ESA STUDY CONTRACT REPORT –

Deliverable D 4.1

Results of mechanical testing – Draft version

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ABSTRACT:
Current report summarize initial efforts on material characterization by means of mechanical tests. All relevant mechanical test procedures identified within the literature review have been produced and initially verified with dedicated prototype specimens. This included designing and machining of dedicated testing equipment as climbing drum peel test setup, compression after impact testing rig, and BVID set up in low velocity impact tower. Aluminium honeycomb structure properties was extracted and verified by analytical approach for estimating the load carrying capacity of produced panels. Furthermore a dedicated compression after impact test set up with all edges restrained have bed designed and tested while simply supported edge support testing jig have been optimized and improved for further tests. Moreover initial impact induced damage tests outline the need for further update and reduction of drop weight for our testing equipment and procedure, this has been considered and redesigned and will be implemented in further tests. Therefore within initial reporting period approximately 200 specimens was tested and evaluated serving both aims: verification of numerical model and for update of production procedure.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organization that prepared it.

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List of abbreviations

E_z^{fc}	core flatwise compressive chord modulus, MPa
τ	core shear stress, MPa
T_p	peel strength, N·m/m
F_z^{ftu}	ultimate flatwise tensile strength, MPa
G_{core}	effective core shear modulus
$\sigma_z^{fc0.02}$	flatwise compressive stress at 2 % deflection, MPa
σ_{node}	node bond strength of the core, MPa
τ_{12i}	shear stress at *i*-th data point, MPa
F_z^{fcu}	Ultimate flatwise compressive strength, MPa
μ	Poisson's ratio
γ_{12}	in-plane shear strain, με
γ_{12}^{m}	maximum shear strain, με
τ_{12}^{m}	maximum in-plane shear stress, MPa
ε_x	longitudinal normal strain, με
ε_y	lateral normal strain, με
A	specimen's cross section area, mm^2
ASTM	American Society for Testing and Materials
b	width
CE	clip-on extensometer
CFRP	carbon fibres reinforced polymer
CV	Coefficient of variation
DIC	Digital image correlation
E^c	Young's modulus estimated in compressive test
E^f	Young's modulus estimated in flexural test
E^t	Young's modulus estimated in tension test
F_{max}	maximum load
G_{12}^{chord}	shear chord modulus of elasticity, GPa
G_{12}	In-plane shear modulus
G_{13}	Out-of-plane shear modulus
GFRP	glass fibres reinforced polymer
h	thickness
LVDT	Linear variable differential transformer
P_i	load at *i*-th data point, N
P^m	maximum load at or below 5% shear strain, N
R^c	Compressive strength
R^f	Flexural strength
R^t	Tensile strength

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SACMA	Suppliers of Advanced Composite Materials Association
SD	standard deviation
SG	strain gauge, only three of all specimens were equipped with strain gauge
Unipreg 100	carbon fibre pre-preg with density 100 g/m^2
Unipreg 200	carbon fibre pre-preg with density 200 g/m^2
v_{12}	In-plane core shear strength
v_{13}	Out-of-plane core shear strength

1 Introduction

Current report first of all presents the mechanical characterization of carbon fibre pre-preg laminate, which is used for sandwich panel skin preparation and parameters required for numerical simulations by FEM. Furthermore aluminium honeycomb, which applied as core material for the panel. Also mechanical characterization of complete panel is presented. Several static tests as tension, compression, shear, flexure and peeling were used. The material characterization is performed according to ASTM standards. Specimen dimensions also were chosen according to standards.

2 Test matrix

2.1 Requirements of each test method

Tension, compression, shear and flexure test gives full spectre of mechanical properties of pre-preg skins required for FEM simulations.

Core plate shear, compression and node tension tests presents mechanical properties of honeycomb core structure which are required for numerical analyses of sandwich structure.

Climbing drum peel test is useful for estimation of skin to core adhesive bond strength and appropriate for comparison and assessment among different adhesives.

By using of flatwise tension is possible to find which adhesive bond in whole panel is the weakest, for example, is it between face to core or between skin and laminate plies.

Panel flatwise compression is similar to bare honeycomb compression, but due to adhesive fillets stabilizing honeycomb, the compression strength values is quite higher than expected in analytical estimation.

Edgewise compression gives edgewise compression strength values of produced panels as well as for residual strength evaluation.

Plate shear test also provides information of the sandwich panel's behaviour and could be integrated in analytical solutions.

Damage introduction, made by quasi-static indentation and low velocity impact with different impactor diameters and indentation forces or impact energies, gives large amount of controllable and repeatable tests.

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Finally, basing on literature review, most reliable method for residual strength estimation is edgewise compression of damaged specimens.

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2.2 Foreseen mechanical tests

In Table 2.1. are listed all completed mechanical tests. Table 2.2. contains expected tests.

Table 2.1. Completed mechanical tests

Test group	Material	Test	Number of specimens
Skin tests	Unipreg 100	0° tension test	10
		90° tension test	10
		0° compression test	10
		90° compression test	10
		45° shear test	10
		short beam shear test	10
		flexure test	10
	Unipreg 200	0° tension test	10
		90° tension test	10
		0° compression test	10
		90° compression test	10
		45° shear test	10
		short beam shear test	10
		flexure test	10
	Unipreg 200 (high stiffness)	0° tension test	10
Core tests	Aluminium honeycomb type 1	Shear	10
		Compression	4
		Node tension	5
	Aluminium honeycomb type 2	Shear	12
		Compression	0
		Node tension	1
	Aluminium honeycomb type 3	Shear	4
		Compression	5
		Node tension	0
Panel tests	Panels with skin layup [60/0/-60] and different honeycomb cores	climbing drum peel test	7
		flatwise tension	7
		flatwise compression	5

Table 2.2. Expected mechanical test in upcoming reporting period

Panel tests	Panels with skin layup [60/0/-60] and different honeycomb cores	climbing drum peel test
		flatwise tension
		flatwise compression
		edgewise compression
		shear
Residual strength estimation	Panels with different skin layups and honeycomb cores	Damage introduction
		Compression after impact

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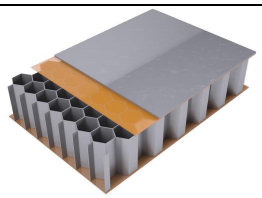
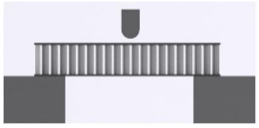
2.3 Overview of test methods

In Table 2.3. are gathered all test methods used in research.

Table 2.3. Review of test methods

Panel components		**Panel**	
Pre-preg skin	*Honeycomb core*	*Virgin panel*	*Damaged panel*
			
tensile ASTM D 3039	shear ASTM C273	compression flatwise or edgewise ASTM C364, ASTM C365	quasi-static indentation ASTM D6264*
compression ASTM D3410	compression ASTM C365	shear ASTM C273	Damage resistance ASTM D7766, ASTM D7136*
flexure ASTM D 7264	node tension ASTM C363	flatwise tension ASTM C297	edgewise compression after impact ASTM 7137*
shear ASTM D 7264, ASTM D 2344		climbing drum peel ASTM D1718	

*custom method for sandwich panels

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3 Mechanical properties of pre-preg laminate skin

3.1 Introduction to mechanical testing of pre-preg laminate

Specimens were machined from CFRP laminate plates previously manufactured by pre-preg layup and thermal consolidation. Totally three types of Unipreg® pre-pregs were used: 100 g/m^2, 200 g/m^2 and 200 g/m^2 high stiffness carbon fibre pre-preg. Detailed information about each plate is shown in Table 3.1. Samples were manufactured as a batch of at least 8 specimens for each test type. For pre-preg cutting was used sharp knife. Layup was conducted on 20 mm thick steel plate after that second 25 mm thick plate was placed on top and all system covered with vacuum bag. Finally consolidation was carried out in oven at 180 ^{o}C within 6 hours under -0.8 bar pressure.

Table 3.1. CFRP laminate plates produced for coupon tests

Laboratory code	Pre-preg type, g/m2	Number of plies	Thickness, mm	Test type	Number of specimens machined
873	100	12	1.13	0° tension	9
874	100	24	1.84	0° compression	12
876	200	10	1.88	0° tension	11
877	200	10	1.90	90° tension	9
879	200 high stiffness	10	1.45	0° tension	10
880	200	16	2.59	0° compression	11
881	100	24	2.20	90° compression	8
882	200	16	2.60	flexure[1]	-
883	100	12	1.15	45° shear	8
884	200	6	1.44	45° shear	8
885	200	16	2.62	90° compression	8
886	100	15	1.18	90° tension	8
905	100	20	1.13	flexure*	-

Several material constants were obtained: E^t, E^c, E^f, G_{12}, G_{13} and μ. Additionally corresponding strength constants obtained: R^f, R^t, R^c, v_{12}, v_{13}. Test matrix is shown in

[1] flexure test includes shear test on coupons lateral side, 3-point flexure test and short beam shear test

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Table 3.2.

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Table 3.2. Test matrix definition

Coupons	Properties	Standard
Tensile Strength and Modulus	E^t, R^t, μ	ASTM D3039
Compressive Strength and Modulus	E^c, R^c	ASTM D3410
In-Plane Shear (+/-45° Laminate)	G_{12}, ν_{12}	ASTM D3518
Short beam In plane shear strength	G_{13}, ν_{12}	ASTM D2344
Short beam shear with coupon on its lateral side	G_{12}, ν_{12}	custom from ASTM D2344
Short beam shear	G_{12}, ν_{12}	ASTM D2344
3 Point Flexural Strength and Modulus	E^t, G_{13}, R^f	ASTM D7264

Three compressive and tensile specimen from each sample was equipped with HBM LY11- 3/350 strain gauge in axial direction of the specimen. Three different methods for strain readings were used, where it was appropriate. Strain gauges, clip-on extensometer and digital image correlation (DIC) system IMETRUM. DIC system gauge length between corresponding targets varies according to available space on specimen surface.

Mean values, as well as max, min and standard deviation values were calculated for each test series for comparison reasons and series quality estimation. Also B-basis and A-basis values were calculated.

3.2 Tension test

3.2.1 0° direction tension test

Test parameters are listed in Table 3.3. In Figure 3.1 are shown test specimens and in Figure 3.2 – test setup. Test results are presented in Table 3.4 for Unipreg 100 g/m^2, Table 3.5 for Unipreg 200 g/m^2 and for Table 3.6 high stiffness Unipreg 200 g/m^2 respectively.

Table 3.3. Test parameters for 0° direction tests

Testing method	ASTM D 3039
Equipment	INSTRON 8802 (250 kN)
Operator ID	Guntis Japins
Test type	Tension test
Testing speed	0.5 mm/min
Specimen's nominal dimensions (length, width)	250 x 15 mm
Non-tabbed section length	100 mm
Extension estimation methods	DIC, SG, CE
Clip-on extensimeter gauge length	25 mm
Space between axial DIC targets (for longitudinal deformation measurement)	11.7 mm
Space between transverse DIC targets (for transversal deformation measurement)	11.7 mm

only three of all specimens were equipped with strain gauge.

