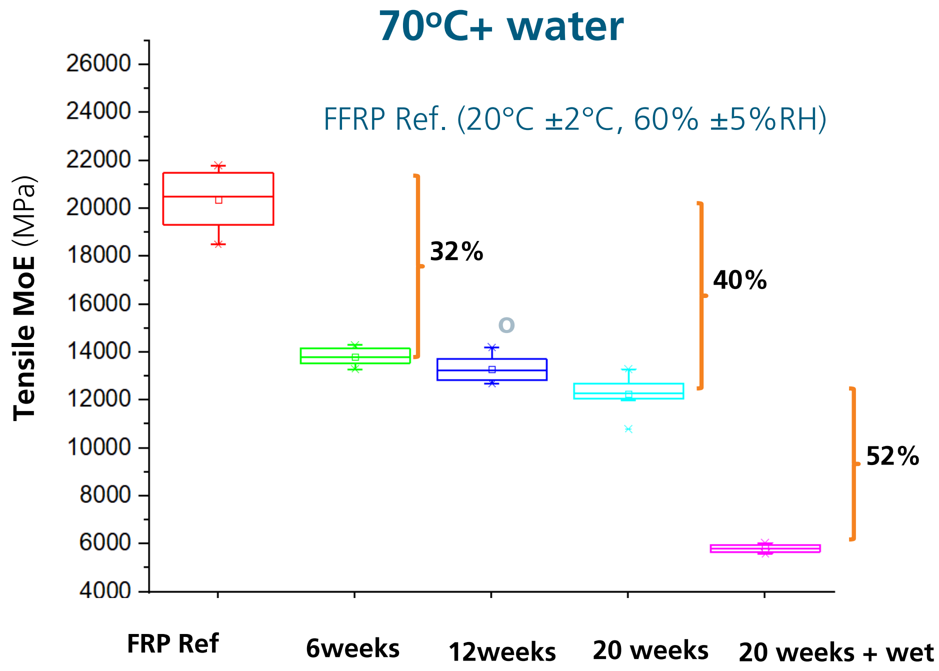
Challenge

Challenge of using plant-based natural FRP composites in construction

- **Lack of long-term durability database under aggressive environments**



Change in tensile strength



Change in tensile modulus

ANOVA: At 0.05 level

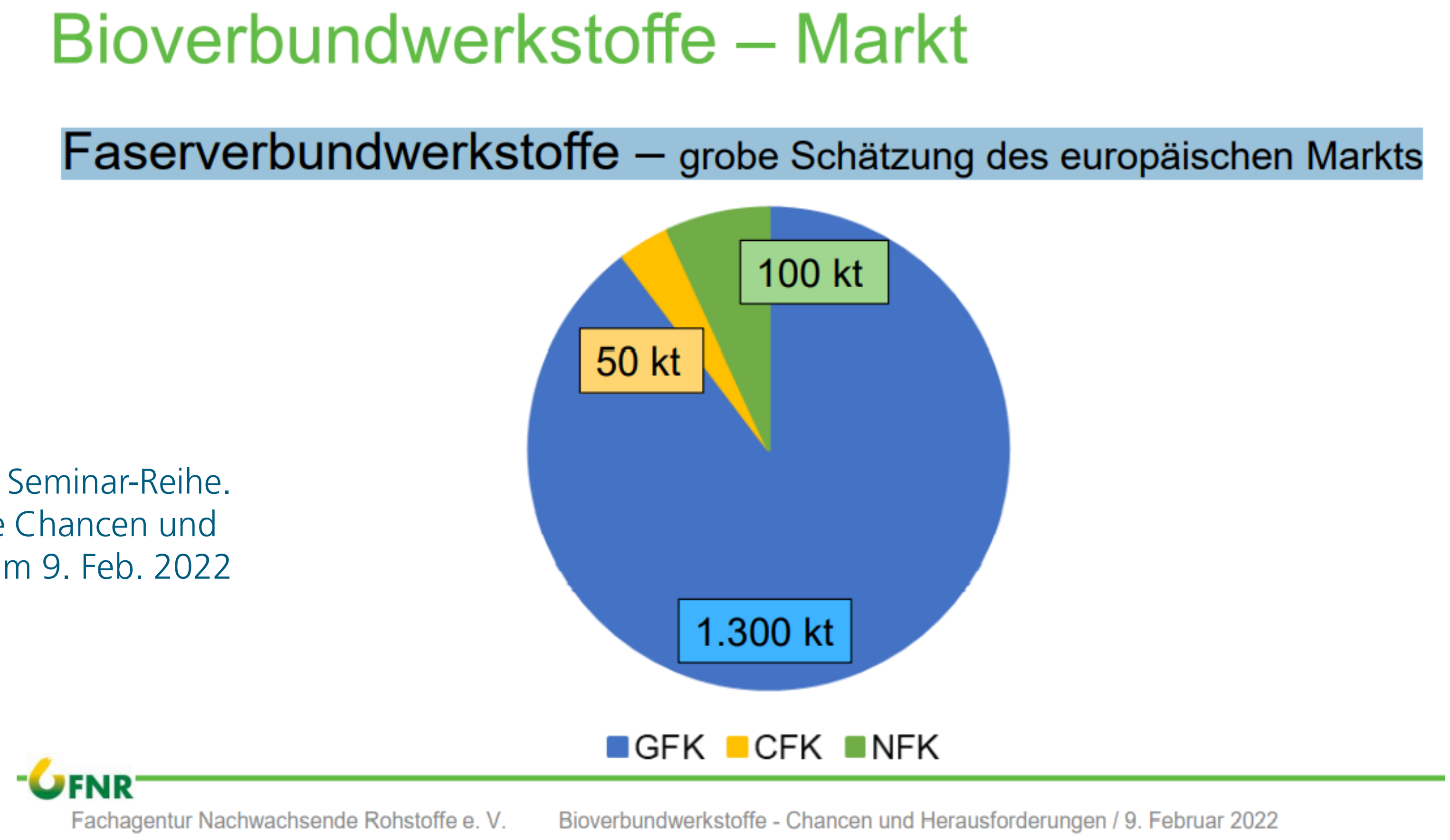
Doctoral work: S. Aldroubi

