ESA STUDY CONTRACT REPORT –

Deliverable D 4.2

Results of mechanical testing

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ABSTRACT:
Current report summarize mechanical test efforts for assessment of both coupon and specimen scale samples. All relevant mechanical test procedures initially identified within the literature review have been produced and verified with dedicated prototype specimens. This allowed to designing as well re-design for 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. Among other characterisation of CFRP and various aluminium honeycomb structure properties enabled both numerical FE based and analytical procedures for estimating the load carrying capacity of produced panels.
Main emphasis of current deliverable is devoted on summarising compression after impact tests. Produced 50 panels and casted approximately 250 specimens for dedicated tests due time consuming procedure and additional test requirement on produced specimens. A summary of compression behaviour is given by statistically comparing similar configuration sandwich panels. Some pattern could be identified, nevertheless some outliers require statistically more mature revisiting of several configurations. Finally, visual illustration for each specimen tested was added to the report with front/back/ both side views of compressed sandwich panels.It should be noted that indentation introduced mechanically is reported in NDE report as numerical analysis was done in automated means by developed software therefore introduced damage level is reported separately in project report D3.2 and D5.4.

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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** NAME OF ESA STUDY MANAGER: DIV: DIRECTORATE:	** ESA BUDGET HEADING:

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List of abbreviations

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
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
E_z^{fc}	core flatwise compressive chord modulus, MPa
$\sigma_z^{fc0.02}$	flatwise compressive stress at 2 % deflection, MPa
μ	Poisson's ratio
γ_{12}	in-plane shear strain, με
$\gamma_{12}{}^{m}$	maximum shear strain, με
$\tau_{12}{}^{m}$	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

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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
FEM	Finite element method
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
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 presents summary of all tested mechanical properties for sandwich panels. Besides providing test results an extensive discussion on extension of procedures for residual strength estimation for sandwich panel's damage assessment are presented.

Characteristics/parameters obtained from mechanical tests of individual components, such as CFRP pre-preg laminate skins and aluminium honeycomb core are required for numerical simulations by FEM. Also mechanical characterization of complete panel is presented. The guidelines for test set-up and testing are taken from several ASTM standards.

Due to high complication level of whole study and gradual increase of experience, the approach to research has changed and upgraded several times as result it led to finding of important basic principles for residual strength estimation method. A number of pre-selected tests from literature review were rejected as they were invalid for particular study.

2 Labeling system used in research

In specific research several constructions of sandwich panels with different sin lay-ups and honeycomb cores were used. This condition led to the creation of appropriate labeling system for test specimens. Sandwich panels were manufactured as approximately 200 mm wide and 450 mm long plates. Each this plate have unique name (for example ESA_001, ESA_002). Number in the label represents the order in which plates were manufactured. Sandwich panels have few important components (skin plates, core and adhesive bonding them together) which should be labeled for its easier recognition. Aluminium honeycomb have four main characteristics: alloy, foil thickness, cell size and thickness (height). Since only one alloy (5052) honeycomb used, it does not appear in the label, also aluminium foil thickness is not added to each specimen. The thickness of the foil is indicated before describing of large sample groups. Each honeycomb specimen's label have only specific cell size and thickness (example is shown in Figure 2.1.).

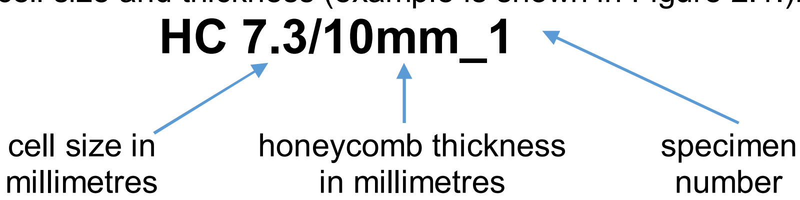


Figure 2.1. Honeycomb specimen's labelling example

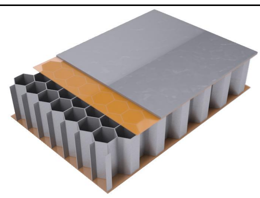
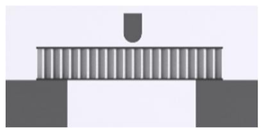
Speaking about labeling of sandwich panel skins, at the initial stage of research three types of carbon fiber pre-pregs (Unipreg® 100, Unipreg® 200 and high stiffness Unipreg® 200) were considered as potential for future research, but only one – Unipreg® 100 – was chosen, so there was no need to mention it in label. Skins are labeled by their lay-ups (direction of fibers in each layer: (90/0), (-60/60/0), (0/60/-60/90)). Same thing is with adhesive used to bond the skins to core. Although several types of adhesives were tested, only one was chosen. For that reason the name of adhesive do not appear in labels. Trade name of default adhesive is Permabond ET538.

3 Test matrix

3.1 Overview of test methods

Tension, compression, shear and flexure test gives full spectre of mechanical properties of pre-preg skins. Core plate shear, compression and node tension tests presents mechanical properties of honeycomb core 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. Flatwise tension of sandwich panel shows which adhesive bond in whole panel is the weakest, for example, is it between face to core or between skin plies. Panel flatwise compression is similar to bare honeycomb compression, but due to adhesive fillets stabilizes honeycomb, the compression strength values is quite higher. Damage introduction is made by quasi-static indentation and low velocity impact with different indenter diameters and indentation forces or impact energies. Edgewise compression is used to estimate damage tolerance of sandwich structures. In Table 3.1. are gathered all test methods used in research.

Table 3.1. 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

3.2 All completed mechanical tests

In Table 3.2. there are listed all completed mechanical tests.

Table 3.2. Completed mechanical tests

Test group	Material	Test	Number of specimens
Skin tests	Unipreg 100	0° tension test	9
		90° tension test	8
		0° compression test	12
		90° compression test	8
		45° shear test	8
		lateral short beam shear test, short beam test	10; 10
		flexure test	10
	Unipreg 200	0° tension test	11
		90° tension test	9
		0° compression test	11
		90° compression test	8
		45° shear test	8
		lateral short beam shear test, short beam test	10; 7
		flexure test	8
	Unipreg 200 (high stiffness)	0° tension test	10
Honeycomb core tests	3.2/10mm (thick foil)	Shear (L and W directions)	12
		Compression	4
		Node tension	1
	3.2/15mm (thick foil)	Shear	4
		Compression	5
	6.4/20mm (thick foil)	Compression	8
		Node tension	4
	3.2/20mm (thick foil)	Compression	5
Panel tests	Total climbing drum peel tests		8
	Total flatwise compression tests		17
	Total flatwise tension tests		12
	Quasi-static indentation tests		152
	Impact tests		47
	Edgewise compression tests		220

4 Mechanical properties of pre-preg laminate skin

4.1 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 4.1. 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 4.1. 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 Table 4.2.

