IN- AND OUT-OF-PLANE SHEAR BEHAVIOUR OF 3D WOVEN CFRP

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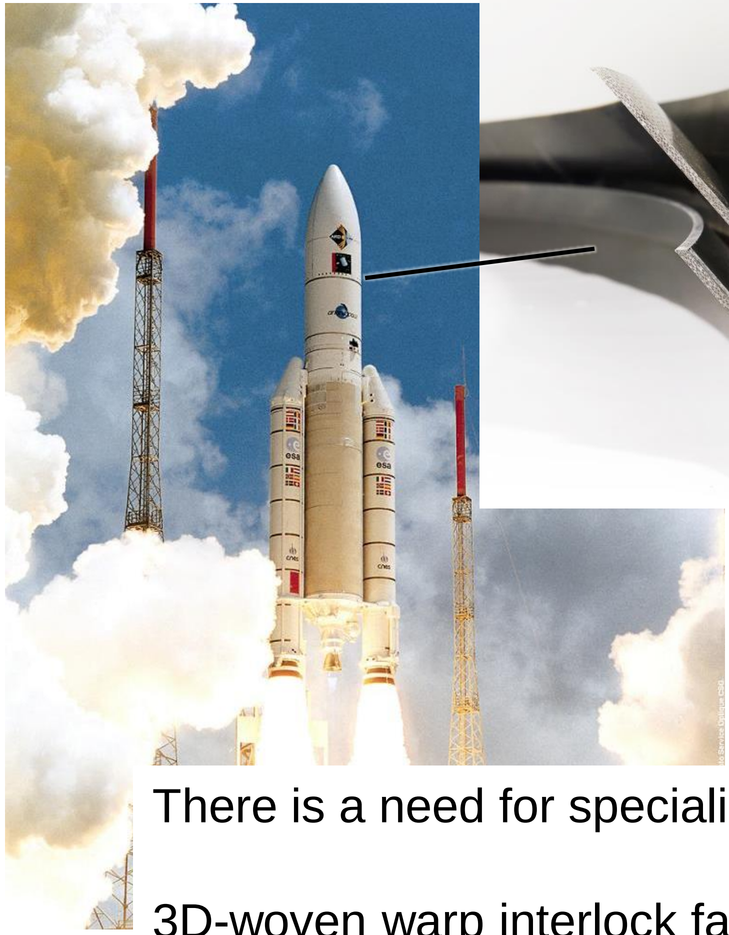
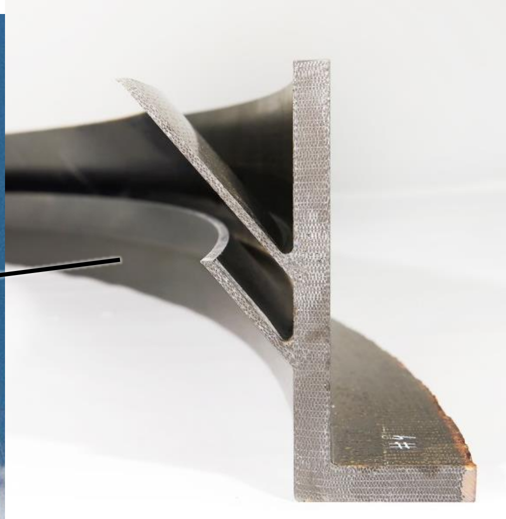
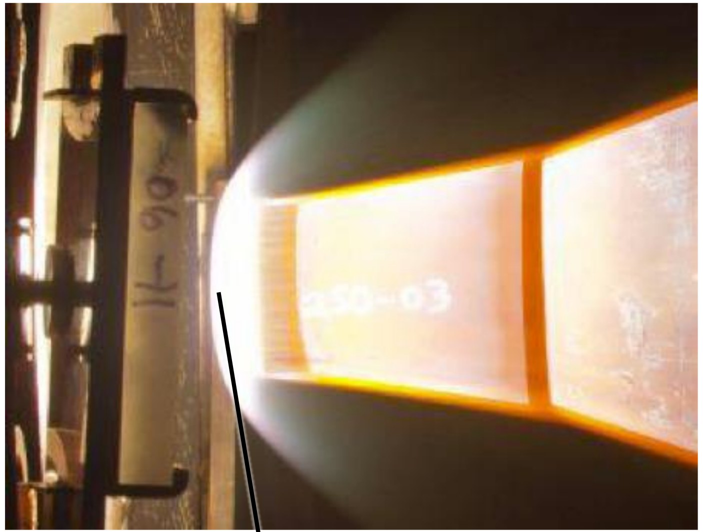
Introduction

Existing 3D-woven prototypes and parts





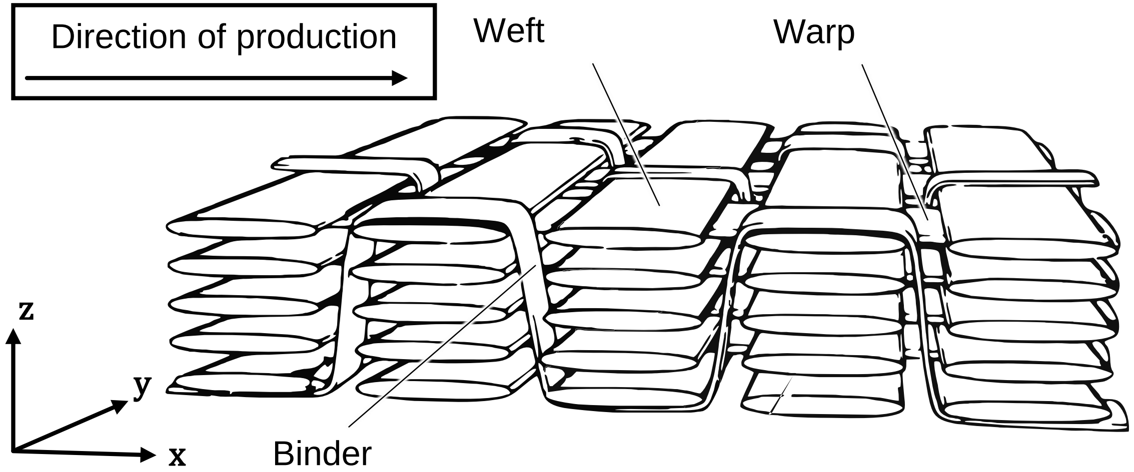


There is a need for specialized lightweight FRP with high delamination- impact- and blast-resistance.

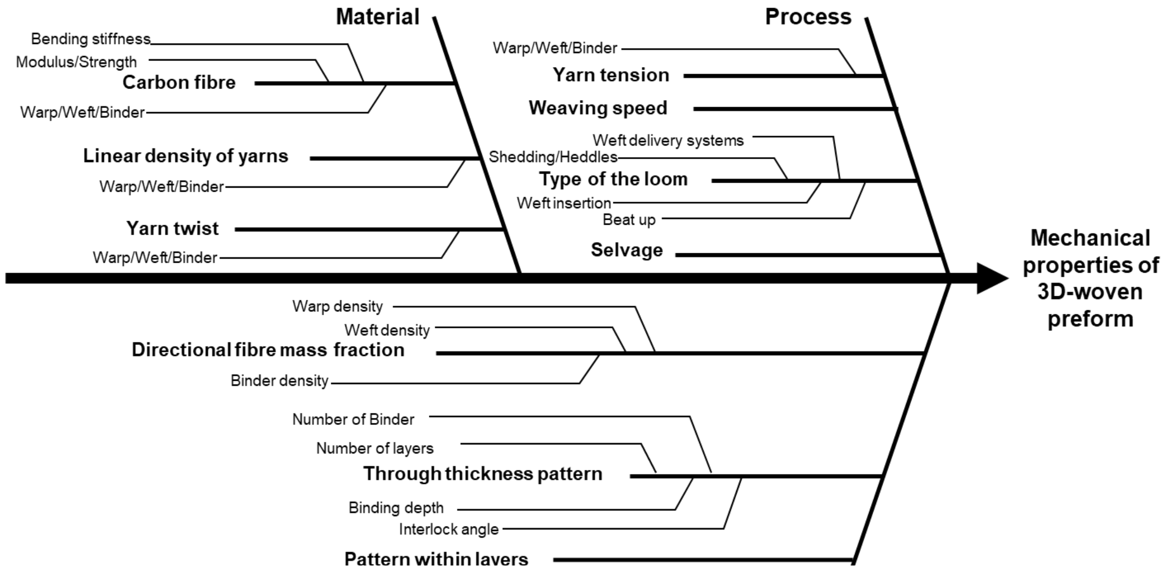
3D-woven warp interlock fabrics have been established as a solution for certain applications