Abbreviations:

CE – clip-on extensometer, DIC – digital image correlation, SG – strain gauge, only three of all specimens were equipped with strain gauge

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Unipreg 100 g/m^2 (873) | Unipreg 200 g/m^2 (876) | Unipreg High stiffness 200 g/m^2 (879)

Figure 3.1. 0° direction tension test specimens

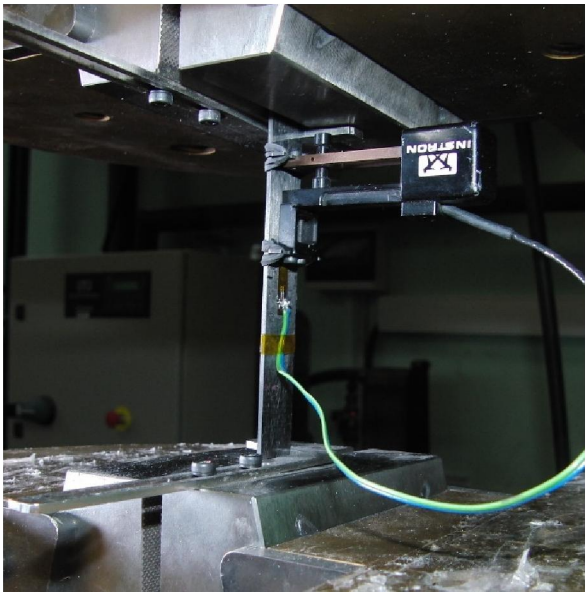

Figure 3.2. 0° direction tension test setup

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Table 3.4. Tensile modulus, tensile strength and Poisson's ratio of Unipreg 100 g/m^2 (0° direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	μ	b, mm	h, mm
873_1	-	109.13	79.64	1620	-	14.08	1.22
873_2	-	118.72	68.56	1300	0.46	13.89	1.27
873_3	-	104.34	77.76	1340	0.41	14.21	1.27
873_4	123.91	118.59	77.16	1380	0.34	14.60	1.27
873_5	-	-	70.06	1480	-	14.69	1.24
873_6	114.82	100.87	76.57	1270	-	14.79	1.20
873_7	129.33	128.35	88.45	1540	-	14.75	1.17
873_8	-	123.67	69.78	1520	0.2	14.08	1.08
873_9	-	123.64	71.71	1740	0.25	14.61	1.24
Mean	**122.69**	**115.91**	**75.52**	**1466**	**0.33**	**14.41**	**1.22**
SD	7.34	9.97	6.31	157	0.11	0.34	0.06
Median	123.91	118.65	76.57	1480	0.34	14.60	1.24
Minimum	114.82	100.87	68.56	1270	0.20	13.89	1.08
Maximum	129.33	128.35	88.45	1740	0.46	14.79	1.27
CV	5.98	8.60	8.36	11	32.3	2.38	4.99
Mean+ 2 SD	137.36	135.85	88.14	1779	0.55	15.10	1.34
Mean - 2 SD	108.01	95.97	62.90	1152	0.12	13.73	1.10
B-basis	77.52	90.16	60.03	1081			
A-basis	45.27	72.50	49.37	816			

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Table 3.5. Tensile modulus, tensile strength and Poisson's ratio of Unipreg 200 g/m^2 (0° direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	μ	b, mm	h, mm
876_1	-	125.85	66.81	1430	0.37	13.92	1.90
876_2	121.02	122.07	-	1290	0.29	15.44	1.89
876_3	-	112.57	66.53	1610	0.32	15.45	1.91
876_4	123.67	127.80	75.14	1570	0.35	15.41	1.89
876_5	127.58	127.67	78.51	1400	0.32	15.18	1.90
876_6	-	119.47	70.97	1850	0.36	15.47	1.89
876_7	-	121.45	90.38	1750	0.33	15.43	1.89
876_8	-	121.84	70.70	1630	0.26	15.48	1.87
876_9	-	118.20	75.54	1410	0.24	14.16	1.87
876_10	-	129.02	70.95	1400	0.59	14.08	1.87
876_11	-	122.07	67.74	1590	0.6	15.21	1.88
Mean	**124.09**	**122.55**	**73.33**	**1539**	**0.37**	**15.02**	**1.89**
SD	3.30	4.86	7.18	169	0.12	0.63	0.01
Median	123.67	121.96	70.97	1500	0.33	15.42	1.89
Minimum	121.02	112.57	66.53	1290	0.24	13.92	1.87
Maximum	127.58	129.02	90.38	1850	0.59	15.48	1.91
CV	2.66	3.97	9.79	11	32.4	4.21	0.64
Mean+ 2 SD	130.69	132.28	87.69	1878	0.61	16.29	1.91
Mean - 2 SD	117.49	112.82	58.97	1200	0.13	13.76	1.86
B-basis	103.77	111.48	56.42	1153			
A-basis	89.27	103.81	44.75	886			

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Table 3.6. Tensile modulus, tensile strength and Poisson's ratio of Unipreg 200 g/m^2 (high stiffness) (0° direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	μ	b, mm	h, mm
879_1	-	166.60	100.98	2140	0.38	15.36	1.47
879_2	-	146.00	101.47	2550	0.32	15.06	1.48
879_3	167.00	176.76	119.45	2330	0.38	14.99	1.49
879_4	-	185.57	104.87	2190	0.46	14.99	1.51
879_5	-	160.98	111.98	2140	0.45	14.94	1.50
879_6	-	141.07	109.68	1700	0.37	14.94	1.50
879_7	161.66	172.16	107.73	1960	-	14.74	1.50
879_8	165.20	173.09	109.60	1650	-	14.74	1.52
879_9	-	154.80	109.56	2190	-	15.02	1.50
879_10	-	164.02	-	1520	0.32	14.88	1.51
Mean	**164.62**	**164.11**	**108.37**	**2037**	**0.38**	**14.97**	**1.50**
SD	2.71	13.85	5.65	326	0.06	0.18	0.01
Median	165.20	165.31	109.56	2140	0.38	14.97	1.50
Minimum	161.66	141.07	100.98	1520	0.32	14.74	1.47
Maximum	167.00	185.57	119.45	2550	0.46	15.36	1.52
CV	1.65	8.44	5.21	16	14.6	1.18	0.98
Mean+ 2 SD	170.05	191.81	119.67	2688	0.49	15.32	1.53
Mean - 2 SD	159.19	136.40	97.07	1386	0.27	14.61	1.47
B-basis	147.92	131.48	94.51	1270			
A-basis	135.99	108.95	84.96	741			

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3.2.2 90° direction tension test

Test parameters are listed in Table 3.7. Test results are presented in Table 3.8 for Unipreg 100 g/m^2 and Table 3.9 for Unipreg 200 g/m^2. Figure 3.3. 90o direction tension test setup.

Table 3.7. Test parameters for 0° direction tension tests

Testing method	ASTM D 3039
Equipment	INSTRON E10000 (10 kN)
Operator ID	Guntis Japins
Test type	Tension test
Testing speed	0.5 mm/min
Specimen's nominal dimensions (length, width)	200 x 25 mm
Non-tabbed section length	100 mm
Extension estimation methods	DIC, SG, CE
Clip-on extensimeter gauge length	25 mm
Space between axial DIC targets (for longitudinal deformation measurement)	20 mm
Space between transverse DIC targets (for transversal deformation measurement)	20 mm

Abbreviations:
CE – clip-on extensometer, DIC – digital image correlation, SG – strain gauge, only three of all specimens were equipped with strain gauge

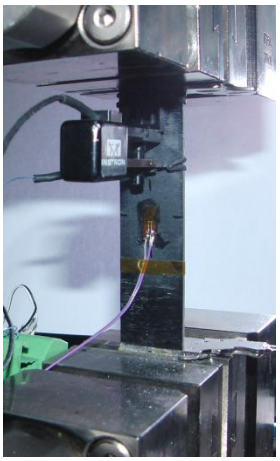

Figure 3.3. 90° direction tension test setup

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Table 3.8. Tensile modulus and tensile strength Unipreg 100 g/m^2 (90° direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	*b*, mm	*h*, mm
886_1	8.74	-	8.97	50.17	25.11	1.23
886_2	-	7.57	8.93	47.22	25.40	1.25
886_3	-	-	9.31	51.07	24.86	1.26
886_4	-	7.89	9.38	40.65	25.38	1.22
886_5	-	7.68	8.97	32.73	24.84	1.22
886_6	8.28	-	8.33	-	25.16	1.22
886_7	-	8.01	8.65	45.11	24.77	1.25
886_8	8.14	-	8.76	53.92	25.38	1.24
Mean	**8.39**	**7.79**	**8.91**	**46**	**25.11**	**1.24**
SD	0.31	0.20	0.34	7	0.26	0.01
Median	8.28	7.79	8.95	47	25.13	1.23
Minimum	8.14	7.57	8.33	33	24.77	1.22
Maximum	8.74	8.01	9.38	54	25.40	1.26
CV	3.70	2.57	3.83	16	1.04	1.18
Mean+ 2 SD	9.01	8.19	9.59	60	25.63	1.27
Mean - 2 SD	7.77	7.39	8.23	31	24.59	1.21
B-basis	6.48	6.95	8.03	21.24		
A-basis	5.11	6.38	7.43	4.40		

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Table 3.9. Tensile modulus and tensile strength Unipreg 200 g/m^2 (90° direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	*b*, mm	*h*, mm
877_1	-	6.68	8.17	41.02	23.22	1.84
877_2	-	6.29	7.97	38.49	25.09	1.87
877_3	6.43	6.67	7.79	40.49	25.04	1.88
877_4	-	6.14	7.68	42.68	25.12	1.90
877_5	-	6.63	8.11	33.46	25.06	1.89
877_6	6.32	6.88	8.03	44.47	25.10	1.91
877_7	6.53	6.87	7.79	45.78	25.13	1.90
877_8	-	7.08	7.63	41.41	24.23	1.91
877_9	-	6.45	7.58	42.55	25.07	1.90
Mean	**6.43**	**6.63**	**7.86**	**41.15**	**24.78**	**1.89**
SD	0.11	0.30	0.22	3.60	0.65	0.02
Median	6.43	6.67	7.79	41.41	25.07	1.90
Minimum	6.32	6.14	7.58	33.46	23.22	1.84
Maximum	6.53	7.08	8.17	45.78	25.13	1.91
CV	1.68	4.50	2.75	8.74	2.63	1.20
Mean+ 2 SD	6.64	7.23	8.29	48.34	26.09	1.93
Mean - 2 SD	6.21	6.04	7.43	33.96	23.48	1.84
B-basis	4.20	5.90	7.33	32.32		
A-basis	2.41	5.40	6.97	26.25		

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3.3 Compression tests

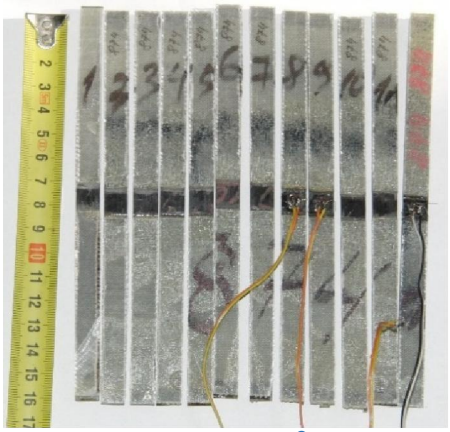
3.3.1 0° direction compression test

Test parameters are listed in Table 3.10. Figure 3.4. 0o direction compression test specimens and Figure 3.5 test setup respectively. Placing of DIC targets on specimen is shown in Figure 3.6. Test results are presented in Table 3.11 for Unipreg 100 g/m^2 and for Unipreg 200 g/m^2.