Table 4.2. 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}, v_{12}	ASTM D3518
Short beam In plane shear strength	G_{13}, v_{12}	ASTM D2344
Short beam shear with coupon on its lateral side	G_{12}, v_{12}	custom from ASTM D2344
Short beam shear	G_{12}, v_{12}	ASTM D2344
3 Point Flexural Strength and Modulus	E^t, G_{13}, R^f	ASTM D7264

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

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.

4.2 Tension test

4.2.1 0° direction tension test

Test parameters are listed in Table 4.3. In Figure 4.1 are shown test specimens and in Figure 4.2 – test setup. Test results are presented in Table 4.4 for Unipreg 100 g/m^2, Table 4.5 for Unipreg 200 g/m^2 and for Table 4.6 high stiffness Unipreg 200 g/m^2 respectively.

Table 4.3. 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.

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

Figure 4.1. 0^o direction tension test specimens

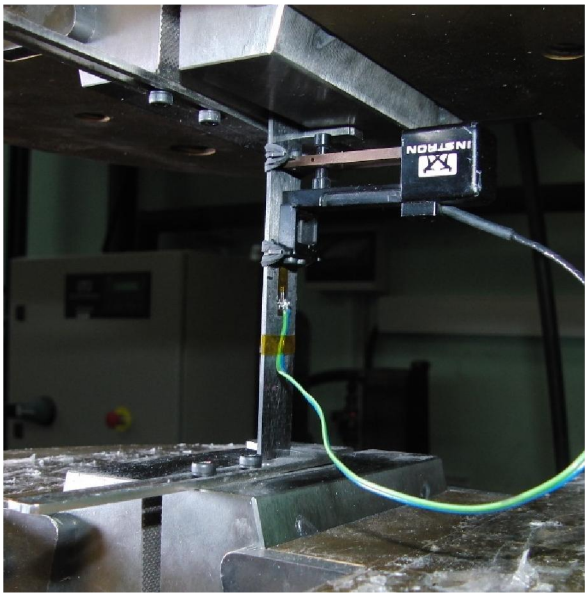


Figure 4.2. 0^o direction tension test setup

Table 4.4. Tensile modulus, tensile strength and Poisson's ratio of Unipreg 100 g/m^2 (0^o direction)

Specimen	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	μ	b, mm	h, mm
1	-	109.13	79.64	1620	-	14.08	1.22
2	-	118.72	68.56	1300	0.46	13.89	1.27
3	-	104.34	77.76	1340	0.41	14.21	1.27
4	123.91	118.59	77.16	1380	0.34	14.60	1.27
5	-	-	70.06	1480	-	14.69	1.24
6	114.82	100.87	76.57	1270	-	14.79	1.20
7	129.33	128.35	88.45	1540	-	14.75	1.17
8	-	123.67	69.78	1520	0.2	14.08	1.08
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			

Table 4.5. Tensile modulus, tensile strength and Poisson's ratio of Unipreg 200 g/m^2 (0^o direction)

Specimen	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	μ	*b*, mm	*h*, mm
1	-	125.85	66.81	1430	0.37	13.92	1.90
2	121.02	122.07	-	1290	0.29	15.44	1.89
3	-	112.57	66.53	1610	0.32	15.45	1.91
4	123.67	127.80	75.14	1570	0.35	15.41	1.89
5	127.58	127.67	78.51	1400	0.32	15.18	1.90
6	-	119.47	70.97	1850	0.36	15.47	1.89
7	-	121.45	90.38	1750	0.33	15.43	1.89
8	-	121.84	70.70	1630	0.26	15.48	1.87
9	-	118.20	75.54	1410	0.24	14.16	1.87
10	-	129.02	70.95	1400	0.59	14.08	1.87
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			

Table 4.6. Tensile modulus, tensile strength and Poisson's ratio of Unipreg 200 g/m^2 (high stiffness) (0^o direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	μ	*b*, mm	*h*, mm
1	-	166.60	100.98	2140	0.38	15.36	1.47
2	-	146.00	101.47	2550	0.32	15.06	1.48
3	167.00	176.76	119.45	2330	0.38	14.99	1.49
4	-	185.57	104.87	2190	0.46	14.99	1.51
5	-	160.98	111.98	2140	0.45	14.94	1.50
6	-	141.07	109.68	1700	0.37	14.94	1.50
7	161.66	172.16	107.73	1960	-	14.74	1.50
8	165.20	173.09	109.60	1650	-	14.74	1.52
9	-	154.80	109.56	2190	-	15.02	1.50
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			

4.2.2 90° direction tension test

Test parameters are listed in Table 4.7. Test results are presented in Table 4.8 for Unipreg 100 g/m^2 and Table 4.9 for Unipreg 200 g/m^2. Figure 4.3. 90o direction tension test setup.