Fraunhofer WKI

Outlook

Outlook of using plant-based natural FRP composites

- **A great market potential in construction, automotive and sport**



Peterek G (2022) FNR Seminar-Reihe. Bioverbundwerkstoffe Chancen und Herausforderungen, am 9. Feb. 2022

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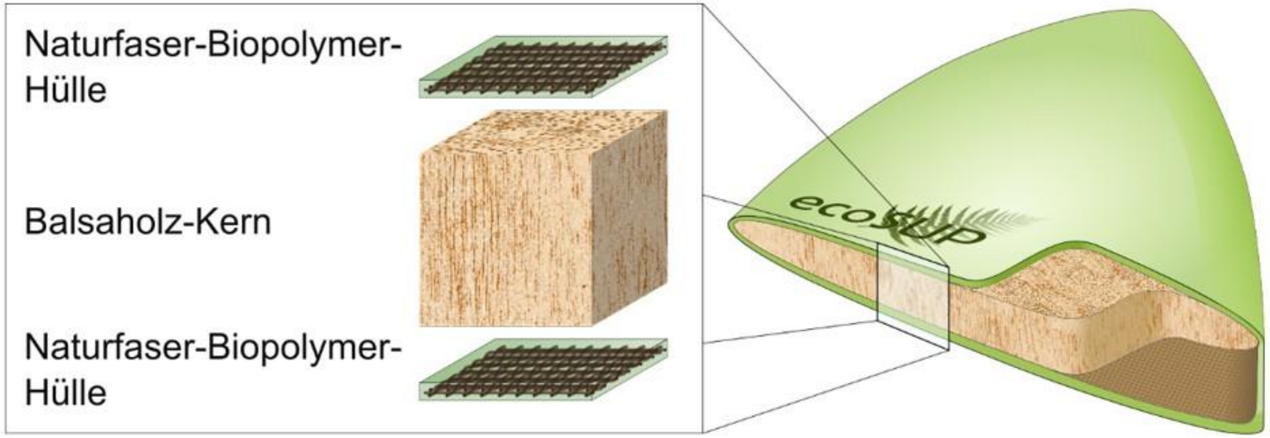
Outlook