Variety of 3D-wovens and influencing factors

Basic scheme of a multilayer fabric



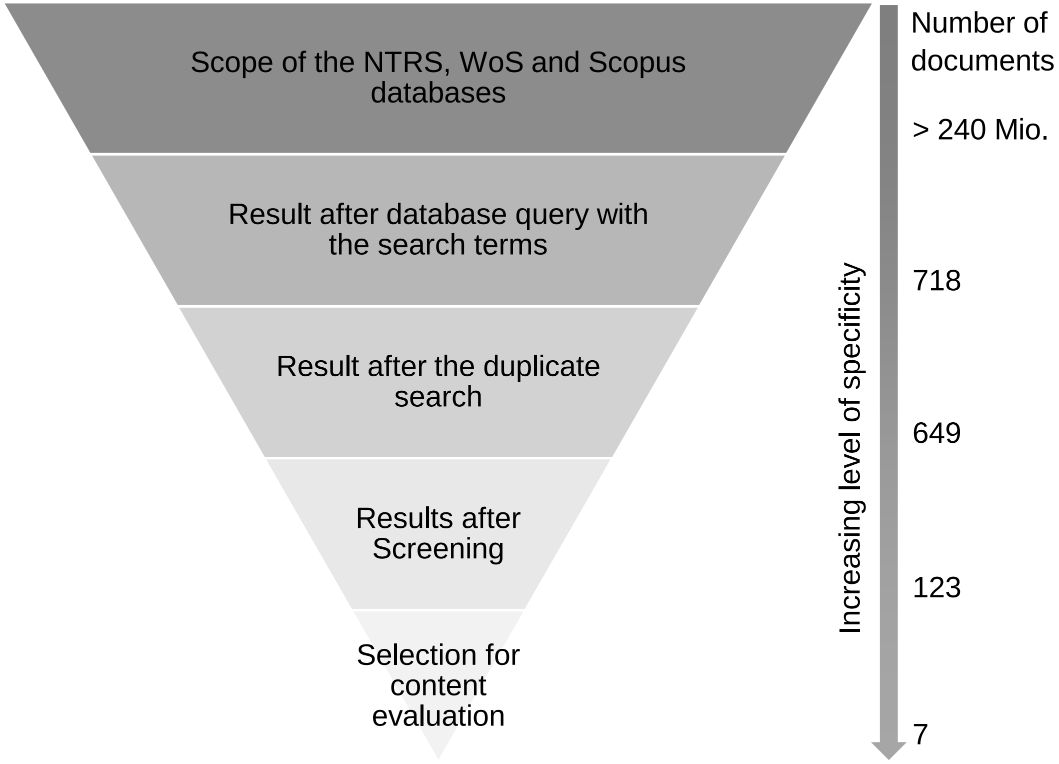
Influencing factors in a simple multilayer fabric



There are a large number of factors that influence the mechanical properties of 3D woven CFRP

Material, process, architecture andpProcessing like draping and infusion, curring influence the final CFRP

Systematic review in Web of Science, Scopus and NTRS

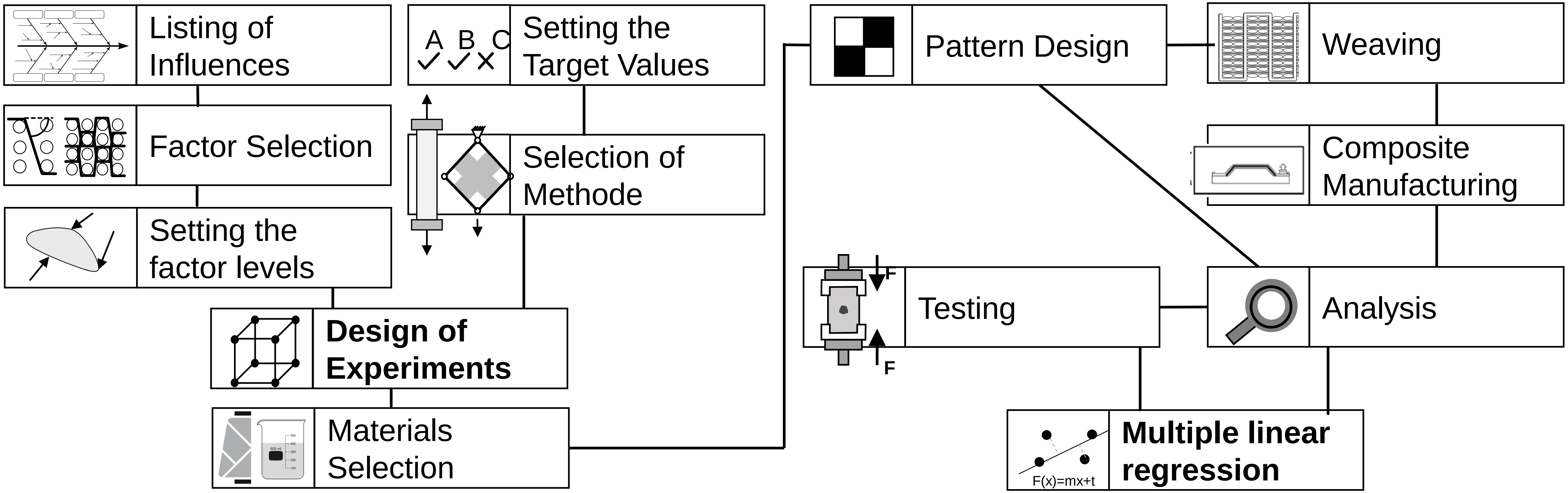


Reference	Architecture	Material	V_{tot} [%]	$E_{n,\pm 45°}$ [GPa]	$\sigma_{n,\pm 45°}$ [MPa]	$\sigma_{n,IIc,x}$ [MPa]	$\sigma_{n,IIc,y}$ [MPa]
BKL+13	O-T	C/P	51,10	10,10	125,37		
SH09	O-T	C/P	54,00			43,08	
SYP+16	O-T	C/P	51,35	8,11	231,11		
TLZ15	O-T	C/P	56,00		121,90		
WLG15	O-T	C/P	51,90	3,99	85,80		
WR17	O-T	C/P	51,03	10,00	80,16		
GSW+12	A-T	C/P	51,00	11,33	119,43	33,98	40,15
GSW+12	A-T	C/P	49,00			39,65	45,01
SYP+16	A-T	C/P	55,40	8,36	163,98		
SYP+16	A-L	C/P	59,16	8,81	117,16		
WLG15	A-L	C/P	50,40	4,27	93,35		
WLG15	A-L	C/P	59,00	4,45	94,34		
SH09	2D	C/P	64,00			21,99	
WR17	2D	C/P	55,26	15,68	154,89		
SH09	NCF	C/P	46,00			34,70	
SH09	NCF	C/P	47,00			36,20	

Very little research on shear behaviour of 3D-woven is available
It is currently not possible to describe mathematical relationships from the empiric SoR

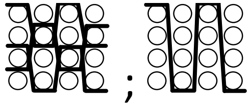
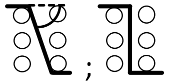
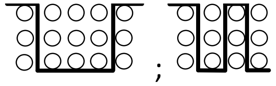
Approach, methods and design of experiments

Approach, Methdos and Design of Experiments



Systematic Design of Experiments and Multiple Linear Regression together with consistency in processing is the basis for empiric modelling

Systematic Design of Experiments (DoE)

Factor	Abbrevation	Type	Level	Pictogramm
Binding	BIN	Qualitativ	LTL; TTT	
Z-angle	zANG	Quantitativ	45° - 90°	
Z-fibre content	zCON	Quantitativ	1% - 33%	