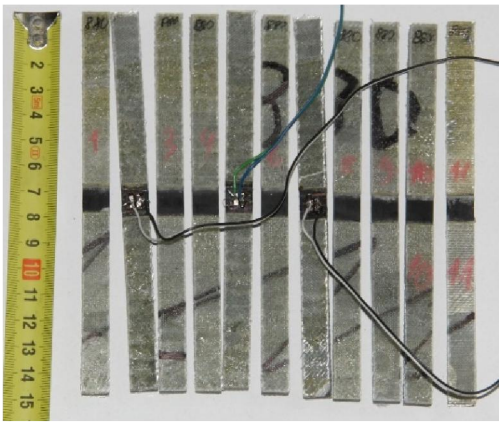
Table 3.10. Test parameters for 0° direction compression tests

Testing method	ASTM D 695
Equipment	INSTRON 8802 (250 kN)
Operator ID	Guntis Japins
Test type	Compression test
Testing speed	2 mm/min
Specimen's nominal dimensions (length, width)	155 x 10 mm
Non tabbed section length	12 mm
Extension estimation methods	DIC, SG
Test fixture	IITRI compression fixture

Abbreviations:
DIC – digital image correlation
SG – strain gauge (only three of five samples were equipped with strain gauge).



Unipreg 100 g/m^2 (874)



Unipreg 200 g/m^2 (880)

Figure 3.4. 0° direction compression test specimens

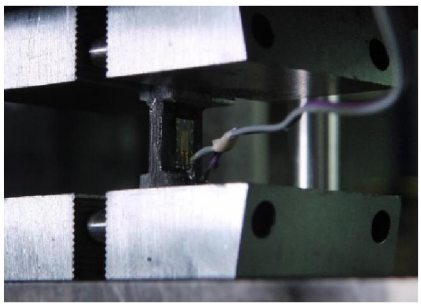


Figure 3.5. 0° direction compression test setup

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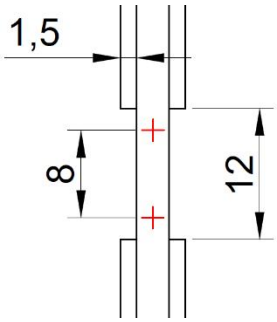

Figure 3.6. DIC targets setup to measure longitudinal deformation in compression test

Table 3.11. Compressive modulus and compressive strength of Unipreg 100 g/m^2 (0° direction)

Specimen label	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	*b*, mm	*h*, mm
874_1	-	-	622.9	9.93	1.72
874_2	-	-	539.8	9.69	1.93
874_3	-	-	320.4	10.36	2.11
874_4	-	110.10	577.6	10.34	2.27
874_5	-	113.03	574.4	10.28	2.4
874_6	-	107.84	510.2	10.13	2.51
874_7	-	103.71	493.2	10.13	2.54
874_8	-	107.53	338.5	10.31	2.56
874_9	-	91.43	428.1	10.21	2.55
874_10	97.61	91.43	423.6	10.24	2.53
874_11	107.61	100.22	545.8	10.33	2.45
874_12	106.52	99.60	392.9	10.33	2.38
Mean	**103.91**	**102.77**	**480.62**	**10.19**	**2.33**
SD	5.49	7.76	98.53	0.20	0.27
Median	106.52	103.71	501.70	10.26	2.43
Minimum	97.61	91.43	320.42	9.69	1.72
Maximum	107.61	113.03	622.93	10.36	2.56
CV	5.28	7.55	20.50	1.96	11.75
Mean+ 2 SD	114.89	118.29	677.67	10.59	2.88
Mean - 2 SD	92.94	87.24	283.57	9.79	1.78
B-basis	70.12	82.64	262.78		
A-basis	45.99	68.79	111.45		

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Table 3.12. Compressive modulus and compressive strength of Unipreg 200 g/m^2 (0° direction)

Specimen label	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	b, mm	h, mm
880_1	-	123.77	788.98	10.31	2.65
880_2	114.26	116.19	629.19	10.39	2.62
880_3	-	118.00	566.17	10.4	2.63
880_4	-	137.14	610.11	10.25	2.63
880_5	118.39	130.70	913.96	10.38	2.63
880_6	-	107.61	893.16	10.63	2.63
880_7	120.16	117.91	680.19	10.37	2.64
880_8	-	114.89	1011.47	10.39	2.63
880_9	-	127.87	793.77	10.44	2.64
880_10	-	128.02	789.13	10.34	2.63
880_11	-	110.04	599.67	10.46	2.68
Mean	**117.60**	**121.10**	**752.35**	**10.40**	**2.64**
SD	3.03	9.15	147.00	0.10	0.02
Median	118.39	118.00	788.98	10.39	2.63
Minimum	114.26	107.61	566.17	10.25	2.62
Maximum	120.16	137.14	1011.47	10.63	2.68
CV	2.58	7.55	19.54	0.93	0.61
Mean+ 2 SD	123.66	139.40	1046.34	10.59	2.67
Mean - 2 SD	111.54	102.81	458.35	10.20	2.60
B-basis	98.95	100.28	32.32		
A-basis	85.64	85.87	26.25		

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3.3.2 90º direction compression test

Test parameters are listed in Table 3.13. Figure 3.7 shows test specimens, Figure 3.8 test setup and Figure 3.9 DIC target placing for strain measurements. Test results are presented in

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Table 3.14 for Unipreg 100 g/m^2 and in Table 3.15 for Unipreg 200 g/m^2.

Table 3.13. Test parameters for 0° direction compression tests

Testing method	ASTM D 695
Equipment	INSTRON E10000 (10 kN)
Operator ID	Guntis Japins
Test type	Compression test
Testing speed	2 mm/min
Specimen's nominal dimensions (length, width)	155 x 25 mm
Non tabbed section length	12 mm
Extension estimation methods	DIC, SG
Test fixture	IITRI compression fixture

Abbreviations:
DIC – digital image correlation, SG – strain gauge (only three of five samples were equipped with strain gauge).

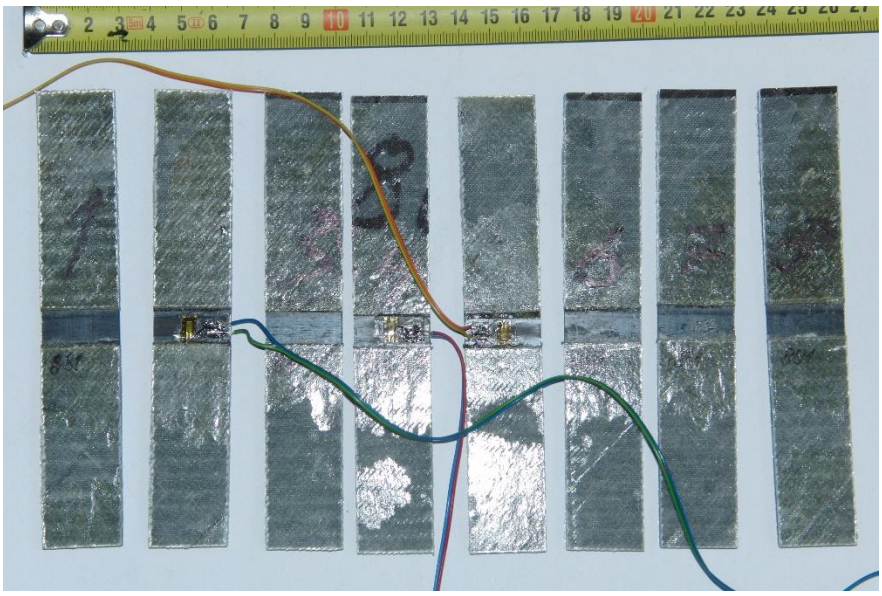

Figure 3.7. 90° direction compression test specimens

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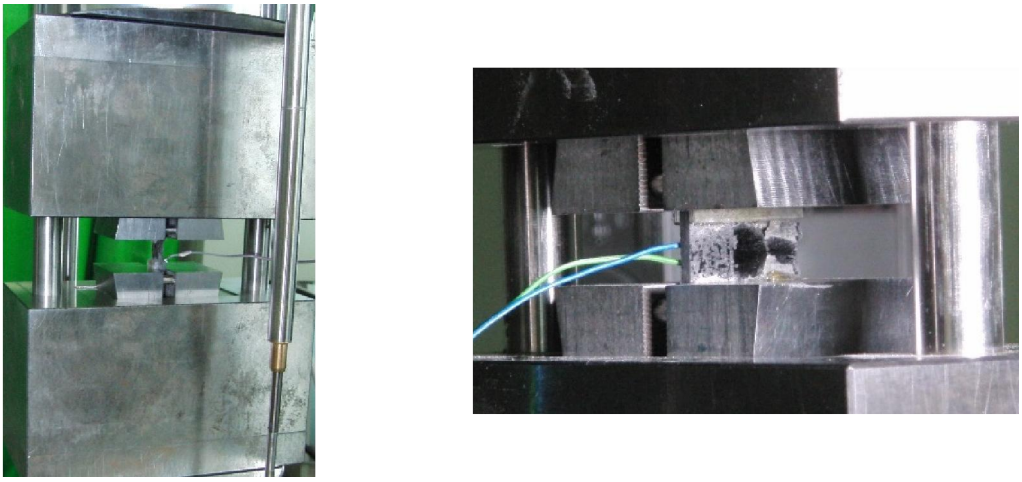

Figure 3.8. 90° direction compression test setup

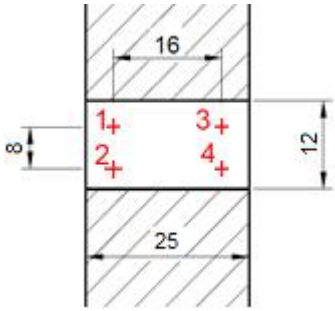

Figure 3.9. DIC targets setup to measure longitudinal deformation in 90° direction compression test

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Table 3.14. Compressive modulus and compressive strength of Unipreg 100 g/m^2 (90° direction)

Specimen label	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	b, mm	h, mm
881_1	-	6.96	148.75	24.95	2.3
881_2	8.40	7.63	143.77	24.98	2.26
881_3	-	7.12	137.73	24.99	2.27
881_4	7.57	5.94	123.76	24.96	2.24
881_5	7.13	6.31	113.54	24.97	2.22
881_6	-	6.32	136.46	25.01	2.3
881_7	-	8.49	148.05	24.87	2.19
881_8	-	7.24	150.04	24.95	2.17
Mean	**7.70**	**7.00**	**137.76**	**24.96**	**2.24**
SD	0.64	0.82	13.08	0.04	0.05
Median	7.57	7.04	140.75	24.97	2.25
Minimum	7.13	5.94	113.54	24.87	2.17
Maximum	8.40	8.49	150.04	25.01	2.30
CV	8.37	11.77	9.50	0.17	2.14
Mean+ 2 SD	8.99	8.65	163.93	25.04	2.34
Mean - 2 SD	6.41	5.35	111.60	24.88	2.15
B-basis	3.73	4.87	103.97		
A-basis	0.90	3.41	80.81		

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Table 3.15. Compressive modulus and compressive strength of Unipreg 200 g/m^2 (90° direction)

Specimen label	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	b, mm	h, mm
885_1	-	-	-	25.33	2.63
885_2	-	6.52	146.24	25.29	2.63
885_3	7.78	8.60	141.98	25.31	2.6
885_4	-	7.63	129.96	25.36	2.62
885_5	7.99	8.12	130.43	25.38	2.61
885_6	7.03	-	140.28	25.31	2.66
885_7	-	7.27	-	25.28	2.69
885_8	-	8.90	158.58	25.38	2.61
Mean	**7.60**	**7.84**	**141.25**	**25.33**	**2.63**
SD	0.50	0.88	10.69	0.04	0.03
Median	7.78	7.88	141.13	25.32	2.63
Minimum	7.03	6.52	129.96	25.28	2.60
Maximum	7.99	8.90	158.58	25.38	2.69
CV	6.62	11.25	7.57	0.16	1.14
Mean+ 2 SD	8.61	9.60	162.62	25.41	2.69
Mean - 2 SD	6.59	6.08	119.87	25.25	2.57
B-basis	4.50	5.19	109.10		
A-basis	2.29	3.38	87.14		

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3.4 45° direction shear test

Test parameters are listed in Table 3.16. Test results are presented in Table 3.17 for Unipreg 100 g/m^2 and in Table 3.18 for Unipreg 200 g/m^2. Digital Image Correlation system was used to capture specimen's longitudinal and transversal deformations. The targets used to measure the longitudinal and transversal deformation are shown in Figure 3.10. Figure 3.11 presents test specimens.