For water sporting - stand-up paddleboard



© Fraunhofer WKI I Christoph Pöhler

Doctoral work: C. Pöhler

Outlook

For automotive engineering – Bio-concept car

© Fraunhofer WKI I Federico Böhm

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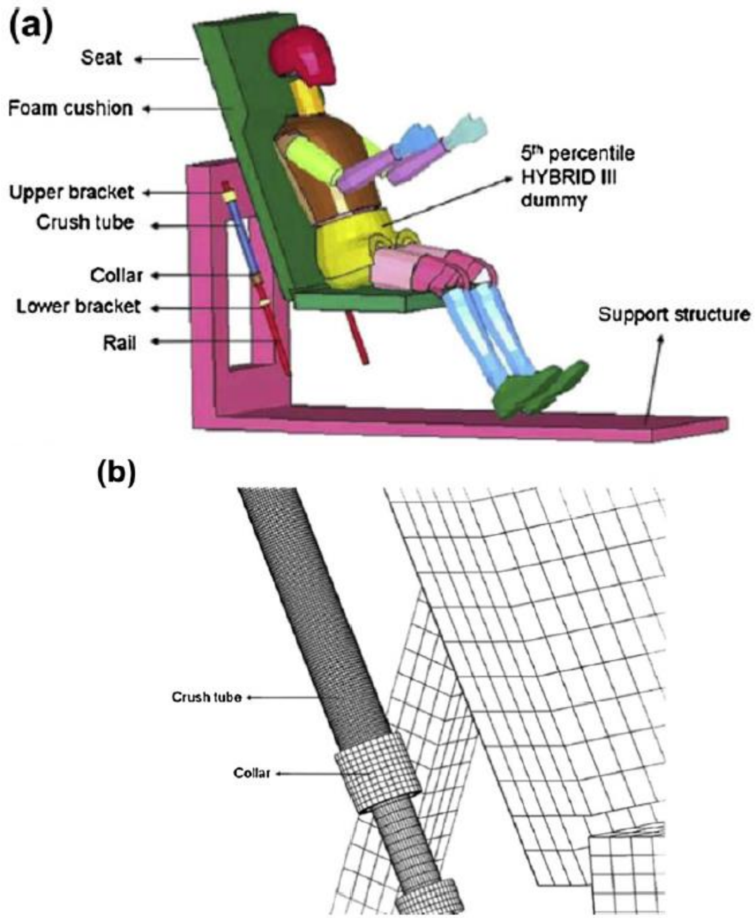
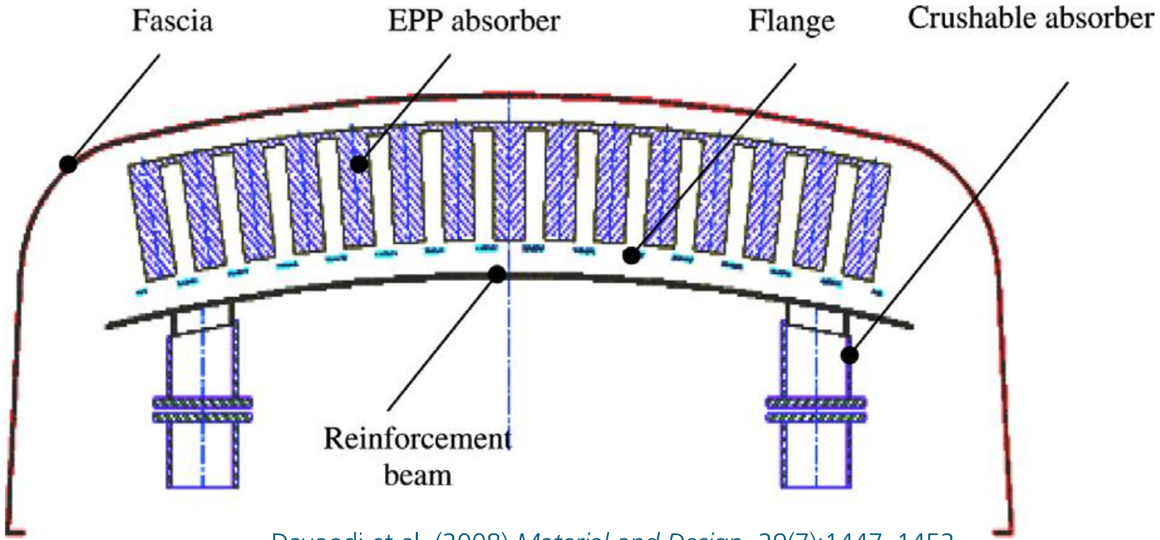
At Fraunhofer WKI, a vehicle door with a biogenic content of 85 percent is being developed. For this, natural fibers, bio-based resin/hardener mixtures and bio-based paint systems are being utilized.