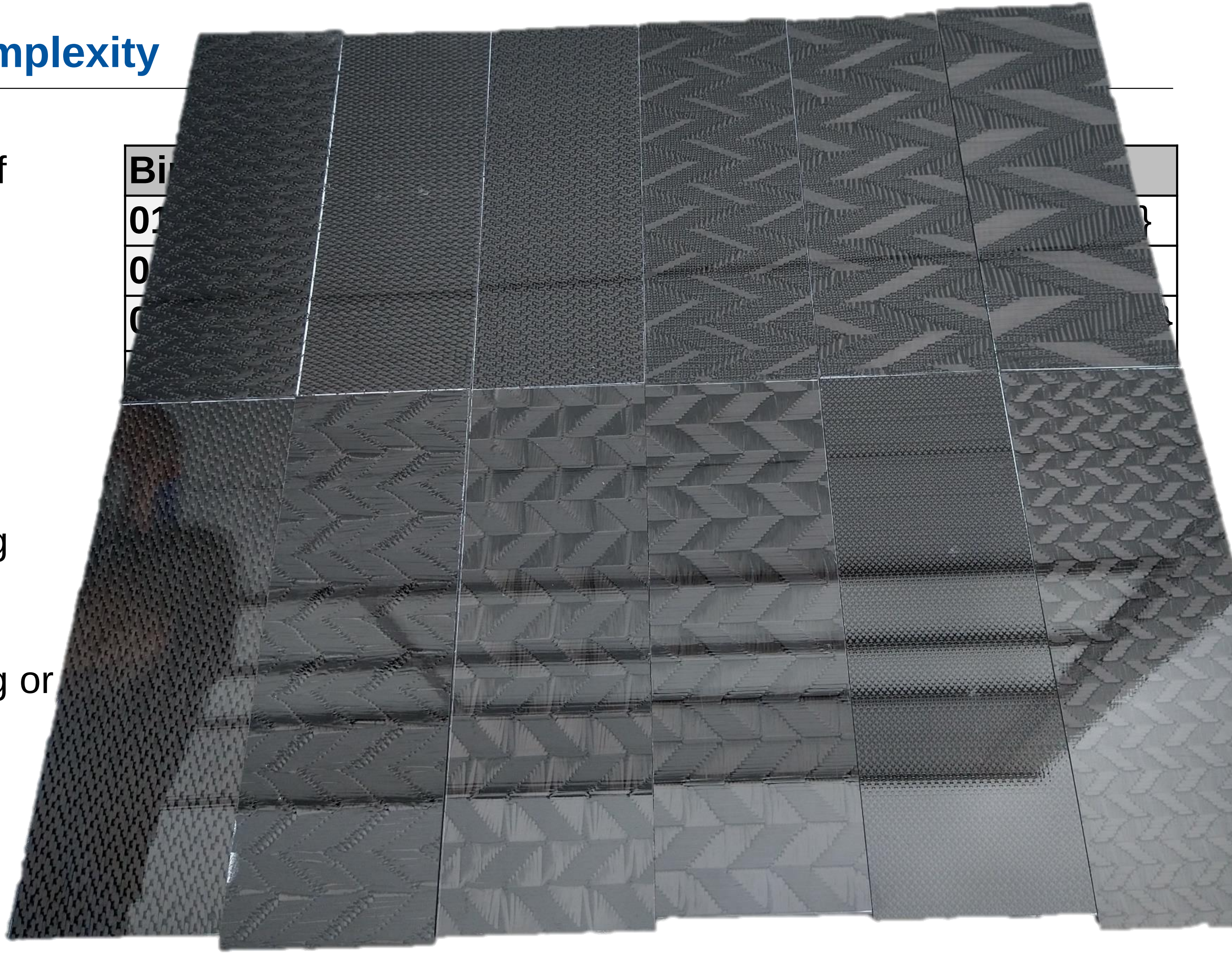
Focus on three through-the-thickness parameters

Binding	Sequence [-]	Binding [-]	z-Angle [°]	z-Cont. [%]
01_LTL_45_01	6	LTL	45	1
02_LTL_90_01	4	LTL	90	1
03_TTT_45_01	12	TTT	45	1
04_TTT_90_01	1	TTT	90	1
05_LTL_45_10	11	LTL	45	10
06_TTT_45_10	9	TTT	45	10
07_LTL_45_33	3	LTL	45	33
08_LTL_90_33	10	LTL	90	33
09_TTT_60_33	2	TTT	60	33
10_TTT_90_33	8	TTT	90	33
11_TTT_45_05	5	TTT	45	5
12_TTT_90_05	7	TTT	90	5
13_REF	13	-	-	-

D-optimal Design with 9 runs and 3 centerpoints, created using MODDE® Pro 13 software from Sartorius Stedim Data Analytics AB, Sweden

Weave pattern design – Reducing complexity

- Uniform thickness and therefore number of layers
- No specific surface patterns
- Uniform base weave (broken twill) for z-reinforcement
- Non-crimp weave within the plies, meaning no binding within one layer
- The z-content is adapted by just increasing or decreasing the floatation of the binders



Boussu F, Cristian I, Nauman S. General definition of 3D warp interlock fabric architecture. Composites Part B: Engineering 2015;81:171–88. https://doi.org/10.1016/j.compositesb.2015.07.013.

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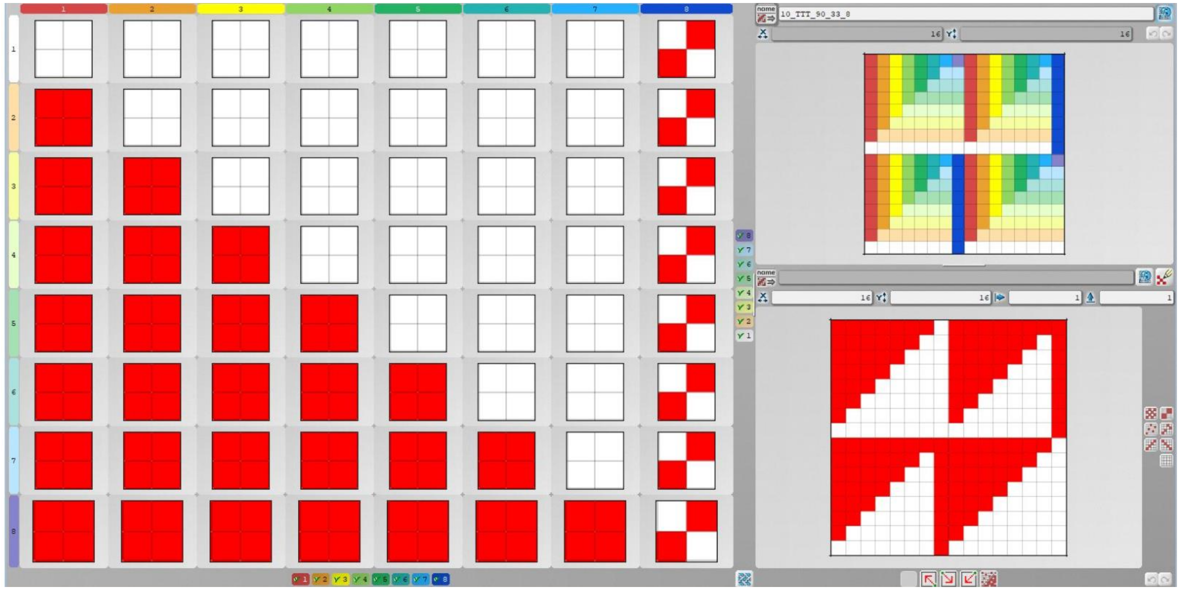
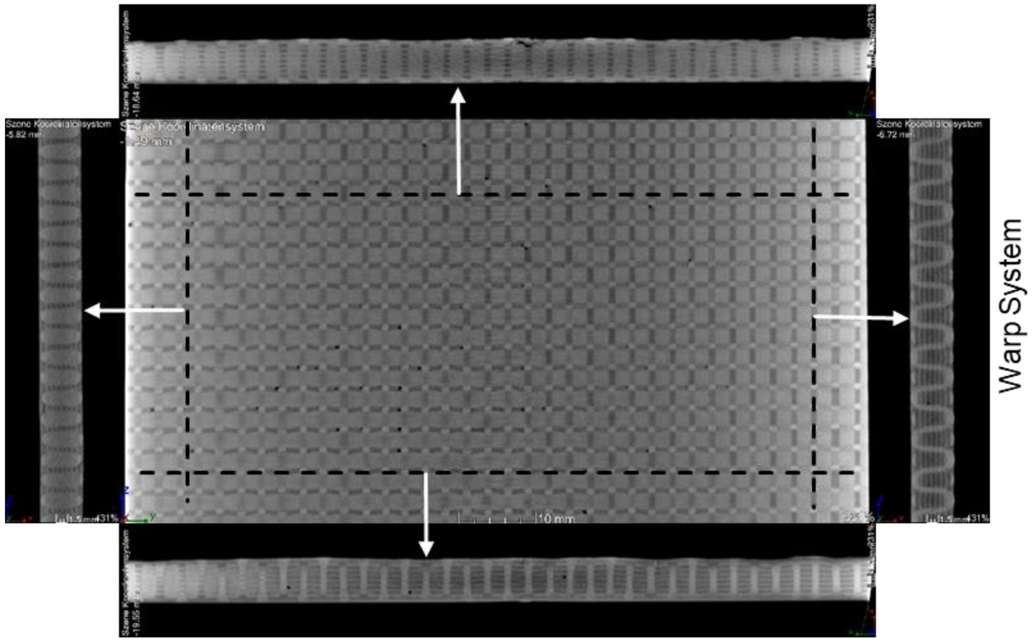
Binding	Classification according to [BCN15]
01_LTL_45_01	AL 8 13-2 {9/13 45° Broken Twill 11e/ 10e\}
02_LTL_90_01	OL 8 11-2 {11/11 Broken Twill 11e/ 11e\}
03_TTT_45_01	AT 8 15-8 {11/15 45° Broken Twill 13e/ 13e\}
04_TTT_90_01	OT 8 11-8 {11/11 Broken Twill 11e/ 11e\}
05_LTL_45_10	AL 8 5-2 {3/5 45° Broken Twill 4e/ 4e\}
06_TTT_45_10	AT 8 7-8 {3/7 45° Broken Twill 5e/ 5e\}
07_LTL_45_33	AL 8 3-2 {4H Satin}
08_LTL_90_33	OL 8 1-2 {plain weave}
09_TTT_60_33	AT 8 3-8 {4H Satin}
10_TTT_90_33	OT 8 1-8 {plain weave}
11_TTT_45_05	AT 8 10-8 {6/10 45° Broken Twill 8e/ 8e\}
12_TTT_90_05	OT 8 6-8 {6/6 Broken Twill 6e/ 6e\}
13_REF	5H Satin