Table 3.16. Test parameters for shear tests

Testing method	According to standard ASTM 3518
Equipment	INSTRON E10000 (10 kN)
Operator ID	Guntis Japins
Speed of testing	5 mm/min
Number of specimens	8
Specimen's nominal dimensions (length, width)	200 x 25 mm
Length of non-tabbed section	100 mm
Space between axial DIC targets (for longitudinal deformation measurement)	20 mm
Space between transverse DIC targets (for transversal deformation measurement)	20 mm
Load applying direction	45°
Shear strain range used to calculate shear chord modulus	500–1500 ± 20 με

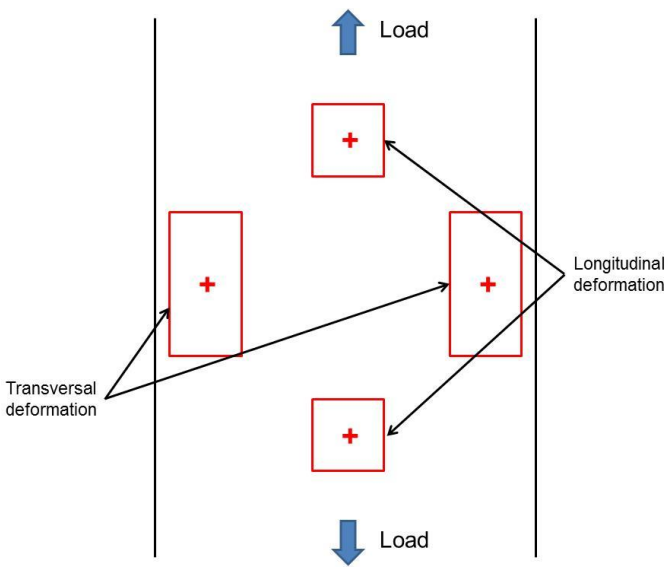

Figure 3.10. DIC target placing on shear specimen

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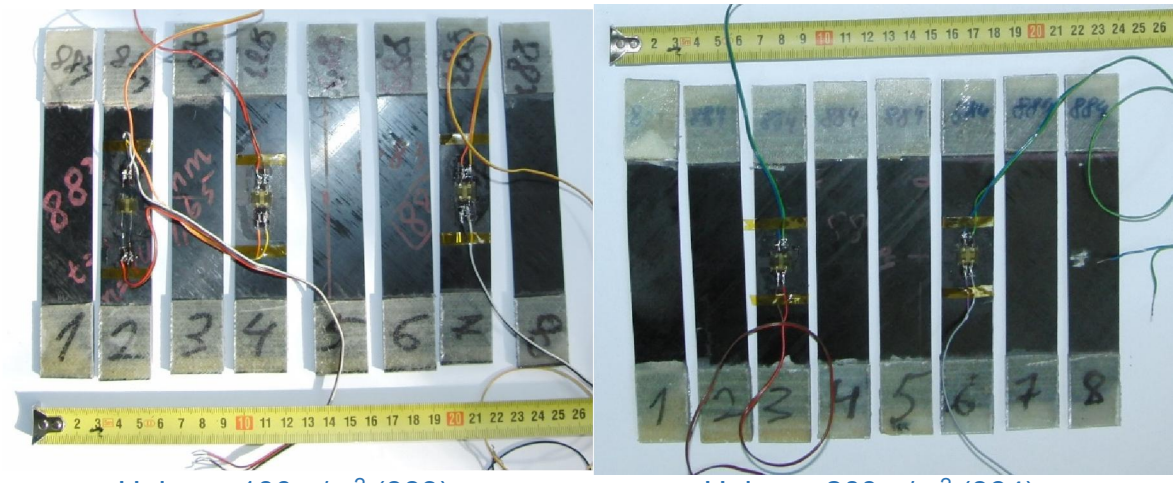

Unipreg 100 g/m^2 (883) Unipreg 200 g/m^2 (884)

Figure 3.11. 45° direction shear test specimens

3.4.1 List of used equations

$$\tau_{12i} = \frac{P_i}{2A}$$

$$\tau_{12}{}^{m} = \frac{P^m}{2A}$$

$$\gamma_{12i} = \varepsilon_{x_i} - \varepsilon_{y_i}$$

$$\gamma_{12}{}^{m} = \min\left\{ \frac{\gamma_{12} at\ 5\%}{\gamma_{12}\ at\ \tau_{12}{}^{m}} \right.$$

$$G_{12}^{chord} = \frac{\Delta\tau_{12}}{\Delta\gamma_{12}}$$

3.4.2 About testing method

Information taken from standard ASTM 3518

"Test performed like a tension test on the ±45° laminate coupon in accordance with Test Method ASTM D 3039/D 3039M, with normal strain instrumentation in both longitudinal and transverse directions and continuous or nearly continuous load-normal strain data recording. If ultimate failure does not occur within 5 % shear strain, the data shall be truncated to the 5 % shear strain mark. When the data is truncated, for the purpose of calculation and reporting, this 5 % shear strain point shall be considered the maximum shear stress."

Effects of Large Deformation - Extreme fibre scissoring can occur in this specimen for the cases of ductile matrices, weak fibre/matrix interfaces, thick specimens with a large number of repeated plies, or a combination of the above. Kellas et al suggest that a general rule of thumb for this specimen is that a fibre rotation of 1° takes place for every 2 % of axial strain (or every 3.5 % shear strain for commonly tested materials). Such fibre scissoring, if left unbounded, would lead to an unacceptable violation of the assumption in this test method of a nominal ±45° laminate. This is the principal rationale for terminating this test at a large strain level, even if load is still increasing on the specimen. This test method terminates data

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reporting at 5 % calculated shear strain; this limits fibre scissoring to about 1.5°, is approximately the limit of foil strain gage technology (if used), and is also well beyond the strain levels required for common engineering practice."

Table 3.17. Shear chord modulus of elasticity and maximum in-plane shear stress for Unipreg 100 g/m^2.

Specimen label	G_{12}^{chord} (SG), GPa	G_{12}^{chord} (DIC), GPa	τ_{12}^{m}, MPa	*b*, mm	*h*, mm
883_1	-	6.02	37.55	25.16	1.177
883_2	6.33	5.81	55.55	25.01	1.15
883_3	-	5.81	58.72	25.15	1.163
883_4	5.53	-	58.52	25.19	1.163
883_5	-	6.33	53.30	25.1	1.17
883_6	-	-	40.13	25.08	1.17
883_7	6.35	6.00	59.92	25.04	1.17
883_8	-	4.70	56.65	25.16	1.167
Mean	**6.07**	**5.78**	**52.54**	**25.11**	**1.17**
SD	0.47	0.56	8.73	0.06	0.01
Median	6.33	5.91	56.10	25.13	1.17
Minimum	5.53	4.70	37.55	25.01	1.15
Maximum	6.35	6.33	59.92	25.19	1.18
CV	7.75	9.69	16.62	0.25	0.67
Mean+ 2 SD	7.01	6.90	70.01	25.24	1.18
Mean - 2 SD	5.13	4.66	35.08	24.98	1.15
B-basis	3.18	4.09	29.99		
A-basis	1.11	2.94	14.53		

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Table 3.18. Shear chord modulus of elasticity and maximum in-plane shear stress for Unipreg 200 g/m^2.

Specimen label	G_{12}^{chord} (SG), GPa	G_{12}^{chord} (DIC), GPa	τ_{12}^{m}, MPa	*b*, mm	*h*, mm
884_1	-	3.54	26.38	25.04	1.48
884_2	-	4.48	67.33	25.14	1.467
884_3	4.74	3.96	30.38	25.18	1.517
884_4	-	-	-	25.11	1.51
884_5	4.66	4.10	66.41	24.99	1.49
884_6	4.57	4.10	26.15	25.06	1.493
884_7	-	4.09	66.52	25.38	1.49
884_8	-	4.09	64.89	25.27	1.49
Mean	**4.66**	**4.05**	**49.72**	**25.15**	**1.49**
SD	0.09	0.28	20.72	0.13	0.02
Median	4.66	4.09	64.89	25.13	1.49
Minimum	4.57	3.54	26.15	24.99	1.47
Maximum	4.74	4.48	67.33	25.38	1.52
CV	1.83	6.83	41.67	0.51	1.05
Mean+ 2 SD	4.83	4.60	91.16	25.40	1.52
Mean - 2 SD	4.49	3.50	8.28	24.89	1.46
B-basis	2.22	3.29	-7.38		
A-basis	0.27	2.77	-46.46		

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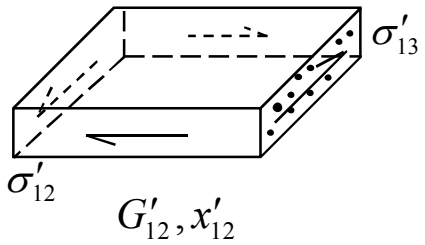
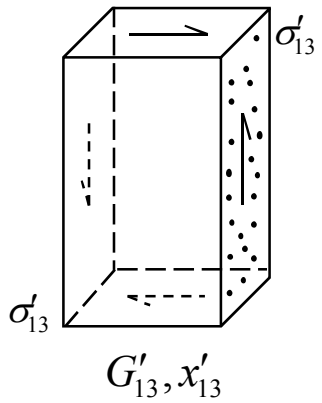
3.5 Three point flexural test

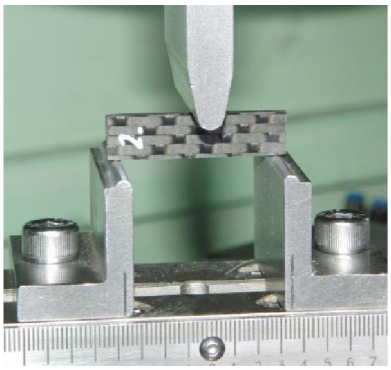
3.5.1 Definition of in-plane shear modulus

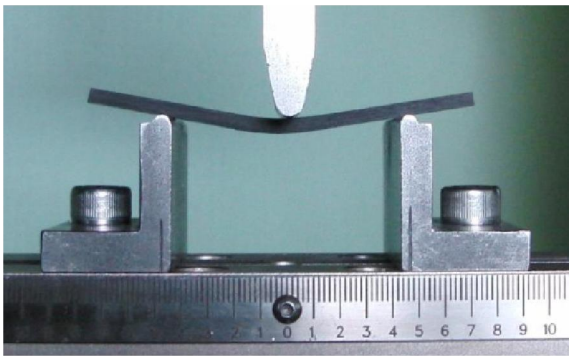
in-plane shear modulus G_{12}



out of-plane shear modulus G_{13}







h_0 – diagonal length between targets, m
h – sample thickness, m
b – sample width, m
F_1 – 1st force value, N
F_2 – 2nd force value, N
s_1 – strain value at F_1
s_2 – stain value at F_2

$$\alpha = \frac{3}{2} - \frac{h_0^{\,2}}{4 \cdot h^2}$$

$$w_1 = s_1 \cdot h_0$$

$$w_2 = s_2 \cdot h_0$$

$$G = \alpha \cdot \frac{h_0}{b \cdot h} \cdot \frac{(F_2 - F_1)}{(w_2 - w_1)}$$

Test parameters are listed in

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Table 3.19. Test results are presented in

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Table 3.20 for Unipreg 100 g/m^2 and in Table 3.21 for Unipreg 200 g/m^2. Figure 3.12 presents test specimens and test setup. Placing of DIC targets for shear modulus estimation shown in Figure 3.13.