Table 4.7. 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

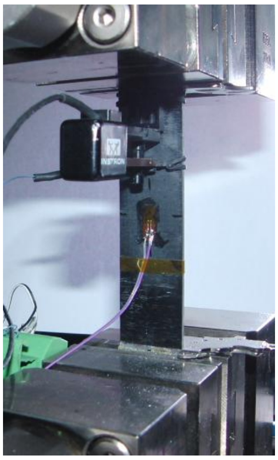


Figure 4.3. 90° direction tension test setup

Table 4.8. Tensile modulus and tensile strength Unipreg 100 g/m^2 (90^o direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	b, mm	h, mm
1	8.74	-	8.97	50.17	25.11	1.23
2	-	7.57	8.93	47.22	25.40	1.25
3	-	-	9.31	51.07	24.86	1.26
4	-	7.89	9.38	40.65	25.38	1.22
5	-	7.68	8.97	32.73	24.84	1.22
6	8.28	-	8.33	-	25.16	1.22
7	-	8.01	8.65	45.11	24.77	1.25
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		

Table 4.9. Tensile modulus and tensile strength Unipreg 200 g/m^2 (90^o direction)

Specimen label	E^t (SG), GPa	E^t (DIC), GPa	E^t (CE), GPa	R^t, MPa	*b*, mm	*h*, mm
1	-	6.68	8.17	41.02	23.22	1.84
2	-	6.29	7.97	38.49	25.09	1.87
3	6.43	6.67	7.79	40.49	25.04	1.88
4	-	6.14	7.68	42.68	25.12	1.90
5	-	6.63	8.11	33.46	25.06	1.89
6	6.32	6.88	8.03	44.47	25.10	1.91
7	6.53	6.87	7.79	45.78	25.13	1.90
8	-	7.08	7.63	41.41	24.23	1.91
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		

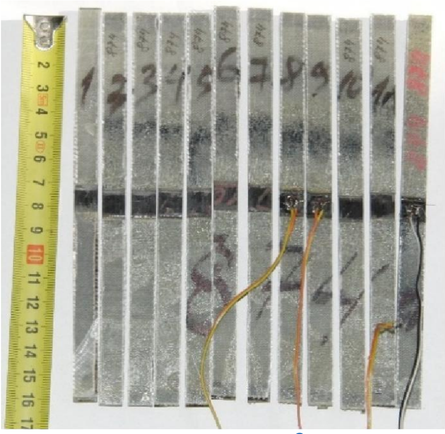
4.3 Compression tests

4.3.1 0^o direction compression test

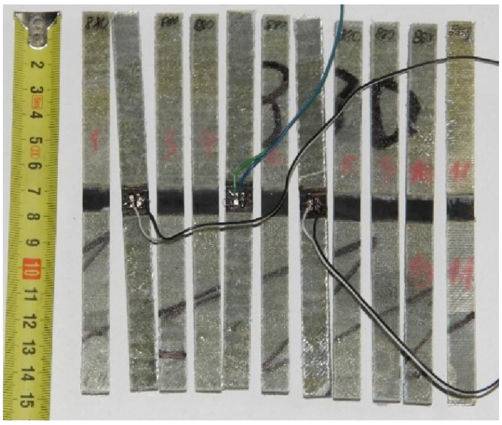
Test parameters are listed in Table 4.10. Figure 4.4. 0o direction compression test specimens and Figure 4.5 test setup respectively. Placing of DIC targets on specimen is shown in Figure 4.6. Test results are presented in Table 4.11 for Unipreg 100 g/m^2 and for Unipreg 200 g/m^2.

Table 4.10. Test parameters for 0^o 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

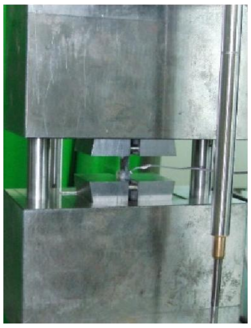


Unipreg 100 g/m^2 (874)



Unipreg 200 g/m^2 (880)

Figure 4.4. 0^o direction compression test specimens



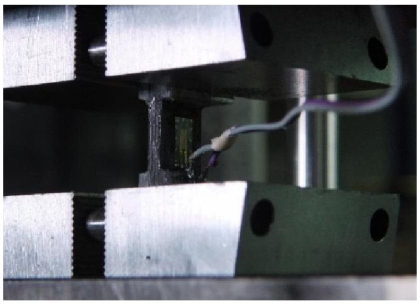


Figure 4.5. 0^o direction compression test setup

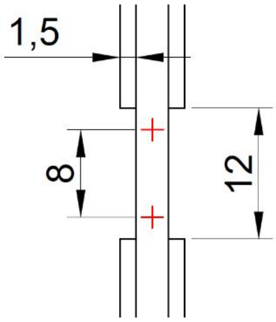


Figure 4.6. DIC targets setup to measure longitudinal deformation in compression test

Table 4.11. Compressive modulus and compressive strength of Unipreg 100 g/m^2 (0^o direction)

Specimen	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	*b*, mm	*h*, mm
1	-	-	622.9	9.93	1.72
2	-	-	539.8	9.69	1.93
3	-	-	320.4	10.36	2.11
4	-	110.10	577.6	10.34	2.27
5	-	113.03	574.4	10.28	2.4
6	-	107.84	510.2	10.13	2.51
7	-	103.71	493.2	10.13	2.54
8	-	107.53	338.5	10.31	2.56
9	-	91.43	428.1	10.21	2.55
10	97.61	91.43	423.6	10.24	2.53
11	107.61	100.22	545.8	10.33	2.45
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 4.12. Compressive modulus and compressive strength of Unipreg 200 g/m^2 (0^o direction)

Specimen label	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	*b*, mm	*h*, mm
1	-	123.77	788.98	10.31	2.65
2	114.26	116.19	629.19	10.39	2.62
3	-	118.00	566.17	10.4	2.63
4	-	137.14	610.11	10.25	2.63
5	118.39	130.70	913.96	10.38	2.63
6	-	107.61	893.16	10.63	2.63
7	120.16	117.91	680.19	10.37	2.64
8	-	114.89	1011.47	10.39	2.63
9	-	127.87	793.77	10.44	2.64
10	-	128.02	789.13	10.34	2.63
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		

4.3.2 90° direction compression test

Test parameters are listed in Table 4.13. Figure 4.7 shows test specimens, Figure 4.8 test setup and Figure 4.9 DIC target placing for strain measurements. Test results are presented in for Unipreg 100 g/m^2 and in Table 4.15 for Unipreg 200 g/m^2.