Boussu F, Cristian I, Nauman S. General definition of 3D warp interlock fabric architecture. Composites Part B: Engineering 2015;81:171–88. https://doi.org/10.1016/j.compositesb.2015.07.013.

Weave pattern design

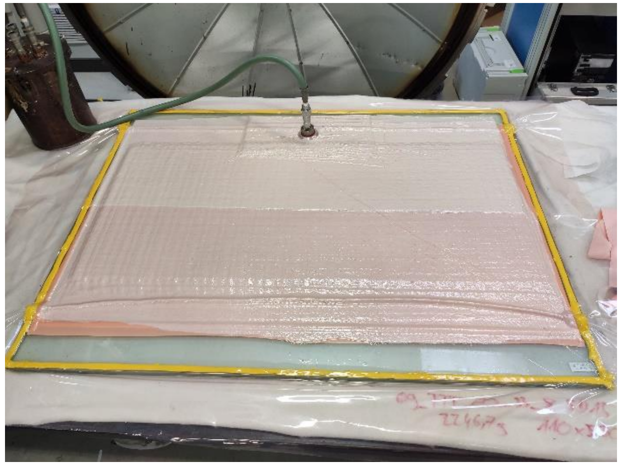




Weave pattern have been designed using Design Scope, EAT GmbH, Krefeld

Experimental Procedure – Steps and Measurements

Weaving → **Infiltration** → **Specimen Preparation**



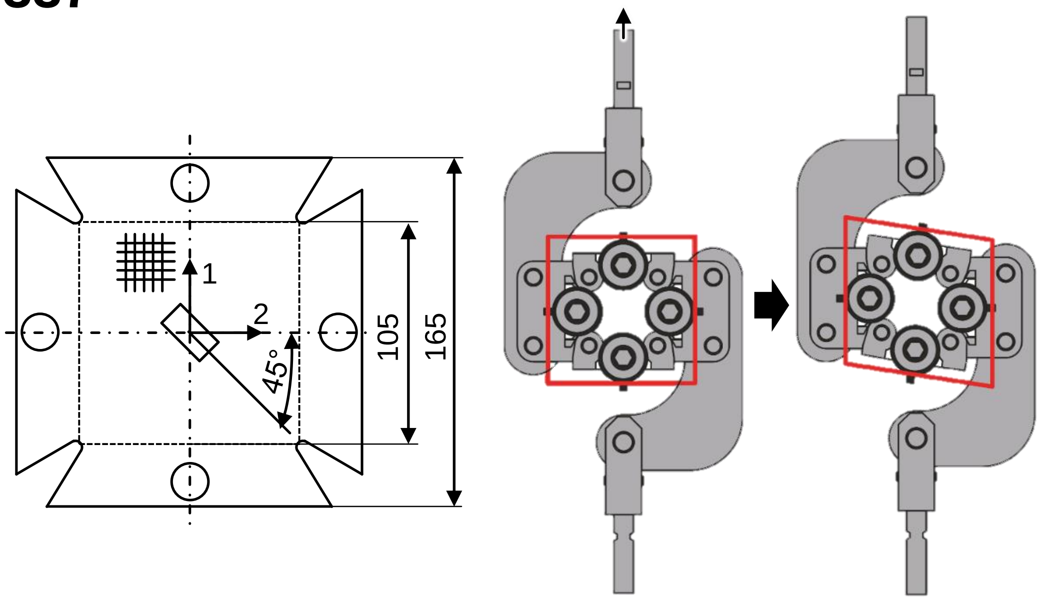
DORNIER TRITOS® PP 3D weaving machine → Vacuum Assisted Process → CNC Milling

Source: DORNIER Composite Systems®

Methods used

Intralmaniar shear:

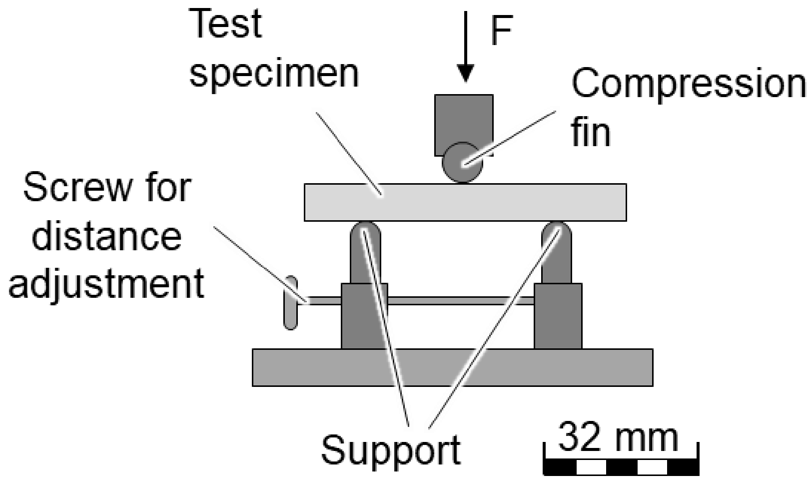
Shear frame test according to DIN EN ISO 20337