Outlook

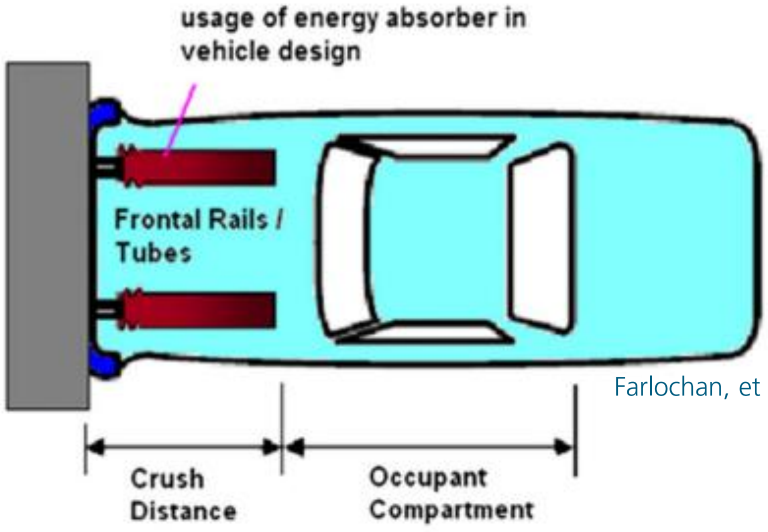
For automotive engineering - tubular structures for energy absorption



Huang & Wang (2010) *International Journal of Crashworthiness*, 15(6):625-634 6



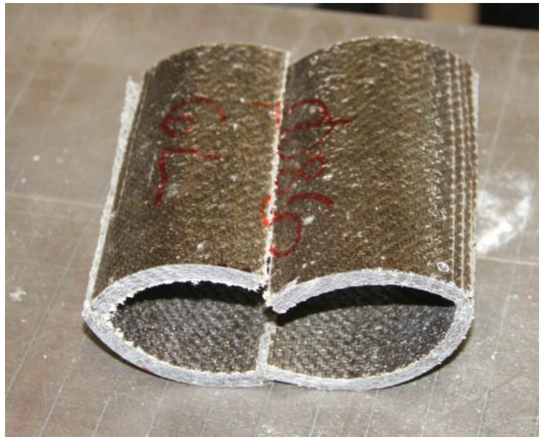
Davoodi et al. (2008) *Material and Design*, 29(7):1447–1452