Table 4.13. 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

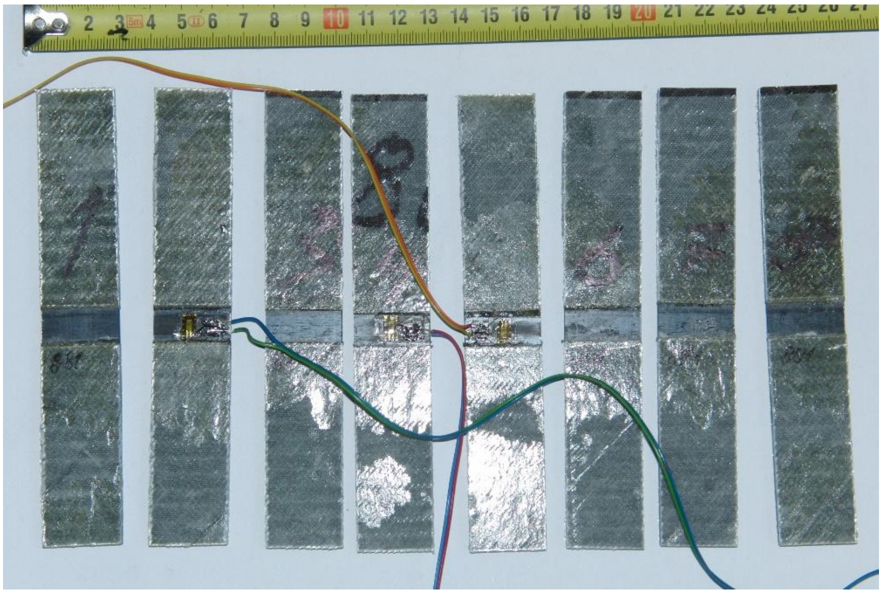

Figure 4.7. 90° direction compression test specimens

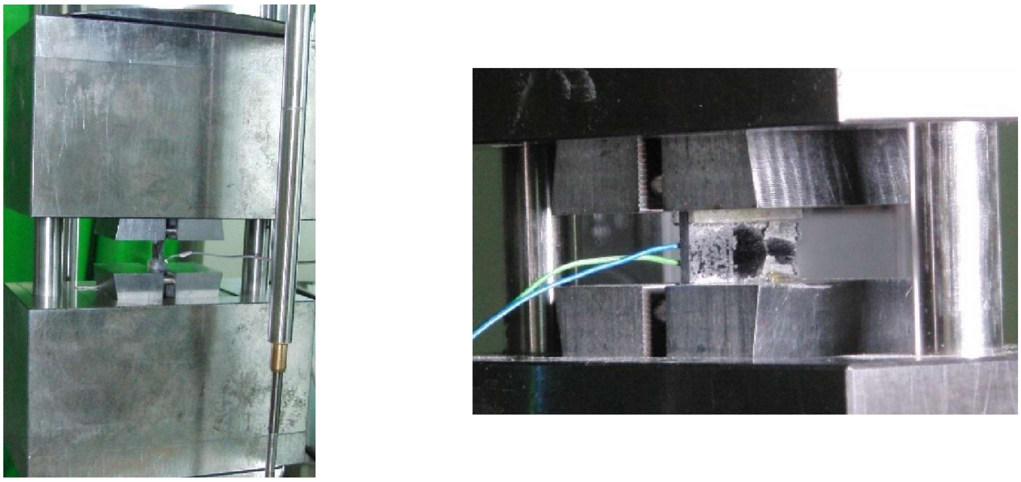

Figure 4.8. 90° direction compression test setup

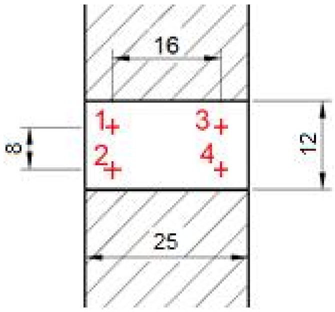

Figure 4.9. DIC targets setup to measure longitudinal deformation in 90° direction compression test

Table 4.14. Compressive modulus and compressive strength of Unipreg 100 g/m^2 (90^o direction)

Specimen	E^C (SG), GPa	E^C (DIC), GPa	R^C, MPa	*b*, mm	*h*, mm
1	-	6.96	148.75	24.95	2.3
2	8.40	7.63	143.77	24.98	2.26
3	-	7.12	137.73	24.99	2.27
4	7.57	5.94	123.76	24.96	2.24
5	7.13	6.31	113.54	24.97	2.22
6	-	6.32	136.46	25.01	2.3
7	-	8.49	148.05	24.87	2.19
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 4.15. 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
1	-	-	-	25.33	2.63
2	-	6.52	146.24	25.29	2.63
3	7.78	8.60	141.98	25.31	2.6
4	-	7.63	129.96	25.36	2.62
5	7.99	8.12	130.43	25.38	2.61
6	7.03	-	140.28	25.31	2.66
7	-	7.27	-	25.28	2.69
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		

4.4 45° direction shear test

Test parameters are listed in Table 4.16. Test results are presented in Table 4.17 for Unipreg 100 g/m^2 and in Table 4.18 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 4.10. Figure 4.11 presents test specimens.

Table 4.16. 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 $\pm$ 20 $\mu\varepsilon$