Measurands: G_{12} and τ_{12}

(Apparent) interlaminar shear

Short beam test according to DIN EN ISO 14130

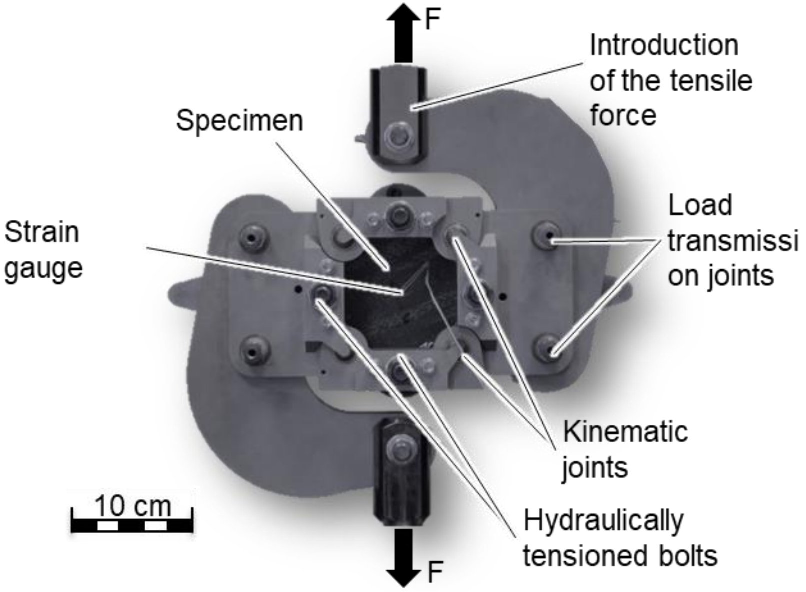


Measurands: τ_{13}

Experimental procedure

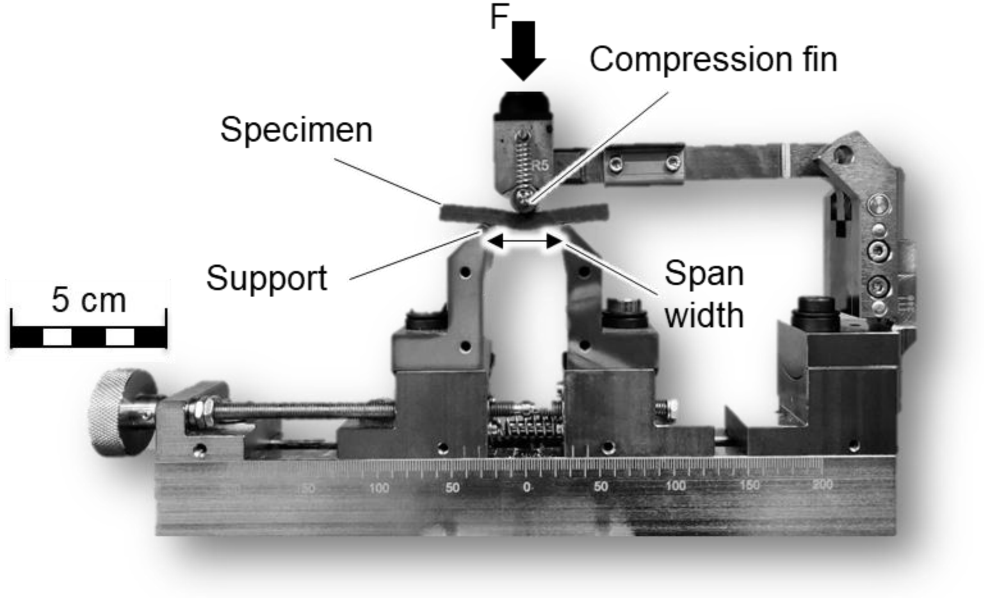
Shear frame set up

Strain measurement with DIC and Strain Gauges



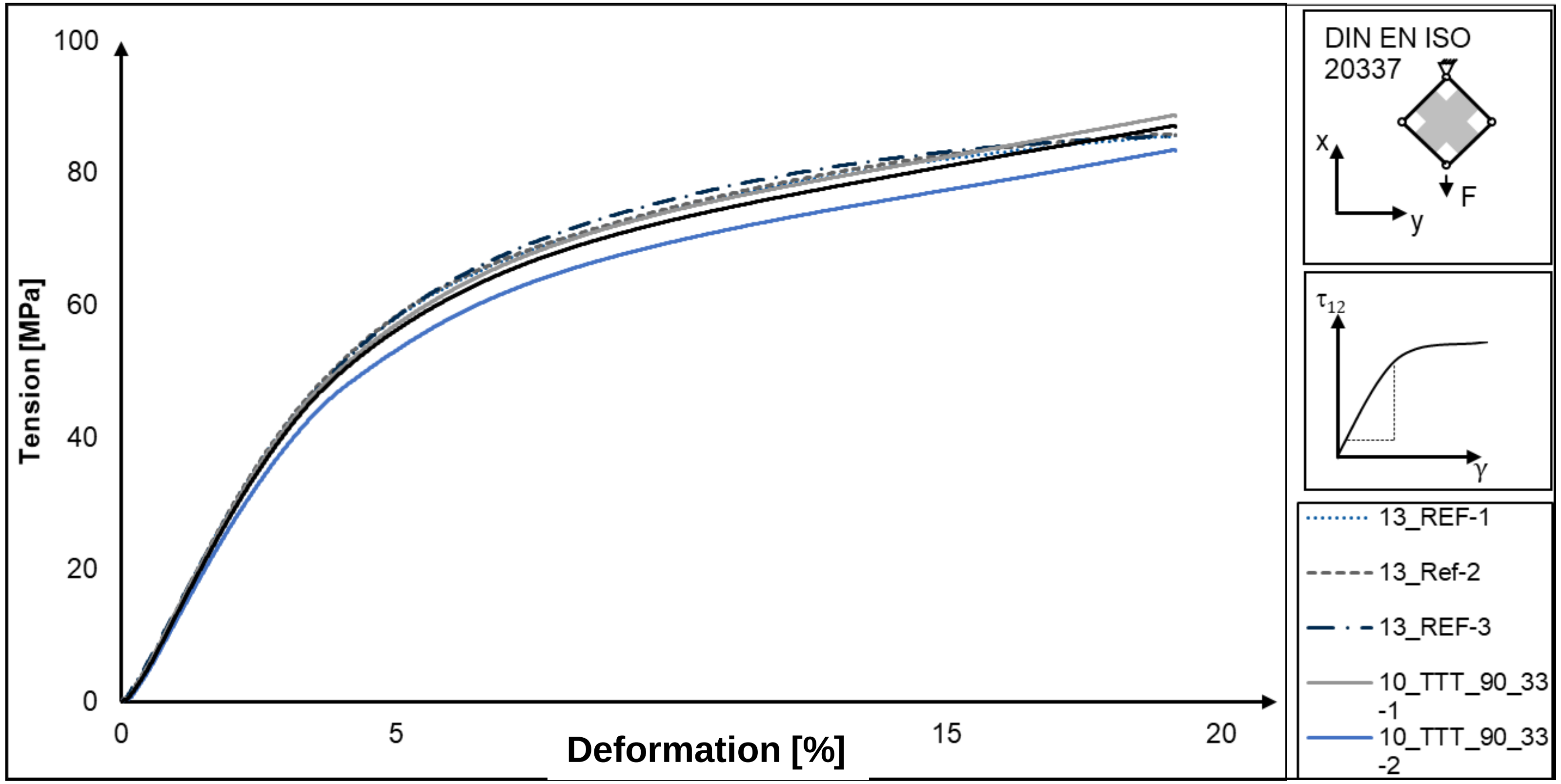
Short beam test

Span width adapted to specimen thickness



Results of the intralaminar shear test

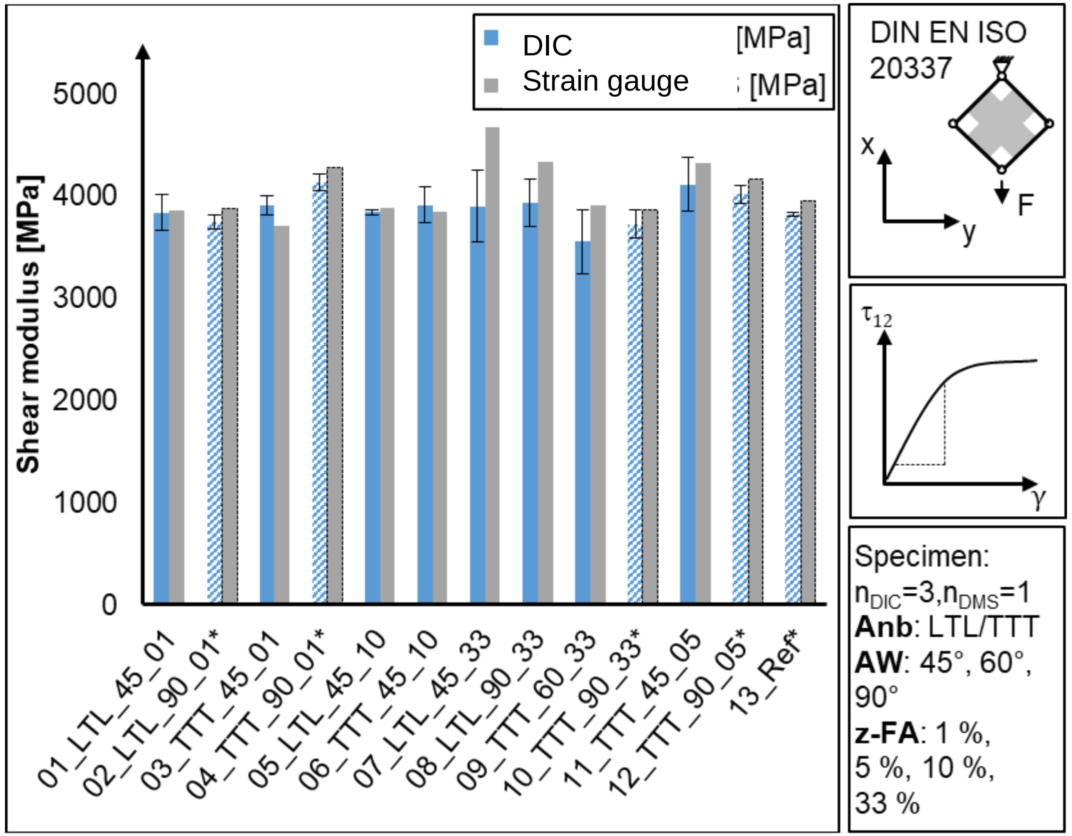
Typical stress-strain cuves Reference vs. 3D fabric