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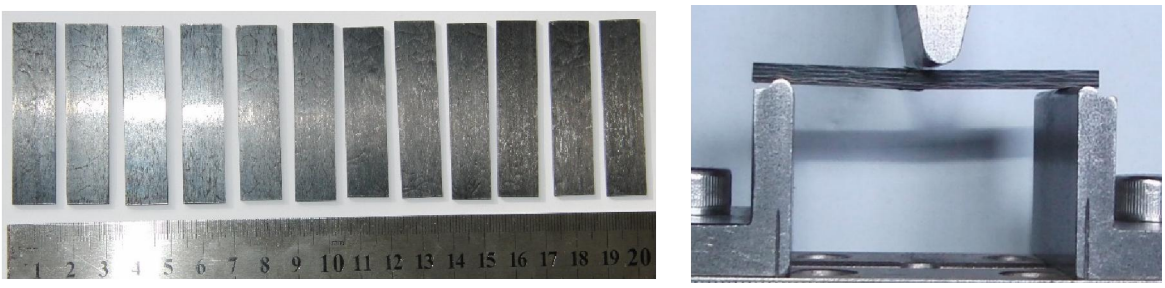
Table 3.19. Test parametrs for 3-point flexure test

Testing method	ASTM D 7264
Equipment	INSTRON E10000
Operator ID	Guntis Japins
Test type	Flexural test 3 point method
Testing speed	1 mm/min
Support span length	48 mm
Radius of loading member	3 mm
Radius of support members	1. 5 mm
Specimen's nominal dimensions (length, width)	56 x 13 mm
Type of loading noses	Fixed
Support span-to thickness ratio	16:1
Diagonal length between DIC targets	3 mm



a b

Figure 3.12. 3 point flexure test specimens (a) and test setup (b)

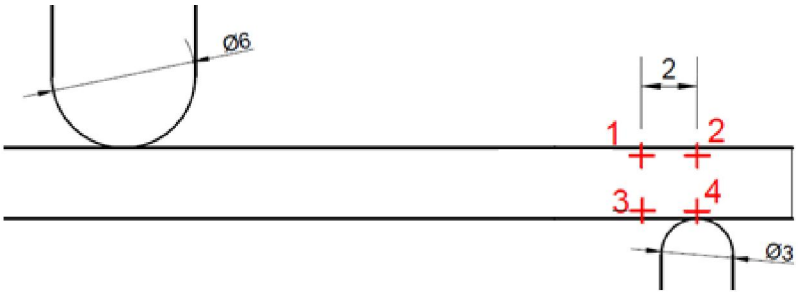


Figure 3.13. DIC targets setup to measure the extension. DIC targets were placed on specimen as shown in picture. Two extensometers were meashuring extension between targets 1 and 4, and between targets 2 and 3.

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Table 3.20. Flexure modulus, flexure shear modulus and flexure strength of Unipreg 100 g/m^2

Specimen label	E^f, GPa	G_{13}^f, GPa	R^f, MPa	b, mm	h, mm
906_1	116.24	0.32	1540.25	13.16	1.43
906_2	114.67	0.51	1531.75	13.06	1.45
906_3	112.21	0.50	1439.79	13.13	1.47
906_4	114.42	0.56	1426.73	13.2	1.47
906_5	114.26	0.56	1376.74	13.23	1.43
906_6	111.17	0.50	1476.27	13.1	1.45
906_7	106.01	0.37	1221.26	13.18	1.48
906_8	111.23	0.33	1411.33	13.18	1.48
906_9	112.82	0.32	1510.72	12.85	1.43
906_10	115.24	-	1335.19	13.12	1.44
Mean	**112.83**	**0.46**	**1427.00**	**13.12**	**1.45**
SD	2.94	0.10	98.28	0.11	0.02
Median	113.24	0.50	1433.26	13.17	1.46
Minimum	106.01	0.32	1221.26	13.06	1.43
Maximum	116.24	0.56	1540.25	13.23	1.48
CV	2.60	22.16	6.89	0.82	1.42
Mean+ 2 SD	118.70	0.66	1623.56	13.34	1.49
Mean - 2 SD	106.95	0.25	1230.45	12.91	1.41
B-basis	105.91	0.21	1195.56		
A-basis	101.14	0.04	1035.76		

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Table 3.21. Flexure modulus, flexure shear modulus and flexure strength of Unipreg 200 g/m^2

Specimen label	E^f, GPa	G_{13}^f, GPa	R^f, MPa	b, mm	h, mm
894_1	100.34	0.84	1156.01	12.40	2.58
894_2	99.76	0.88	1183.30	12.29	2.56
894_3	104.91	1.63	1277.66	12.22	2.50
894_4	98.63	0.95	1117.94	12.07	2.53
894_5	108.53	0.96	1222.74	12.25	2.44
894_6	112.42	0.84	1251.19	12.39	2.39
894_7	105.12	1.11	1194.25	12.32	2.43
894_8	118.55	0.89	1329.59	12.32	2.41
Mean	**106.03**	**1.01**	**1216.59**	**12.28**	**2.48**
SD	6.89	0.26	68.39	0.11	0.07
Median	105.02	0.92	1208.50	12.31	2.47
Minimum	98.63	0.84	1117.94	12.07	2.39
Maximum	118.55	1.63	1329.59	12.40	2.58
CV	6.50	25.97	5.62	0.86	2.91
Mean+ 2 SD	119.81	1.54	1353.37	12.49	2.62
Mean - 2 SD	92.25	0.49	1079.80	12.07	2.34
B-basis	88.23	0.33	1039.93		
A-basis	76.03	-0.13	918.80		

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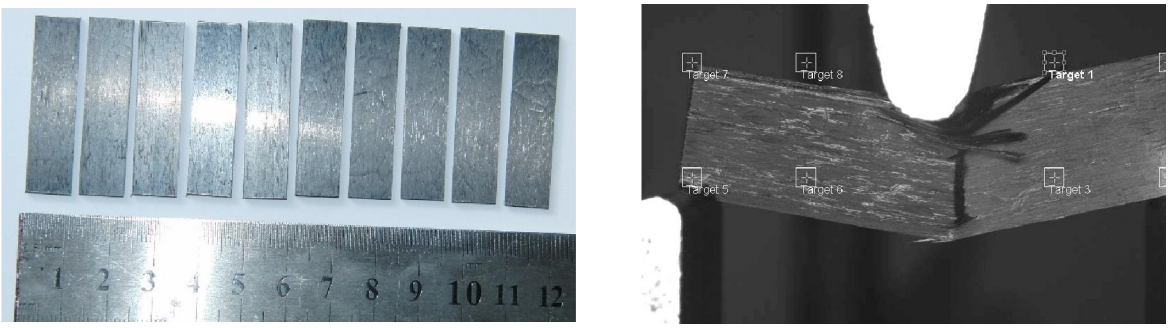
3.6 Short beam test for shear with coupon on its lateral side

Test parameters are listed in Table 3.22. Test results are presented in Table 3.23 for Unipreg 100 g/m^2 and in

Table 3.24 for Unipreg 200 g/m^2. Figure 3.14 presents test specimens and test setup. Placing of DIC targets for shear modulus estimation shown in Figure 3.15.

Table 3.22. Test parameters for short beam test for shear with coupon on its lateral side

Testing method	ASTM D 2344
Equipment	INSTRON E10000
Operator ID	Guntis Japins
Test type	Short-beam flexural test 3 point method
Testing speed	1 mm/min
Support span length	36 mm
Radius of loading member	3 mm
Radius of support members	1. 5 mm
Specimen's nominal dimensions (length, width)	40 x 10 mm
Type of loading noses	Fixed
Support span-to thickness ratio	4:1
Diagonal length between DIC targets	3 mm



a b

Figure 3.14. Specimens (a) and test setup (b) of short beam shear test with coupon on its lateral side

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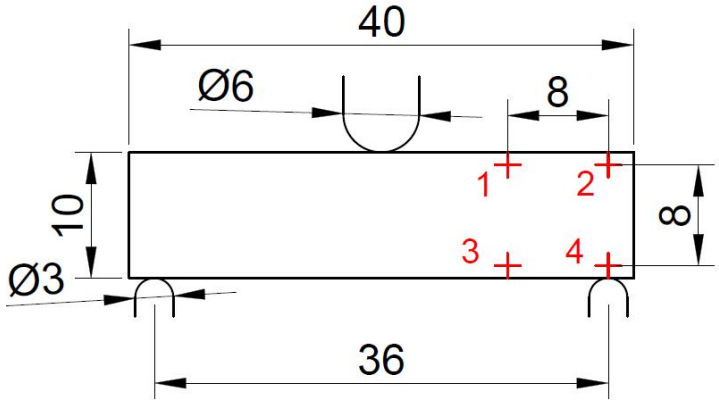

Figure 3.15. DIC targets were placed on specimen as shown in picture. Two extensometers were measuring extension between targets 1 and 4, and between targets 2 and 3.