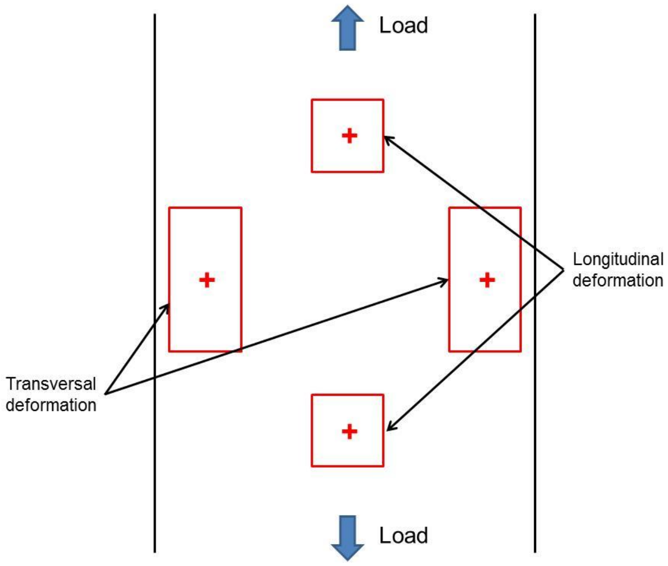
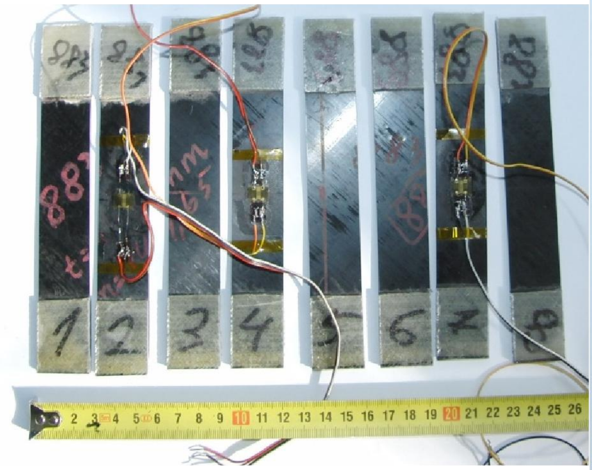
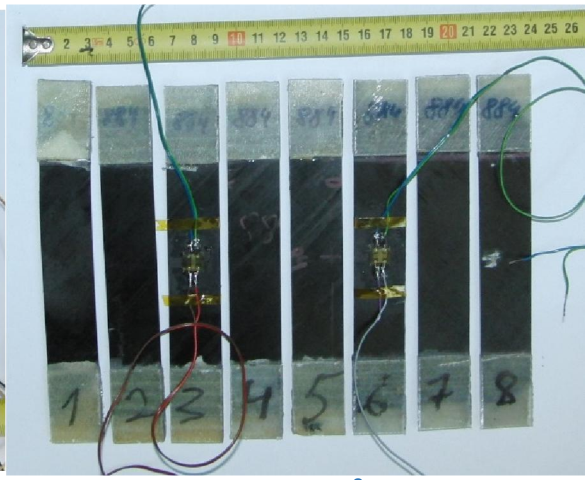


Figure 4.10. DIC target placing on shear specimen



Unipreg 100 g/m^2 (883)



Unipreg 200 g/m^2 (884)

Figure 4.11. 45^o direction shear test specimens

4.4.1 List of used equations

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

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

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

$$\gamma_{12}{}^m = \min\begin{cases} \gamma_{12} at\, 5\% \\ \gamma_{12}\ at\ \tau_{12}{}^m \end{cases}$$

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

4.4.2 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 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."

4.4.3 Shear test results

Table 4.17. Shear chord modulus of elasticity and maximum in-plane shear stress for Unipreg 100 g/m^2.

Specimen	G_{12}^{chord} (SG), GPa	G_{12}^{chord} (DIC), GPa	τ_{12}^{m}, MPa	*b*, mm	*h*, mm
1	-	6.02	37.55	25.16	1.177
2	6.33	5.81	55.55	25.01	1.15
3	-	5.81	58.72	25.15	1.163
4	5.53	-	58.52	25.19	1.163
5	-	6.33	53.30	25.1	1.17
6	-	-	40.13	25.08	1.17
7	6.35	6.00	59.92	25.04	1.17
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		

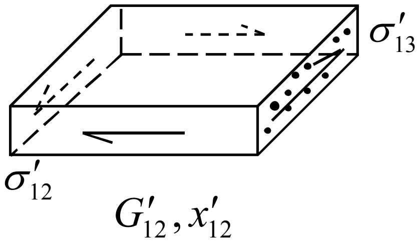
Table 4.18. Shear chord modulus of elasticity and maximum in-plane shear stress for Unipreg 200 g/m^2.

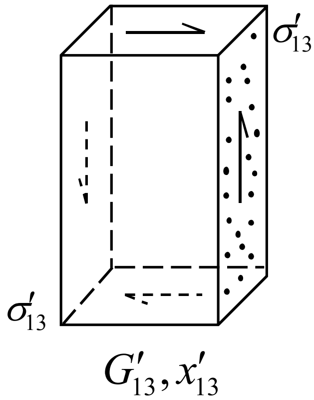
Specimen	G_{12}^{chord} (SG), GPa	G_{12}^{chord} (DIC), GPa	τ_{12}^{m}, MPa	*b*, mm	*h*, mm
1	-	3.54	26.38	25.04	1.48
2	-	4.48	67.33	25.14	1.467
3	4.74	3.96	30.38	25.18	1.517
4	-	-	-	25.11	1.51
5	4.66	4.10	66.41	24.99	1.49
6	4.57	4.10	26.15	25.06	1.493
7	-	4.09	66.52	25.38	1.49
8	-	4.09	64.89	25.27	1.49
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		

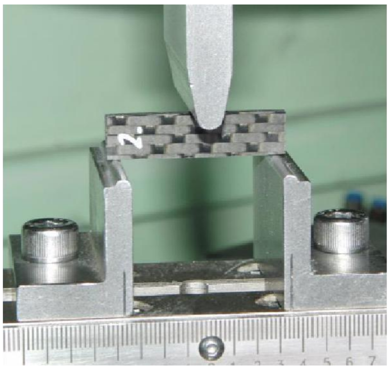
4.5 Three point flexural test

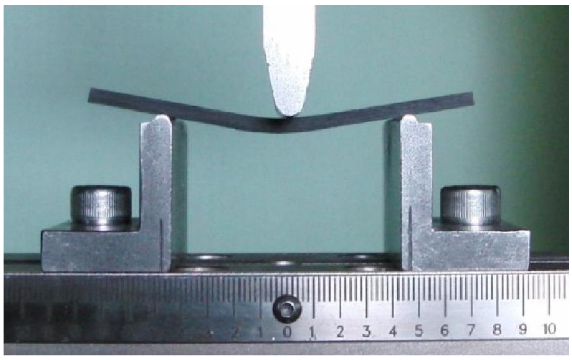
4.5.1 Definition of in-plane shear modulus

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

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

$$w_1 = s_1 \cdot h_0$$

$$w_2 = s_2 \cdot h_0$$

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

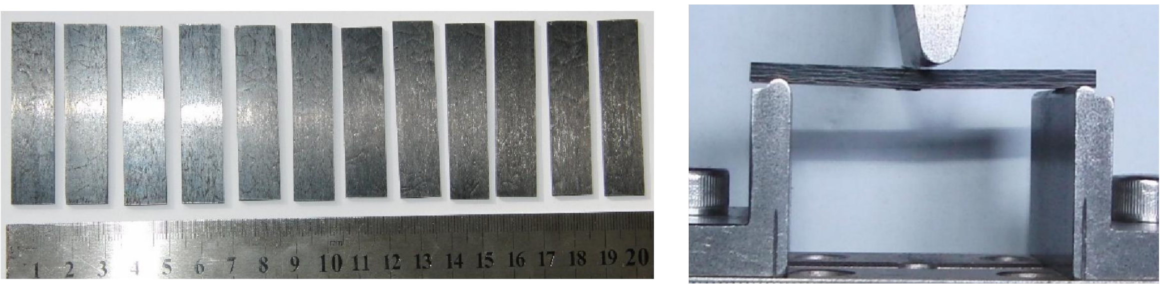
4.5.2 Test parameters are listed in

Table 4.19. Test results are presented in for Unipreg 100 g/m^2 and in Table 4.21 for Unipreg 200 g/m^2. Figure 4.12 presents test specimens and test setup. Placing of DIC targets for shear modulus estimation shown in Figure 4.13.