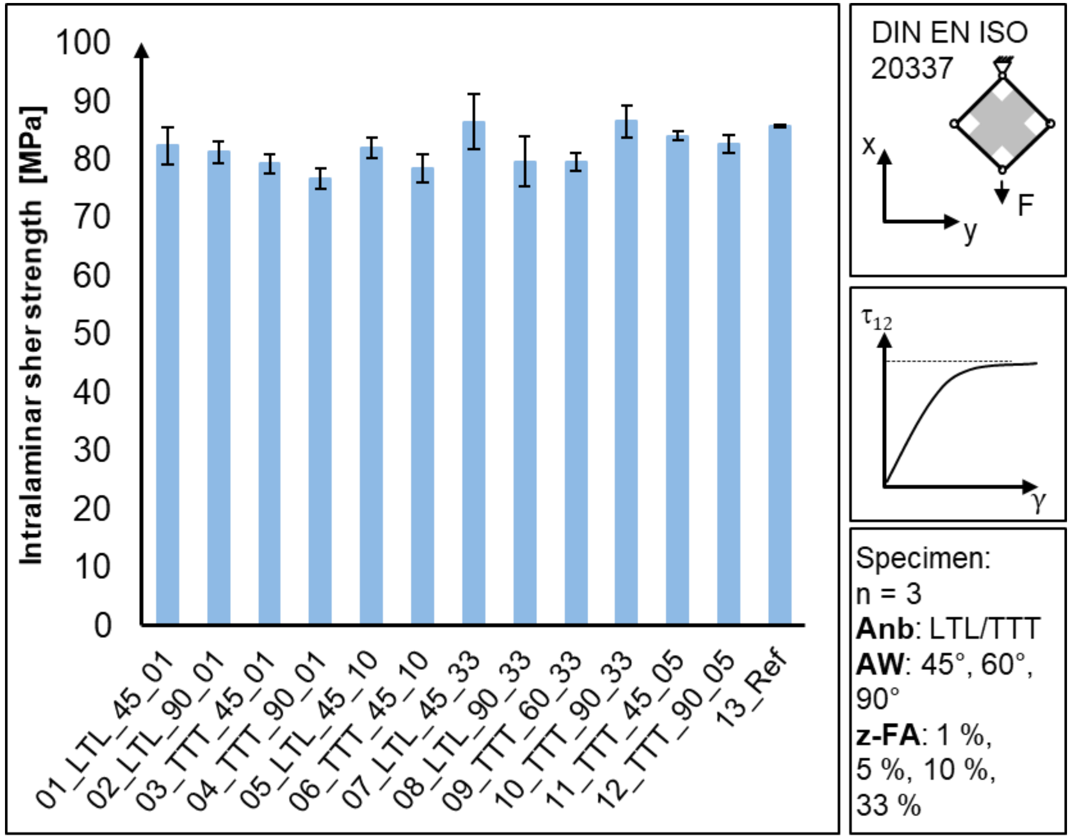
- Same behavior:
- Linear-elastic initial range
- Subsequent area of increasing damage with decreasing stiffness
- Final linear increasing stress-strain region
- Since no global maximum or inter-fibre failure occurs, all specimens are terminated at a deformation of 20 %.

Results of the intralaminar shear testing

Shear modulus



Shear strength



Results of the (apparent) interlaminar shear testing

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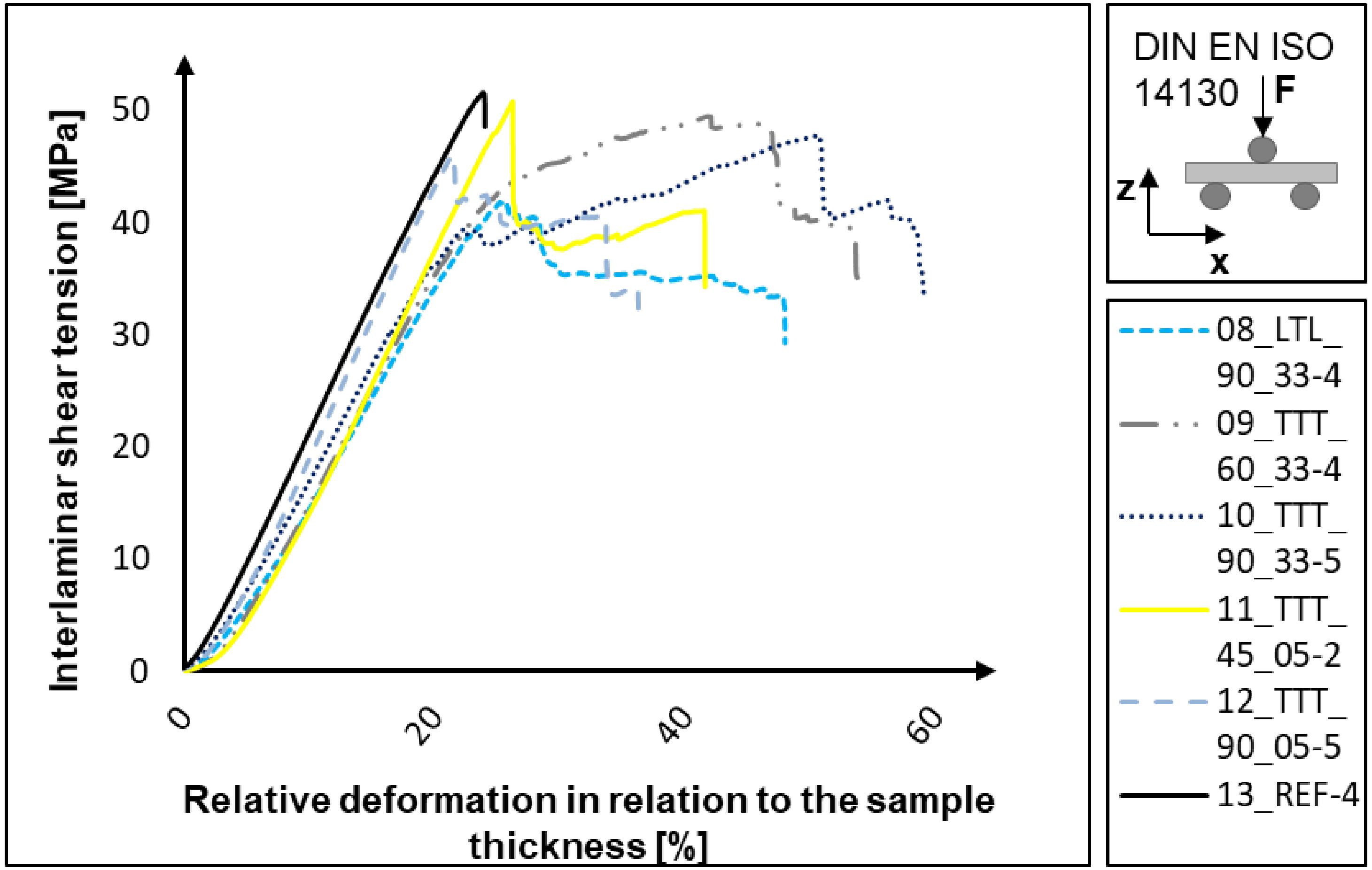
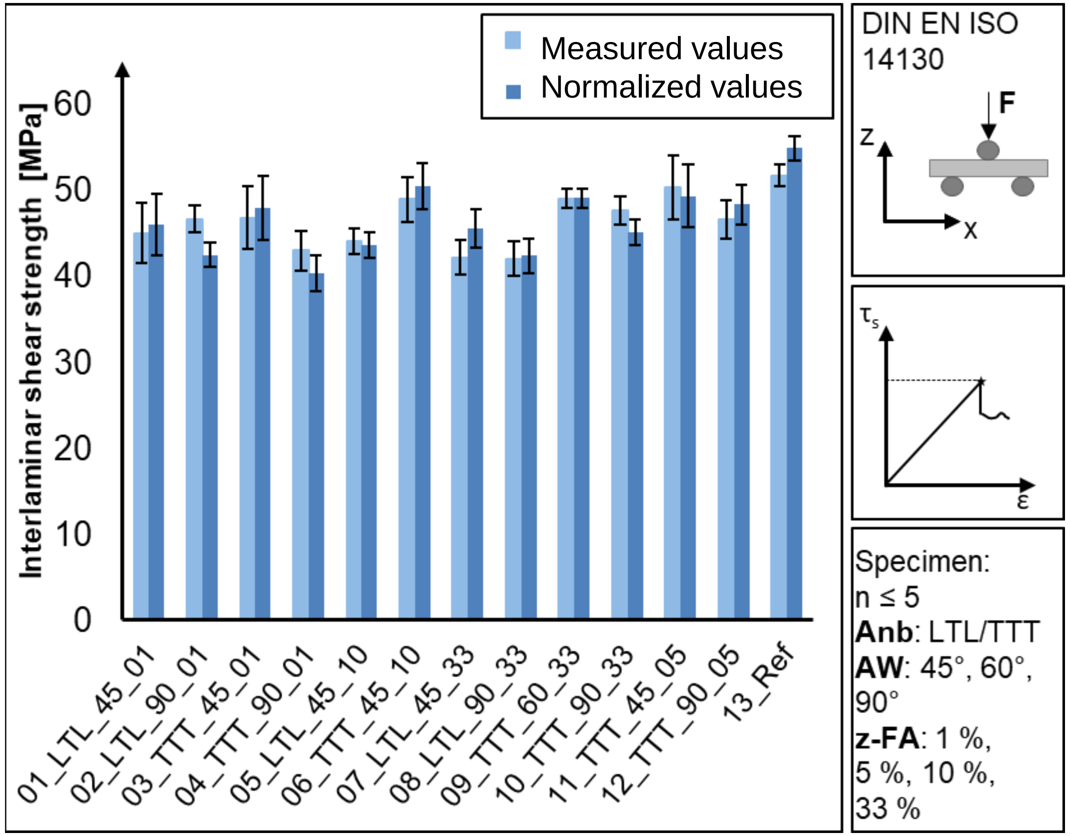
Typical stress-strain cuves Reference vs. 3D fabrics