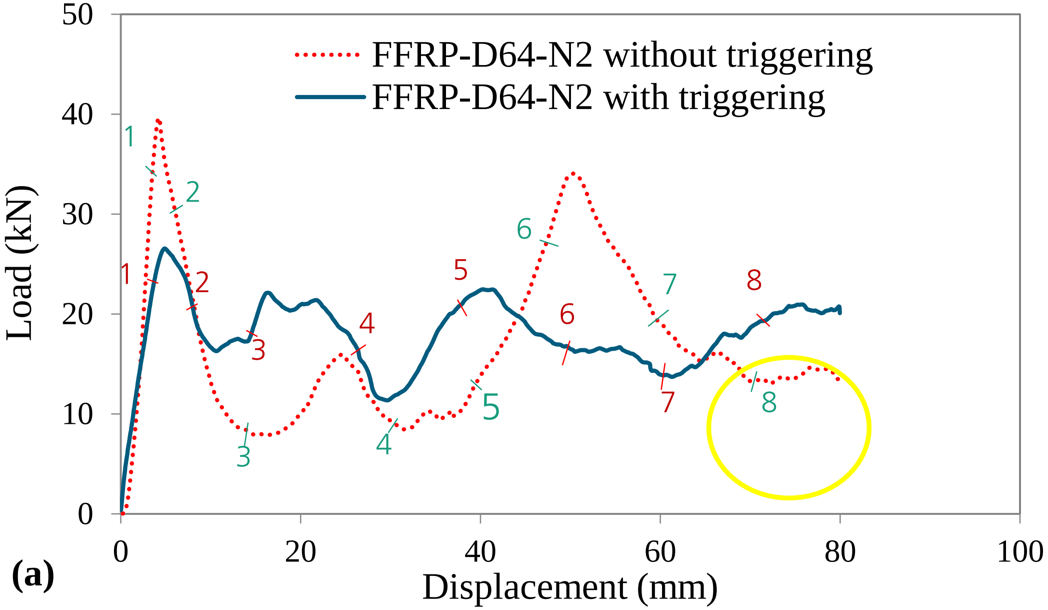


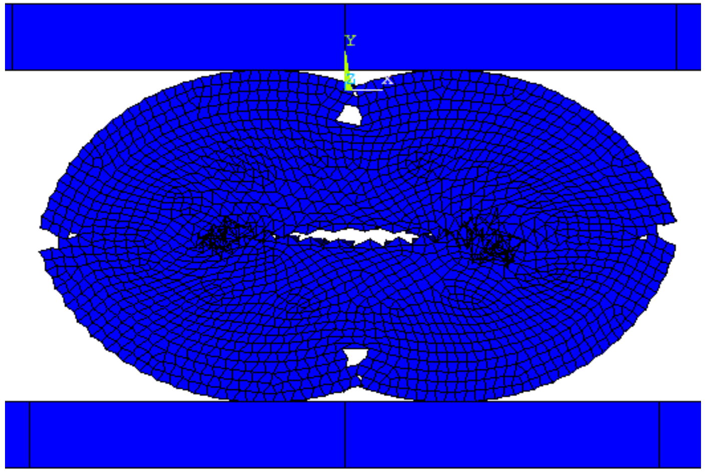
Farlochan, et al. (2012).. *Compos. B 43*, 2198–2208.

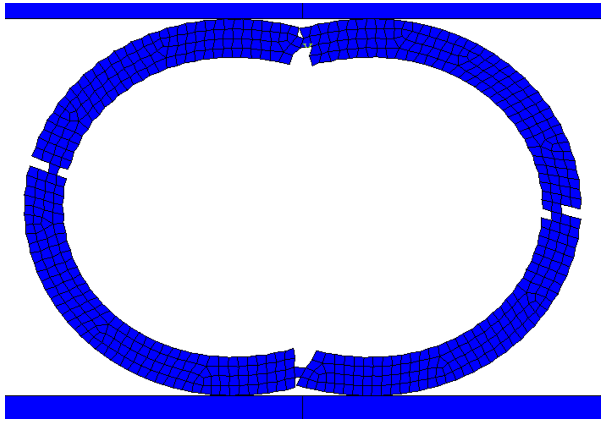
Outlook

For automotive engineering - tubular structures for energy absorption









Deformed foam-filled and hollow flax FRP tube at failure load:
experimental and (b) simulation

Fraunhofer
WKI

With the support of FNR (Nachwuchsgruppe, FKZ: 22011617, 01.12.2018 – 30.11.2023), our Junior Research Group also workes on other sustainable building materials. For more details, please refer to

https://www.wki.fraunhofer.de/en/departments/zeluba/profile/bmel-fnr-junior-research-group.html

Textile weave machine at Fraunhofer WKI

FNR
Fachagentur Nachwachsende Rohstoffe e.V.

Fachagentur Nachwachsende Rohstoffe e. V.
(Agency for Renewable Resources)

Gefördert durch:

Bundesministerium für Ernährung und Landwirtschaft

aufgrund eines Beschlusses des Deutschen Bundestages

  Intern

Fraunhofer WKI

Thank you for your attention

Libo Yan

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