4.5.3 Flexural test results

Table 4.19. 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 4.12. 3 point flexure test specimens (a) and test setup (b)

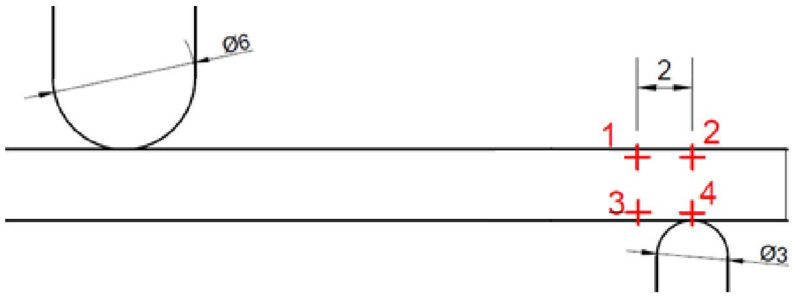


Figure 4.13. DIC targets setup to measure the extension. DIC targets were placed on specimen as shown in picture. Two extensometers were meashuring extension between targets 1 and 4, and between targets 2 and 3.

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Table 4.20. Flexure modulus, flexure shear modulus and flexure strength of Unipreg 100 g/m^2

Specimen	E^f, GPa	G_{13}^f, GPa	R^f, MPa	b, mm	h, mm
1	116.24	0.32	1540.25	13.16	1.43
2	114.67	0.51	1531.75	13.06	1.45
3	112.21	0.50	1439.79	13.13	1.47
4	114.42	0.56	1426.73	13.2	1.47
5	114.26	0.56	1376.74	13.23	1.43
6	111.17	0.50	1476.27	13.1	1.45
7	106.01	0.37	1221.26	13.18	1.48
8	111.23	0.33	1411.33	13.18	1.48
9	112.82	0.32	1510.72	12.85	1.43
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		

Table 4.21. Flexure modulus, flexure shear modulus and flexure strength of Unipreg 200 g/m^2

Specimen	E^f, GPa	G_{13}^f, GPa	R^f, MPa	b, mm	h, mm
1	100.34	0.84	1156.01	12.40	2.58
2	99.76	0.88	1183.30	12.29	2.56
3	104.91	1.63	1277.66	12.22	2.50
4	98.63	0.95	1117.94	12.07	2.53
5	108.53	0.96	1222.74	12.25	2.44
6	112.42	0.84	1251.19	12.39	2.39
7	105.12	1.11	1194.25	12.32	2.43
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		

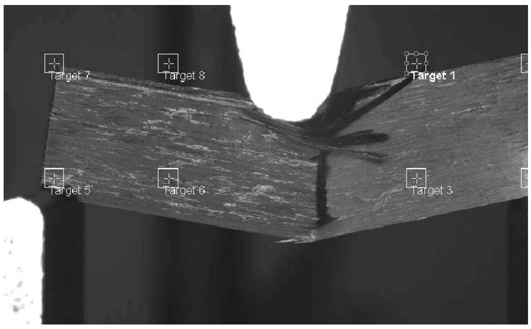
4.6 Short beam test for shear with coupon on its lateral side

Test parameters are listed in Table 4.22. Test results are presented in Table 4.23 for Unipreg 100 g/m^2 and in

Table 4.24 for Unipreg 200 g/m^2. Figure 4.14 presents test specimens and test setup. Placing of DIC targets for shear modulus estimation shown in Figure 4.15.

Table 4.22. 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 4.14. Specimens (a) and test setup (b) of short beam shear test with coupon on its lateral side

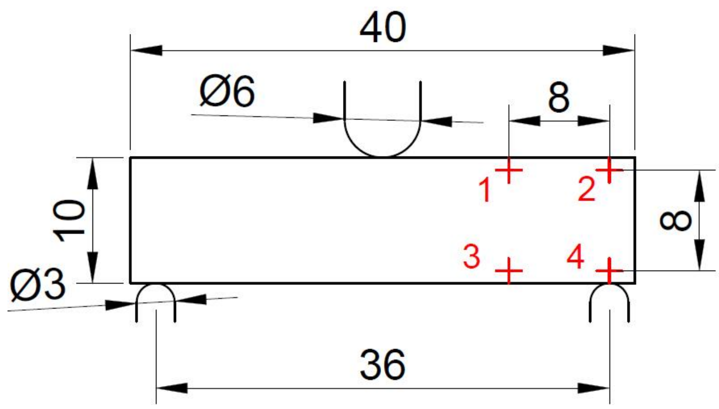


Figure 4.15. DIC targets were placed on specimen as shown in picture. Two extensometers were measuring extension between targets 1 and 4, and between targets 2 and 3.