Table 3.23. Lateral short beam flexure shear modulus and shear strength of Unipreg 100 g/m^2

Specimen label	G_{12}^{f} ,GPa	ν_{12}^{f} , MPa	*b*, mm	*h*, mm
905_1	2.75	194.27	1.49	10.01
905_2	3.67	179.37	1.49	10.12
905_3	3.13	262.81	1.18	10.04
905_4	2.36	187.89	1.44	9.88
905_5	2.30	179.61	1.46	9.85
905_6	2.78	203.50	1.44	10.12
905_7	2.65	227.79	1.44	10.04
905_8	3.47	223.52	1.46	9.98
905_9	3.83	203.18	1.47	10.07
905_10	3.05	203.15	1.48	10.18
Mean	**3.00**	**206.51**	**1.44**	**10.03**
SD	0.53	25.60	0.09	0.10
Median	2.92	203.16	1.46	10.04
Minimum	2.30	179.37	1.18	9.85
Maximum	3.83	262.81	1.49	10.18
CV	17.59	12.40	6.39	1.04
Mean+ 2 SD	4.06	257.71	1.62	10.24
Mean - 2 SD	1.94	155.30	1.25	9.82
B-basis	1.76	146.21		
A-basis	0.90	104.58		

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Table 3.24. Lateral short beam flexure shear modulus and shear strength of Unipreg 200 g/m^2

Specimen label	G_{12}^{f} ,GPa	ν_{12}^{f} , MPa	*b*, mm	*h*, mm
893_1	4.20	206.97	10.42	2.92
893_2	3.44	240.33	10.29	2.93
893_3	4.26	222.73	10.27	2.93
893_4	4.34	225.95	10.36	2.87
893_5	3.29	253.86	10.42	2.86
893_6	3.77	252.89	10.3	2.94
893_7	4.35	241.65	10.08	3.01
893_8	3.37	242.38	10.45	2.98
893_9	3.09	196.24	10.42	2.99
893_10	2.98	250.97	10.42	3.04
Mean	**3.71**	**233.39**	**10.34**	**2.95**
SD	0.54	19.87	0.11	0.06
Median	3.61	240.99	10.39	2.94
Minimum	2.98	196.24	10.08	2.86
Maximum	4.35	253.86	10.45	3.04
CV	14.61	8.51	1.09	1.97
Mean+ 2 SD	4.79	273.13	10.57	3.06
Mean - 2 SD	2.63	193.66	10.12	2.83
B-basis	2.43	186.61		
A-basis	1.55	154.30		

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3.7 Short beam test

Test parameters are listed inTable 3.25. Test results are presented in Table 3.26 for Unipreg 100 g/m^2 and in Table 3.27 for Unipreg 200 g/m^2. Figure 3.16 presents test specimens and test setup. Placing of DIC targets for shear modulus estimation shown in Figure 3.17.

Table 3.25. Test parameters for Short beam test for shear with coupon on its lateral side

Testing method	ASTM D 2344
Equipment	INSTRON E10000
Operator ID	Guntis Japins
Test type	Short-beam flexural test 3 point method
Testing speed	1 mm/min
Support span length	12 mm
Radius of loading member	3 mm
Radius of support members	1. 5 mm
Specimen's nominal dimensions (length, width)	20 x 10 mm
Type of loading noses	Fixed
Support span-to thickness ratio	4:1

a b

Figure 3.16. Specimens (a) and test setup (b) of short beam shear test

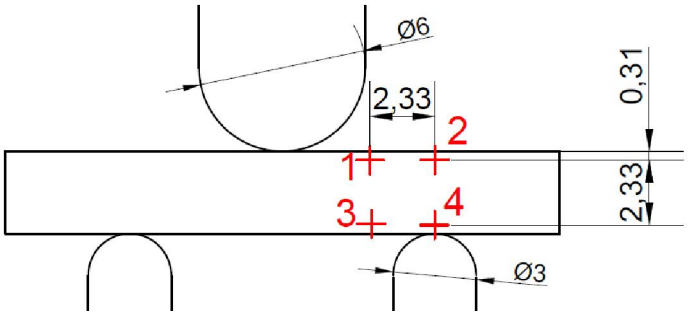

Figure 3.17. DIC targets were placed on specimen as shown in picture. Two extensometers were measuring extension between targets 1 and 4, and between targets 2 and 3.

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Table 3.26. Short beam flexure shear modulus and shear strength of Unipreg 100 g/m^2

Specimen label	G_{13}, GPa	ν_{13}, MPa	*b*, mm	*h*, mm
907_1	2.48	699.99	10.20	1.49
907_2	2.84	695.90	10.22	1.49
907_3	2.45	656.04	10.18	1.49
907_4	2.03	655.09	10.16	1.47
907_5	2.74	613.34	10.09	1.48
907_6	2.38	621.54	10.09	1.47
907_7	2.26	637.04	10.11	1.49
907_8	2.39	640.54	10.11	1.48
907_9	2.90	685.64	10.16	1.46
907_10	2.06	691.62	10.11	1.49
Mean	**2.45**	**654.13**	**10.14**	**1.48**
SD	0.27	33.84	0.05	0.01
Median	2.45	655.09	10.16	1.49
Minimum	2.03	613.34	10.09	1.47
Maximum	2.84	699.99	10.22	1.49
CV	11.17	5.17	0.46	0.74
Mean+ 2 SD	3.00	721.81	10.24	1.50
Mean - 2 SD	1.91	586.45	10.05	1.46
B-basis	1.81	574.44		
A-basis	1.36	519.42		

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Table 3.27. Short beam flexure shear modulus and shear strength of Unipreg 200 g/m^2

Specimen label	G_{13}, GPa	ν_{13}, MPa	*b*, mm	*h*, mm
895_1	2.77	2100.00	2.92	12.39
895_2	2.62	1878.00	2.91	12.41
895_3	2.91	1858.50	2.54	12.16
895_4	2.83	2129.75	2.44	12.25
895_5	2.37	2232.56	2.39	12.25
895_6	2.47	1978.47	2.43	12.32
895_7	3.44	1885.89	2.56	12.29
Mean	**2.77**	**2009.02**	**2.60**	**12.30**
SD	0.35	146.48	0.22	0.09
Median	2.77	1978.47	2.54	12.29
Minimum	2.37	1858.50	2.39	12.16
Maximum	3.44	2232.56	2.92	12.41
CV	12.70	7.29	8.64	0.71
Mean+ 2 SD	3.48	2301.98	3.05	12.47
Mean - 2 SD	2.07	1716.06	2.15	12.12
B-basis	1.80	1605.33		
A-basis	1.14	1329.07		

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3.8 Conclusions for pre-preg laminate mechanical testing

Specimen failure observed in coupon tests was within test zone for all specimens. No tab delamination, no unusual strain gauge separation observed for all specimens. The most accurate values obtained by employing strain gauges, other two strain measurement methods can be used for fast proof of known material properties. Some limitation related with DIC system alignment to the specimen surface or some unknown degree of slippage of clip-on extensometer can be the reason for less accurate, but otherwise usable results. The final comparison of obtained material properties presented in table.

Legend:
Method of estimation:
BlueHill2 (clip-on extensometer in case of tension tests)
MGCpuss (strain gage)
DIC Imetrum

Property		Mean values								
		Unipreg 100 g/m^2			Unipreg 200 g/m^2			Unipreg 200 g/m^2 (high stiffness)		
E^t, GPa	0°	122.69	115.91	75.52	124.09	122.55	73.33	164.62	164.11	108.37
	90°	8.39	7.79	8.91	6.43	6.63	7.86	-		
E^c, GPa	0°	103.91	102.77		117.60	121.1		-		
	90°	7.70	7.00		7.60	7.84		-		
E^f, GPa		112.83			106.03			-		
G_{12}^{chord}, GPa		6.07	5.78		4.66	4.05		-		
G_{12}, GPa		3.00			3.71			-		
G_{13}, GPa		2.45			2.77			-		
μ	0°	0.33			0.37			0.38		
R^t, MPa	0°	1466			1539			2037		
	90°	46			41			-		
R^c, MPa	0°	481			752			-		
	90°	138			141			-		
τ_{12}^m, MPa		53			50					
R^f, MPa		1427			1217			-		
v_{12}, MPa		207			233			-		
v_{13}, MPa		654			2009			-		

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4 Mechanical properties of honeycomb core

4.1 Introduction for honeycomb testing

The basic honeycomb core mechanical tests are compression, plate shear and tensile-node bond strength.

Aluminium honeycomb materials were delivered unexpanded, therefore special desk (Figure 4.1.) for honeycomb expansion was prepared. Specimens were cut out from expanded honeycomb by using sharp knife. Totally six types of honeycomb materials were used (

Figure 4.1. Desk for honeycomb expansion

Table 4.1.). Mechanical description of honeycomb were based on three tests gathered in Table 4.2.

Figure 4.1. Desk for honeycomb expansion

Table 4.1. Honeycomb materials used in testing

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No:	thickness	cell size	wall thickness
	mm	mm	mm
1	10	7.3	0.08
2	20	7.3	0.08
3	10	3.2	0.03
4	15	3.2	0.03
5	20	3.2	0.03
6	20	6.4	0.03

Table 4.2. Honeycomb core test matrix definition

Coupons	Properties	Standard
Plate shear test	τ , G_{core}	ASTM C273
Flatwise compression	F_z^{fcu} , E_z^{fc} , $\sigma_z^{fc0.02}$	ASTM C365
Honeycomb node tension	σ_{node}	ASTM C363

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For easier recognition of honeycomb test specimens, special labelling system was created. Example shown in Figure 4.2.

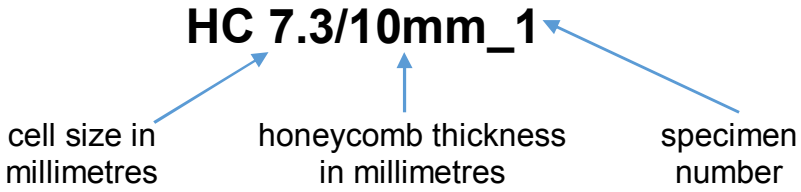

Figure 4.2. Honeycomb specimen labelling example

4.2 Plate shear test (In-plane shear test)

From this test the honeycomb shear strengths and moduli are determined. In most designs these are the critical core properties. There are two ways of performing this test: compressive plate shear or tensile plate shear. Here the honeycomb is bonded to thick steel plates. Both of these tests give the same results. The compressive method may be quicker and it is easier to load the specimen on the test machine; however, the tensile method may be safer as the steel blocks cannot drop off the test setup at failure. The specimen length should be equal to or greater than 12 x core thickness.

Test parameters are listed in

Table 4.3. In Figure 4.3. is shown test setup. For accurate strain measurements linear variable differential transformer (LVDT) system was used. Test results are presented in Table 4.4.