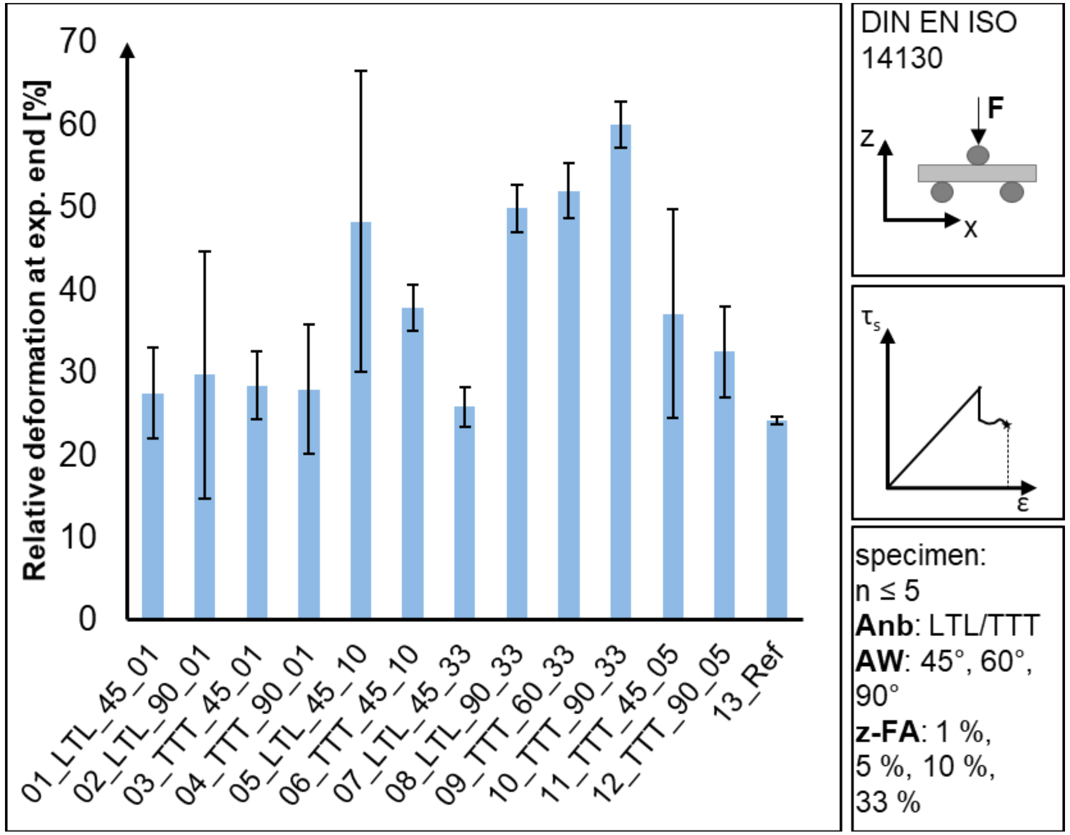
- Similar behaviour up until first failure
- Initial linear-elastic range
- Sudden and catastrophic failure of laminated reference
- All 3D-wovens show the ability to widtstand signifcant forces after initial failure
- This „damage tolerance“ varies between and within the series