Table 4.23. Lateral short beam flexure shear modulus and shear strength of Unipreg 100 g/m^2

Specimen	G_{12}^{f} ,GPa	ν_{12}^{f} , MPa	*b*, mm	*h*, mm
1	2.75	194.27	1.49	10.01
2	3.67	179.37	1.49	10.12
3	3.13	262.81	1.18	10.04
4	2.36	187.89	1.44	9.88
5	2.30	179.61	1.46	9.85
6	2.78	203.50	1.44	10.12
7	2.65	227.79	1.44	10.04
8	3.47	223.52	1.46	9.98
9	3.83	203.18	1.47	10.07
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		

Table 4.24. Lateral short beam flexure shear modulus and shear strength of Unipreg 200 g/m^2

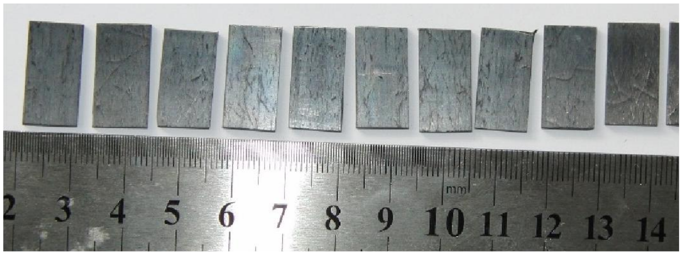
Specimen	G_{12}^f ,GPa	ν_{12}^f , MPa	*b*, mm	*h*, mm
1	4.20	206.97	10.42	2.92
2	3.44	240.33	10.29	2.93
3	4.26	222.73	10.27	2.93
4	4.34	225.95	10.36	2.87
5	3.29	253.86	10.42	2.86
6	3.77	252.89	10.3	2.94
7	4.35	241.65	10.08	3.01
8	3.37	242.38	10.45	2.98
9	3.09	196.24	10.42	2.99
10	2.98	250.97	10.42	3.04
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		

4.7 Short beam test

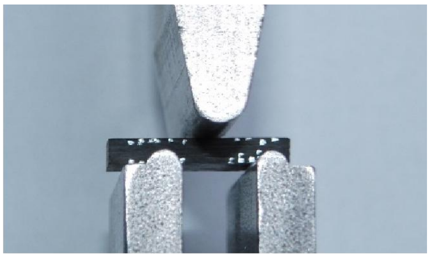
Test parameters are listed inTable 4.25. Test results are presented in Table 4.26 for Unipreg 100 g/m^2 and in Table 4.27 for Unipreg 200 g/m^2. Figure 4.16 presents test specimens and test setup. Placing of DIC targets for shear modulus estimation shown in Figure 4.17.

Table 4.25. 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 4.16. Specimens (a) and test setup (b) of short beam shear test

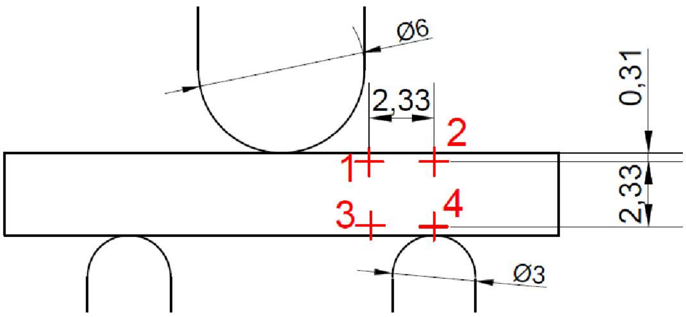


Figure 4.17. DIC targets were placed on specimen as shown in picture. Two extensometers were measuring extension between targets 1 and 4, and between targets 2 and 3.

Table 4.26. 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
1	2.48	699.99	10.20	1.49
2	2.84	695.90	10.22	1.49
3	2.45	656.04	10.18	1.49
4	2.03	655.09	10.16	1.47
5	2.74	613.34	10.09	1.48
6	2.38	621.54	10.09	1.47
7	2.26	637.04	10.11	1.49
8	2.39	640.54	10.11	1.48
9	2.90	685.64	10.16	1.46
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		

Table 4.27. Short beam flexure shear modulus and shear strength of Unipreg 200 g/m^2

Specimen	G_{13}, GPa	ν_{13}, MPa	*b*, mm	*h*, mm
1	2.77	2100.00	2.92	12.39
2	2.62	1878.00	2.91	12.41
3	2.91	1858.50	2.54	12.16
4	2.83	2129.75	2.44	12.25
5	2.37	2232.56	2.39	12.25
6	2.47	1978.47	2.43	12.32
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		

4.8 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

<table>
<tr><th rowspan="2" colspan="2">Property</th><th colspan="9">Mean values</th></tr>
<tr><th colspan="3">Unipreg 100 g/m²</th><th colspan="3">Unipreg 200 g/m²</th><th colspan="3">Unipreg 200 g/m² (high stiffness)</th></tr>
<tr><td rowspan="2">E^t, GPa</td><td>0°</td><td>122.69</td><td>115.91</td><td>75.52</td><td>124.09</td><td>122.55</td><td>73.33</td><td>164.62</td><td>164.11</td><td>108.37</td></tr>
<tr><td>90°</td><td>8.39</td><td>7.79</td><td>8.91</td><td>6.43</td><td>6.63</td><td>7.86</td><td colspan="3">-</td></tr>
<tr><td rowspan="2">E^c, GPa</td><td>0°</td><td>103.91</td><td colspan="2">102.77</td><td>117.60</td><td colspan="2">121.1</td><td colspan="3">-</td></tr>
<tr><td>90°</td><td>7.70</td><td colspan="2">7.00</td><td>7.60</td><td colspan="2">7.84</td><td colspan="3">-</td></tr>
<tr><td colspan="2">E^f, GPa</td><td colspan="3">112.83</td><td colspan="3">106.03</td><td colspan="3">-</td></tr>
<tr><td colspan="2">G_{12}^{chord}, GPa</td><td>6.07</td><td colspan="2">5.78</td><td>4.66</td><td colspan="2">4.05</td><td colspan="3">-</td></tr>
<tr><td colspan="2">G_{12}, GPa</td><td colspan="3">3.00</td><td colspan="3">3.71</td><td colspan="3">-</td></tr>
<tr><td colspan="2">G_{13}, GPa</td><td colspan="3">2.45</td><td colspan="3">2.77</td><td colspan="3">-</td></tr>
<tr><td>μ</td><td>0°</td><td colspan="3">0.33</td><td colspan="3">0.37</td><td colspan="3">0.38</td></tr>
<tr><td rowspan="2">R^t, MPa</td><td>0°</td><td colspan="3">1466</td><td colspan="3">1539</td><td colspan="3">2037</td></tr>
<tr><td>90°</td><td colspan="3">46</td><td colspan="3">41</td><td colspan="3">-</td></tr>
<tr><td rowspan="2">R^c, MPa</td><td>0°</td><td colspan="3">481</td><td colspan="3">752</td><td colspan="3">-</td></tr>
<tr><td>90°</td><td colspan="3">138</td><td colspan="3">141</td><td colspan="3">-</td></tr>
<tr><td colspan="2">τ_{12}^m, MPa</td><td colspan="3">53</td><td colspan="3">50</td><td colspan="3"></td></tr>
<tr><td colspan="2">R^f, MPa</td><td colspan="3">1427</td><td colspan="3">1217</td><td colspan="3">-</td></tr>
<tr><td colspan="2">v_{12}, MPa</td><td colspan="3">207</td><td colspan="3">233</td><td colspan="3">-</td></tr>
<tr><td colspan="2">v_{13}, MPa</td><td colspan="3">654</td><td colspan="3">2009</td><td colspan="3">-</td></tr>
</table>