Table 4.3. Test parameters of plate shear tests

Testing method	ASTM C273
Equipment	INSTRON E10000
Operator ID	Guntis Japins
Test type	Tensile plate shear
Testing speed	0.5 mm/min
Extension determination by:	DIC
Space between DIC targets	200 mm

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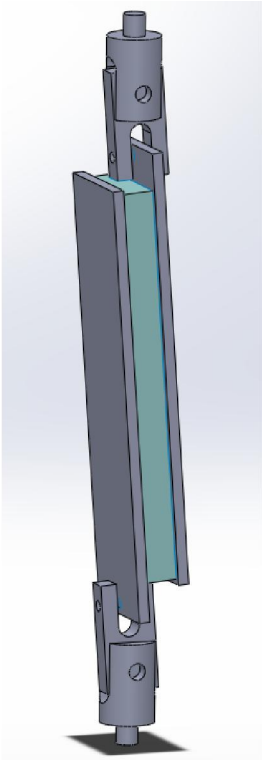

Figure 4.3. Plate shear test setup

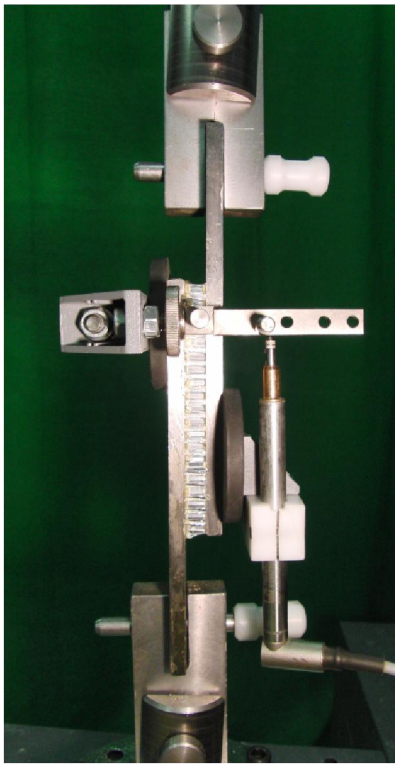

Figure 4.4. Test specimen with attached LVDT

Table 4.4. Plate shear strength and shear modulus

HC 3.2/10mm

Specimen label	L direction				W direction			
	G_{core}, GPa	τ, MPa	*b*, mm	*h*, mm	G_{core}, GPa	τ, MPa	*b*, mm	*h*, mm
HC 3.2/10mm_1	0.28	1.97	50	120	0.21	1.52	50	120
HC 3.2/10mm_2	0.33	1.90	49	123	0.11	1.24	49	122
HC 3.2/10mm_3	0.31	2.09	50	120				
HC 3.2/10mm_4	-	2.09	50	120				
HC 3.2/10mm_5	0.29	2.13	50	123				
HC 3.2/10mm_6	-	2.26	50	130				
HC 3.2/10mm_7	0.28	2.21	50	130				
HC 3.2/10mm_8	0.30	2.19	50	120				
HC 3.2/10mm_9	0.24	2.18	50	120				
HC 3.2/10mm_10	0.26	1.94	50	120				
Mean	**0.29**	**2.10**	**49.90**	**122.6**	**0.16**	**1.38**	**49.50**	**121.0**
SD	0.03	0.12	0.32	4.09	0.07	0.20	0.71	1.41
Median	0.29	2.11	50.00	120.0	0.16	1.38	49.50	121.0

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Minimum	0.24	1.90	49.00	120.0	0.11	1.24	49.00	120.0
Maximum	0.33	2.26	50.00	130.0	0.21	1.52	50.00	122.0
CV	9.97	5.87	0.63	3.33	44.19	14.35	1.43	1.17
Mean+ 2 SD	0.34	2.34	50.53	130.8	0.30	1.78	50.91	123.8
Mean - 2 SD	0.23	1.85	49.27	114.4	0.02	0.98	48.09	118.2

HC 3.2/15mm

Specimen label	L direction			
	G_{core}, GPa	τ, MPa	*h*, mm	*b*, mm
HC 3.2/15mm_1	0.57	0.70	50	240
HC 3.2/15mm_2	0.15	1.12	50	240
HC 3.2/15mm_3	0.38	1.12	50	240
HC 3.2/15mm_4	1.03	1.04	50	240
Mean	**0.53**	**1.00**	**50.00**	**240.0**
SD	0.37	0.20	0.00	0.00
Median	0.47	1.08	50.00	240.0
Minimum	0.15	0.70	50.00	240.0
Maximum	1.03	1.12	50.00	240.0
CV	70.72	20.17	0.00	0.00
Mean+ 2 SD	1.28	1.40	50.00	240.0
Mean - 2 SD	-0.22	0.59	50.00	240.0

4.3 Honeycomb flatwise compression test

This test method covers the determination of compressive strength and modulus of sandwich cores, including honeycomb.

The compression tests consist of two types: the bare compression method (with no facings) and the stabilized compression method. Flatwise compressive strength and modulus are fundamental mechanical properties of sandwich cores that are used in designing of sandwich panels.

Test parameters are listed in Table 4.5. In Figure 4.5. is shown test setup. Test results are presented in Table 4.6. Honeycomb is bonded to two plywood sheets with polyurethane resin UT-100. If compressive strain overcomes 2% the $\sigma_z^{fc0.02}$ (stress at 2% strain) value is used instead of ultimate strength F_z^{fcu}.

Table 4.5. Test parameters of flatwise compression tests

Testing method	ASTM C365
Equipment	ZWIC Z100
Operator ID	Guntis Japins

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Test type	Flatwise compression
Testing speed	0.5 mm/min
Extension determination by:	Crosshead displacement

Figure 4.5. Flatwise compression test setup

Table 4.6. Core flatwise compressive chord modulus, ultimate flatwise compressive strength and flatwise compressive stress at 2 % strain

HC 3.2/10mm (bare honeycomb)

Specimen label	E_z^{fc}, GPa	F_z^{fcu} MPa	*b*, mm	*h*, mm
HC 3.2/10mm_1	1.90	2.22	51	51
HC 3.2/10mm_2	2.59	2.58	51	51
HC 3.2/10mm_3	1.73	2.03	51	51
HC 3.2/10mm_4	1.93	2.39	51	51
Mean	**2.04**	**2.30**	**51**	**51**
SD	0.38	0.24	0	0
Median	1.92	2.31	51	51
Minimum	1.73	2.03	51	51
Maximum	2.59	2.58	51	51
CV	18.42	10.25	0	0
Mean+ 2 SD	2.79	2.78	51	51
Mean - 2 SD	1.29	1.83	51	51

HC 3.2/15mm (bare honeycomb)

Specimen label	E_z^{fc}, GPa	F_z^{fcu} MPa	*b*, mm	*h*, mm
HC 3.2/15mm_1	11.83	3.87	49.50	52.00
HC 3.2/15mm_2	10.76	4.13	52.80	47.60

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HC 3.2/15mm_3	11.79	4.32	52.78	48.83
HC 3.2/15mm_4	11.26	3.92	47.90	51.60
HC 3.2/15mm_5	9.98	3.82	51.13	49.18
Mean	**11.12**	**4.01**	**50.82**	**49.84**
SD	0.77	0.21	2.13	1.89
Median	11.26	3.92	51.13	49.18
Minimum	9.98	3.82	47.90	47.60
Maximum	11.83	4.32	52.80	52.00
CV	6.96	5.18	4.19	3.79
Mean+ 2 SD	12.67	4.43	55.08	53.62
Mean - 2 SD	9.58	3.60	46.56	46.07

4.4 Tensile node bond strength test

The honeycomb tensile-node bond strength is a fundamental property than can be used in determining whether honeycomb cores can be handled during cutting, machining and forming without the nodes breaking. The tensile-node bond strength is the tensile stress that causes failure of the honeycomb by rupture of the bond between the nodes. It is usually a peeling-type failure.

Test parameters are listed in

Table 4.7. In Figure 4.6. is shown test setup. Test results are presented in Table 4.8.

Table 4.7. Test parameters of flatwise compression tests

Testing method	ASTM C365
Equipment	ZWIC Z100
Operator ID	Guntis Japins
Test type	Node tension
Testing speed	25 mm/min
Extension determination by:	Crosshead displacement

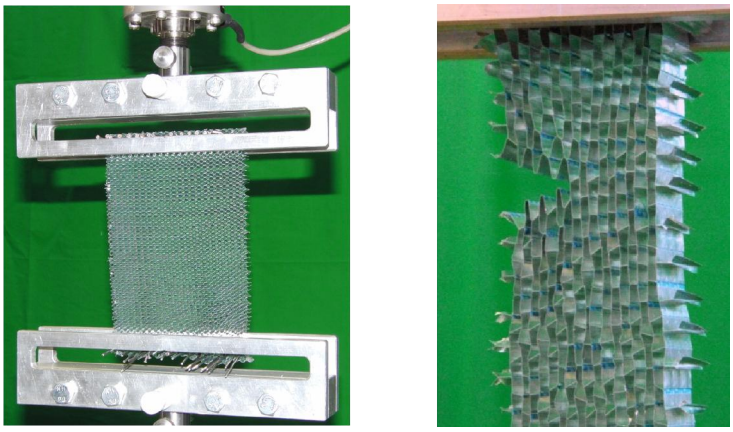

Figure 4.6. Tensile node bond strength test setup and typical failure

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Table 4.8. Core tensile node bond strength

Specimen label	σ_{node} MPa	*b*, mm	*h*, mm
HC 7.3/20mm_1	0.176	120	200
HC 7.3/20mm_2	0.199	120	200
HC 7.3/20mm_3	0.192	120	200
HC 7.3/20mm_4	0.220	130	227
Mean	**0.20**	**123**	**207**
SD	0.02	5	14
Median	0.20	120	200
Minimum	0.18	120	200
Maximum	0.22	130	227
CV	9.27	4	7
Mean+ 2 SD	0.23	133	234
Mean - 2 SD	0.16	113	180

Specimen label	σ_{node} MPa	*b*, mm	*h*, mm
HC 3.2/10mm_1	0.28	130	200

5 Mechanical properties of CFRP skin/aluminium honeycomb core sandwich panels

5.1 Introduction in sandwich panels testing

There are several tests for properties determination of honeycomb sandwich panels. Flatwise tension and climbing drum peel test are good ways of evaluating the integrity of a honeycomb sandwich panel and how well the skins are bonded to the honeycomb, flatwise compression, plate shear, flexural shear (all the same as the honeycomb tests), edgewise compression and long beam flexure.

Applied test methods for CFRP skin and aluminium honeycomb sandwich panels gathered in Table 5.1.

Table 5.1. Test methods applied for sandwich panels

Coupons	Properties	Standard
Plate shear	τ , G_{core}	ASTM C273
Flatwise compression	F_z^{fcu} , E_z^{fc} , $\sigma_z^{fc0.02}$	ASTM C365
Flatwise tension	F_z^{ftu}	ASTM C297

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Climbing drum peel test	T_p	ASTM D1781

5.2 Plate shear test

This test method is suitable not only for bare honeycomb but provides information on the force-deflection behaviour of sandwich constructions too.

Test parameters are listed in Table 5.2. In Error! Reference source not found.. is shown test setup, while Figure 4.4. presents placing of DIC targets for extension measurement.

Table 5.2. Test parameters of plate shear tests

Testing method	ASTM C273
Equipment	INSTRON E10000
Operator ID	Guntis Japins
Test type	Tensile plate shear
Testing speed	0.5 mm/min
Extension determination by:	DIC
Space between DIC targets	200 mm

5.3 Flatwise compression test

Test parameters are listed in Table 5.3. In Figure 4.5. is shown test setup. Test results are presented in Table 5.4.

Table 5.3. Test parameters of flatwise compression tests

Testing method	ASTM C365
Equipment	ZWIC Z100
Operator ID	Guntis Japins
Test type	Flatwise compression
Testing speed	0.5 mm/min
Extension determination by:	Crosshead displacement

Table 5.4. Core flatwise compressive chord modulus, ultimate flatwise compressive strength and flatwise compressive stress at 2 % deflection

Specimen label	E_z^{fc}, GPa	F_z^{fcu} MPa	*b*, mm	*h*, mm
920_SP_1	0.19	4.35	50	50
920_SP_2	0.183	3.67	50	50
933_SP_1	2.58	2.73	50	50
933_SP_2	2.30	2.80	50	50
936_SP_1	2.17	2.45	50	50

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5.4 Flatwise tension test

Sandwich construction is subjected to a uniaxial tensile force normal to the plane of the sandwich. This test method can be used to provide information on the strength and quality of core-to-facing bonds, also it can be used to produce flatwise tensile strength data for the core material.

Test parameters are listed in Table 5.5. In Figure 5.1. is shown test setup. Test results are presented in

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Table 5.6.