Results of the (apparent) interlaminar shear testing

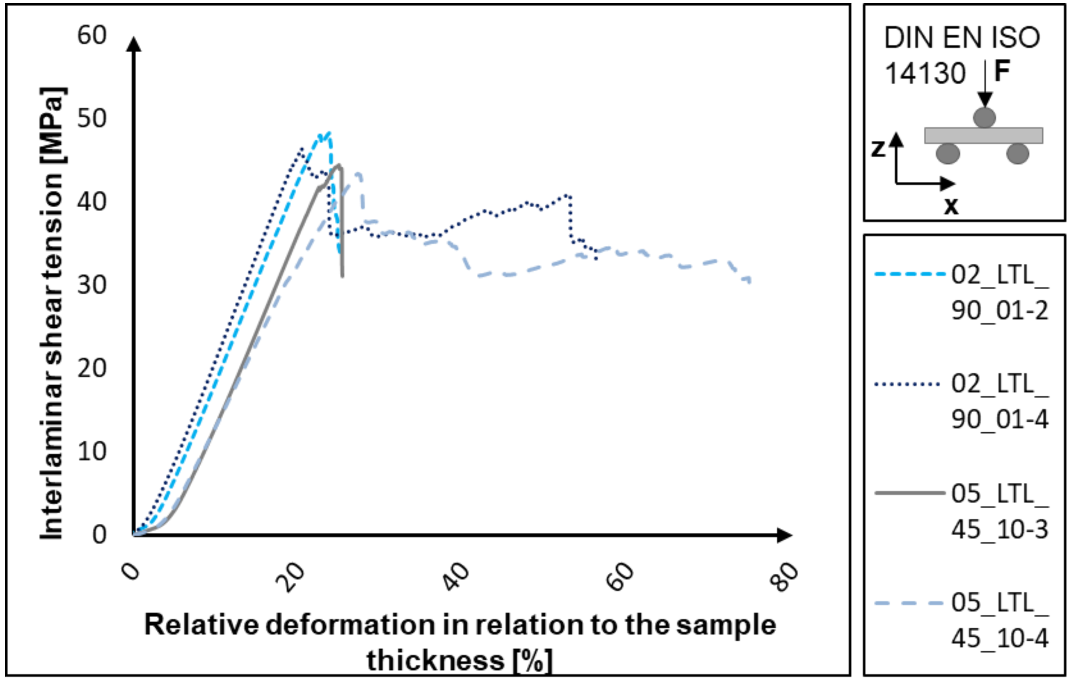
Interlaminar shear strength

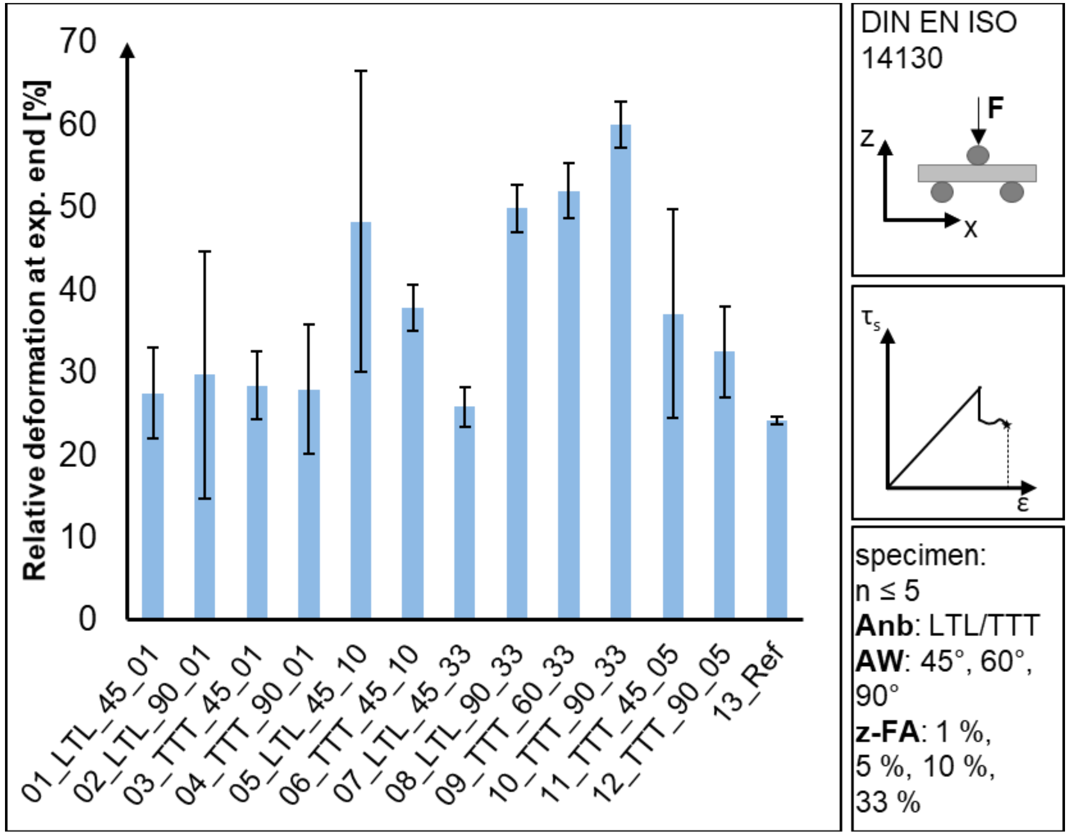


Relative deformation at end of experiment



Results of the (apparent) interlaminar shear testing





Influence due to the test procedure and the termination criteria

Modelling by Multiple Linear Regression (MLR)

Modelling by Multiple Linear Regression (MLR)

- $\tau_{12} = 1{,}33 * \mathrm{Anb(LTL)} - 1{,}33 * \mathrm{Anb(TTT)} - 2{,}25 * \mathrm{zAW} + 0{,}11 * \mathrm{zFA} + 0{,}02 * \mathrm{zAW}^2 - 0{,}12 * Anb(LTL) * zFA + 0{,}12 * Anb(TTT) * zFA + 148{,}97$

- $\mathrm{G}_{12,\mathrm{DIC}} = -20{,}14 * \mathrm{Anb(LTL)} + 20{,}14 * \mathrm{Anb(TTT)} - 104{,}33 * \mathrm{zFA} + 112{,}13 * \mathrm{Anb(LTL)} * \mathrm{zFA} - 112{,}13 * \mathrm{Anb(TTT)} * \mathrm{zFA} + 3826{,}41$

- $\tau_{13M} = -1{,}76 * \mathrm{Anb(LTL)} + 1{,}76 * \mathrm{Anb(TTT)} - 0{,}08 * \mathrm{zAW} + 51{,}1$

- $\epsilon_{13\mathrm{M}} = 1{,}47 * \mathrm{Anb(LTL)} - 1{,}47 * \mathrm{Anb(TTT)} - 0{,}05 * zAW + 0{,}89 * zFA - 0{,}4 * \mathrm{zFa}^2 - 0{,}26 * \mathrm{Anb(LTL)} * \mathrm{zFA} + 0{,}26 * \mathrm{Anb(TTT)} * \mathrm{zFa} + 0{,}02 * \mathrm{zAW} + \mathrm{zFA} + 29{,}94$

	Intralaminar shear strength	Intralaminar module (DIC)	Interlaminar shear strength	rel. Deformation at end of test
R^2	0,35	0,49	0,41	0,68
R_a^2	0,24	0,44	0,39	0,65
Q^2	0,08	0,33	0,34	0,60
Reproducibility	0,54	0,46	0,58	0,65

Useful models can be derived - the small differences in the strengths/modules limit the significance

Summary and conclusion

Summary and conclusion

Intra- and interlaminar Shear strength of 3D-wovens is similar to laminated fabrics with same matrix material

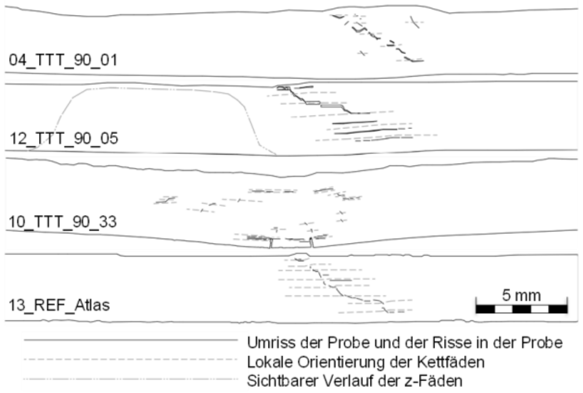
- Imperfections and resin rich areas result in sligthly earlier interlaminar failure
- z-fibres cause a considerable ability to bear loads even after the initial damage

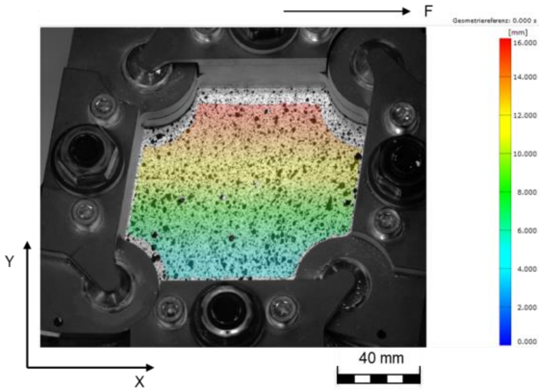
- Mathematical models could be established with ok significance
- However, for an initial design for first damage, the values of comparable laminates with safety factor can be used

- Short bending tests are only suitable to a limited extent for 3D fabrics
- However, shear frame tests are very suitable

- Data are available for modelling/simulation

We love to collaborate





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Thank you for your attention!

Appendix

Scopus

TITLE-ABS-KEY((“3d” OR “3 d” OR “3-d” OR three*dimension OR 3*dimension*)

PRE/2 (woven OR weav* OR textile OR fib* OR composite OR component OR plastic)

AND (((torsi* OR bend* OR mechanic* OR compress* OR tensi* OR flex* OR impact) PRE/2 (stress OR load* OR force* OR strain OR propert* OR failure OR fatigue OR damage)))

AND ({z-} OR orthogonal OR angle OR interlock)

AND NOT ("nonwoven" OR "print*" OR "*bio*" OR "therm*" OR concrete))

AND LANGUAGE (german OR english)

AND PUBYEAR > 2000

Web of Science

https://www.webofscience.com/wos/woscc/summary/3ba64493-ff46-4239-b2db-40097a21f5dd-548d28fc/relevance/1

(erstellt am 30.08.2022)

NTRS

Suchstring 10/2022 (Filtereinstellung Publication Date > 31.12.1999)

(3d|"3 d"|"3-d"|three*dimension|3*dimension)+("woven"|weav*)+(“textile”|fib*|”composite”|”component|”plastic”)+(torsi*|bend*|mechanic*|compres*|tensi*|flex*|impact)+(stress|load*|force*|strain|propert*|failure|fatique|damage)+(“z-“|orthogonal|angle|interlock)-(nonwoven|print*|*bio*|therm*|concrete)

Defintion of 3D-woven warp interlock fabrics according to Boussu et al.

$$3D\ warp\ interlock\ \mathrm{X1}-\mathrm{X2}\{\mathrm{N}\}\mathrm{Y1_k}-\mathrm{Y2_k}Binding\mathrm{W}b_{\mathrm{k}}\{\mathrm{B_k i}\}-Surface\ \mathrm{Ws}\{\mathrm{Ci}\}-Stuffer\ \{\mathrm{Si}\} \qquad (1.1)$$

- X1 represents the type of angle of binding warp yarn, O (orthogonal) or A (angle)
- X2 corresponds to the type of depth of the binding warp yarn, L (layer to layer) or T (through the thickness)
- {N} corresponds to the repetitive sequence of the different number of weft layers for each column of the 3D warp interlock fabric elementary pattern.
- $Y1_k$ is equal to the path of the binding warp yarn of group k
- $Y2_k$ is equal to the depth of the binding warp yarn of group k
- Binding term corresponds to binding warp yarns
- Wbk is related to the type of weave diagram on fabric surface of binding warp yarns of group k
- B_k i contains the numbering of binding warp yarns of group k with inter-ply i position
- Surface term corresponds to surface weave warp yarns and disappears if surface weave warp yarns are not included
- Ws is related to the type of weave diagram of surface weave warp yarns
- Ci contains the numbering of surface weave warp yarns with inter-ply i position
- Stuffer term corresponds to stuffer warp yarns and disappears if stuffer warp yarns are not included
- Si represents the numbering of stuffer warp yarns with inter-ply i position.

Boussu F, Cristian I, Nauman S. General definition of 3D warp interlock fabric architecture. Composites Part B: Engineering 2015;81:171–88. https://doi.org/10.1016/j.compositesb.2015.07.013.

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