Table 5.5. Test parameters of flatwise tension tests

Testing method	ASTM C297
Equipment	ZWIC Z100
Operator ID	Guntis Japins
Test type	Flatwise tension
Testing speed	0.5 mm/min
Extension determination by:	Crosshead displacement

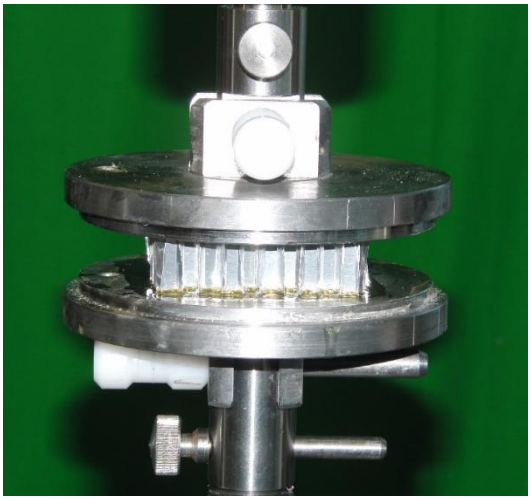

Figure 5.1. Flatwise tension test setup

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Table 5.6. Results of ultimate flatwise tensile strength

920_SP

Specimen ID	Layup	F_z^{ftu}, MPa	Honeycomb		b, mm	h, mm	Adhesive	Failure type
			cell size, mm	thickness, mm				
920_SP_1	[0,90,0]	1.32	3.2	10	49.4	49.4	STC epoxy	Facing to core adhesive failure
920_SP_2	[0,90,0]	0.79	3.2	10	49.5	49.6	STC epoxy	
Mean		**1.06**	**3.2**	**10.6**	**49.45**	**49.50**		
SD		0.37	0.00	0	0.07	0.14		
Median		1.06	3.20	10.6	49.45	49.50		
Minimum		0.79	3.20	10.6	49.40	49.40		
Maximum		1.32	3.20	10.6	49.50	49.60		
CV		35.52	0.00	0.0	0.14	0.29		
Mean+ 2 SD		1.80	3.20	10.6	49.59	49.78		
Mean - 2 SD		0.31	3.20	10.6	49.31	49.22		

933_SP

Specimen ID	Layup	F_z^{ftu}, MPa	Honeycomb		b, mm	h, mm	Adhesive	Failure type
			cell size, mm	thickness, mm				
933_SP_1	[+60/0/-60]	1.01	3.2	10.6	50	50	PU18	Facing to core adhesive failure
933_SP_2	[+60/0/-60]	0.63	3.2	10.6	50	50	PU18	
933_SP_3	[+60/0/-60]	0.41	3.2	10.6	50	50	PU18	
933_SP_4	[+60/0/-60]	0.63	3.2	10.6	50	50	PU18	
933_SP_5	[+60/0/-60]	0.69	3.2	10.6	50	50	PU18	
Mean		**0.65**	**3.2**	**10.6**	**50**	**50**		
SD		0.03	0.00	0	0	0		
Median		0.63	3.20	10.6	50	50		
Minimum		0.63	3.20	10.6	50	50		
Maximum		0.69	3.20	10.6	50	50		
CV		5.33	0.00	0	0	0		
Mean+ 2 SD		0.72	3.20	10.6	50	50		
Mean - 2 SD		0.58	3.20	10.6	50	50		

5.5 Climbing drum peel test

Climbing drum peel test carried out by using ASTM D1781 test method or EN2243 DIN53295. The climbing drum peel test should be performed on sandwich panels with relatively thin skins. The maximum thicknesses should be approximately

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0.813 mm for alumina, 0.508 mm for steel and 1.016 mm for fiberglass or carbon fibre face sheets. Test outcome is adhesion properties of the adhesive used to bond facing sheets to core material.

Table 5.7. Test parameters of climbing drum peel tests are gathered in Table 5.7. Climbing drum peel test set-up shown in Figure 5.2. Test results are presented in

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Table 5.8.

Table 5.7. Test parameters of climbing drum peel tests

Testing method	ASTM D1718
Equipment	ZWIC Z100
Operator ID	Guntis Japins
Test type	Climbing drum peel
Testing speed	25 mm/min
Extension determination by:	Crosshead displacement

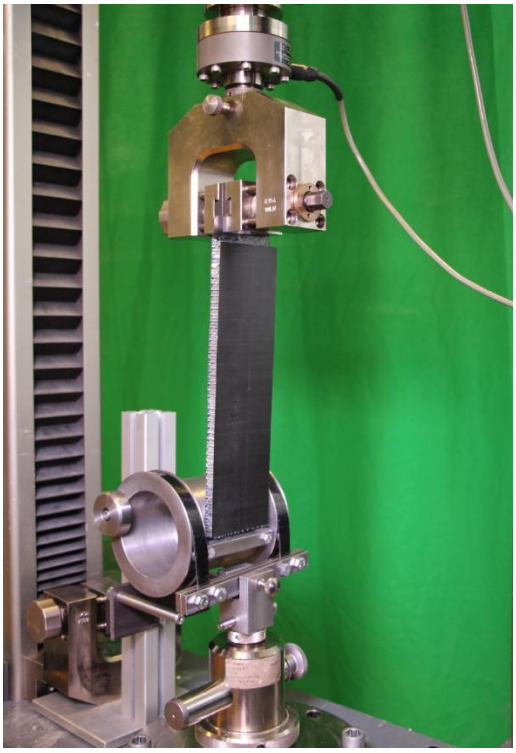

Figure 5.2. Climbing drum peel test setup

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Table 5.8. Peel strength of tested panels

Specimen label	Pre-preg, g/m^2	Layup	Honeycomb	Adhesive	T_p N·m/m	*b*, mm	*h*, mm
914_SP	100	[0,+45,-45,90]	7.3/10mm	UT-100	78.6	94	10.7
915_SP	100	[0/+60/-60]	7.3/10mm	UT-100	87.2	99	11.2
918_SP	100	[0,+45,-45,90]	7.3/10mm	STC	49.7	79	12.5
928_SP	100	[0/90/0]	3.2/10mm	UT-100	22.7	80	10.5
933_SP	100	[0/60/-60]	3.2/10mm	PU18	13.2	76	10.5
936_SP	100	[0/60/-60]	3.2/10mm	ET538	59.2	76	10.5
937_SP	100	[0/60/-60]	3.2/10mm	VM100	5.9	75	10.5

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6 Residual strength estimation

6.1 Damage introduction

Artificial damage introduction in sandwich panel will be carried out by using two alternative methods quasi-static indentation and low velocity impact. Low velocity impact tests are based on ASTM D7766 and ASTM D7136, where a flat, rectangular plate specimen is subjected to an out-of-plane, concentrated impact using a drop-weight device with a hemispherical impactor. Quasi-static indentation is carried out by using ASTM D6264, where a flat, square composite plate is subjected to an out-of-plane, and concentrated force by slowly pressing a hemispherical indenter into the surface.

Table 5.7. Test parameters of climbing drum peel tests are gathered in Table 6.1. and test set-up shown in Figure 6.1. In

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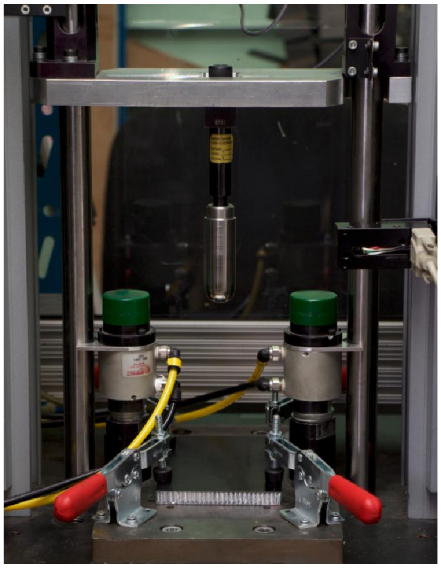
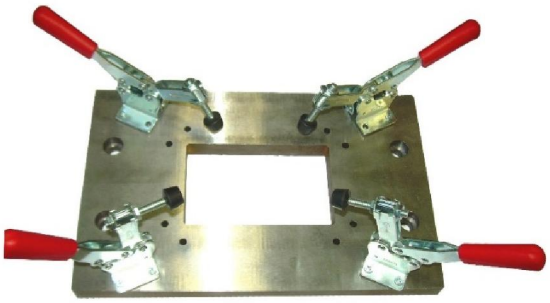
Table 6.2. there are shown quasi-static indentation test parameters respectively.

Table 6.1. Test parameters of low velocity impact tests

Testing method	ASTM D7766 and custom from ASTM D7136
Equipment	Intron Dynatup 9250HV
Operator ID	Guntis Japins
Test type	Impact test
Testing speed, m/s	varies
Impactor type	Hemispherical
Impactor diameters, mm	12.7, 20, 25.4
Impact energies, J	1, 2, 3



Low velocity impact test setup



Specimen clamping device for impact and quasi-static tests

Figure 6.1. Low velocity impact test setup for artificial damage introduction

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Table 6.2. Test parameters of quasi-static indentation tests

Testing method	custom from ASTM D6264
Equipment	Instron E3000
Operator ID	Guntis Japins
Test type	quasi-static indentation test
Testing speed, mm/min	0.5
Impactor type	Hemispherical
Impactor diameters, mm	12.7, 20, 25.4
Indentation forces, N	100, 200, 300

6.2 Testing of damaged specimens

After artificial damage is introduced in specimen, appropriate and robust method for residual strength estimation must be applied. For this purpose suitable test is edgewise compression based on ASTM D7137 method.

Compression after impact test parameters are show in Table 6.3. and test setup in Figure 6.2.

Table 6.3. Test parameters of quasi-static indentation tests

Testing method	custom from ASTM D7137
Equipment	ZWICK Z100
Operator ID	Guntis Japins
Test type	edgewise compression
Test fixture	SACMA compression after impact test rig
Testing speed, mm/min	0.5
Extension measurement devices	LVDT, DIC

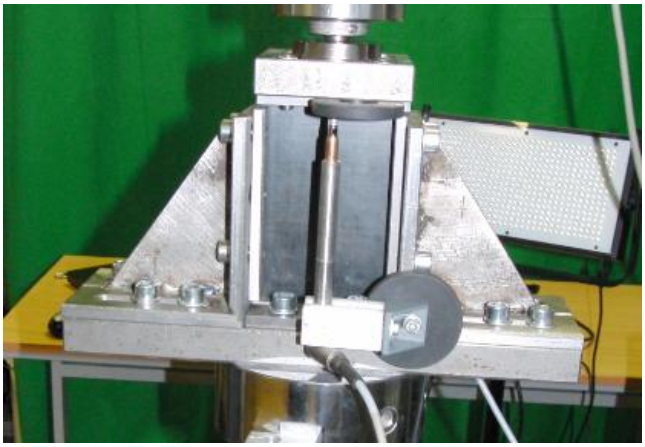

Figure 6.2.Compression after impact test setup

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7 Conclusions

At current moment all required test fixtures advised in literature review have been manufactured and at least some specimens tested and verified. Material properties for CFRP composite and AL-honeycomb which are required for detailed FEM analysis have been examined and even verified by means of NDT and FEM. A further effort of mechanical testing will be given to BVID introduction in produced panels as well as compression after impact and bending after impact tests.