5 Mechanical properties of honeycomb core

5.1 Introduction for honeycomb testing

Aluminium honeycomb materials were delivered unexpanded, therefore special desk (Figure 5.1.) for honeycomb expansion was prepared. Specimens were cut out from expanded honeycomb by using sharp knife. Totally six types of honeycomb materials were used (Table 5.1.). Mechanical characterisation of honeycomb cores were based on three tests (Table 5.2.).

Figure 5.1. Desk for honeycomb expansion

Table 5.1. Honeycomb materials used in research

No:	thickness	cell size	foil thickness
	mm	mm	mm
1	10	6.4	0.0381
2	20	6.4	0.0381
3	10	3.2	0.0381
4	15	3.2	0.0381
5	20	3.2	0.0381
6	10	3.2	0.0178
7	15	3.2	0.0178
8	20	3.2	0.0178
9	20	6.4	0.0178
10	30	3.2	0.0178
11	30	6.4	0.0178

Table 5.2. Honeycomb core test matrix definition

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

5.2 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 × core thickness.

Test parameters are listed in

Table 5.3. In Figure 5.2. is shown test setup. For accurate strain measurements linear variable differential transformer (LVDT) system was used (Figure 5.3.). Test results are presented in Table 5.4.

Table 5.3. 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:	LVDT
Space between DIC targets	200 mm

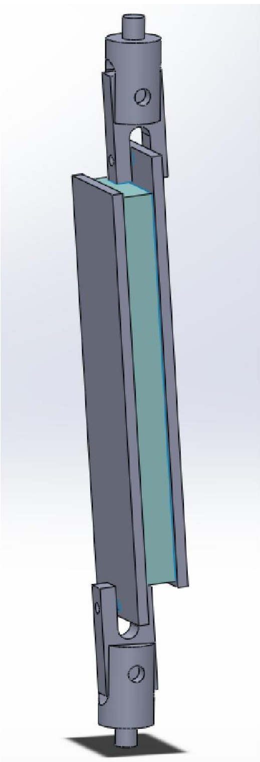


Figure 5.2. Plate shear test setup

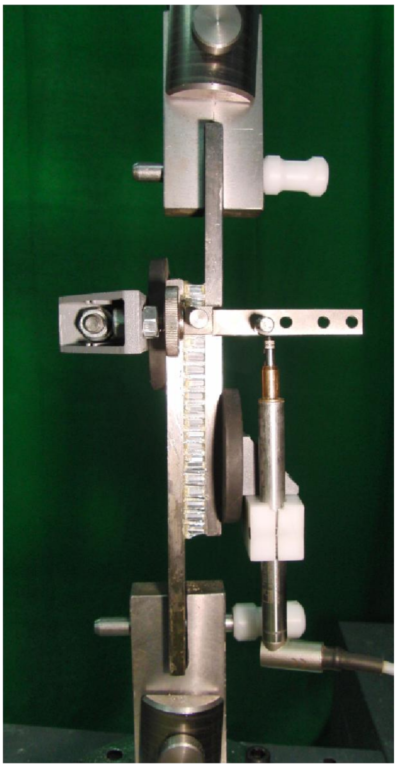


Figure 5.3. Test specimen with attached LVDT

Table 5.4. Plate shear strength and shear modulus

HC 3.2/10mm (thick foil)

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
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 (thick foil)

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

5.3 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 5.5. In Figure 5.4. is shown test setup. Test results are presented in Table 5.6. 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 5.5. 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

Figure 5.4. Flatwise compression test setup

Table 5.6. Core flatwise compressive chord modulus, ultimate flatwise compressive strength

HC 3.2/10mm (thick foil)

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 (thick foil)

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
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

HC 3.2/20mm (thick foil)

Specimen label	E_z^{fc}, GPa	F_z^{fcu} MPa	*b*, mm	*h*, mm
HC 3.2/20mm_1	0.86	3.76	50	50
HC 3.2/20mm_2	0.92	3.82	50	50
HC 3.2/20mm_3	0.90	3.80	50	50
HC 3.2/20mm_4	0.90	3.77	50	50
HC 3.2/20mm_5	1.02	4.06	50	50
Mean	**0.92**	**3.84**	**50**	**50**
SD	0.06	0.13	0	0
Median	0.90	3.80	50	50
Minimum	0.86	3.76	50	50
Maximum	1.02	4.06	50	50
CV	6.47	3.30	0	0
Mean+ 2 SD	1.04	4.09	50	50
Mean - 2 SD	0.80	3.59	50	50

HC 6.4/20mm (thick foil)

Specimen label	F_z^{fcu} MPa	*b*, mm	*h*, mm
HC 6.4/20mm_1	2.98	75	75
HC 6.4/20mm_2	3.08	75	75
HC 6.4/20mm_3	3.24	75	75
HC 6.4/20mm_4	3.34	75	75
HC 6.4/20mm_5	3.34	75	75
HC 6.4/20mm_6	3.2	75	75
HC 6.4/20mm_7	3.23	75	75
HC 6.4/20mm_8	3.14	75	75
Mean	**3.19**	**75**	**75**
SD	0.12	0	0

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Median	3.22	75	75
Minimum	2.98	0	0
Maximum	3.34	75	75
CV	3.89	0	0
Mean+ 2 SD	3.44	75	75
Mean - 2 SD	2.95	75	75

5.4 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 5.7. In Figure 5.5. is shown test setup. Test results are presented in

Table 5.8.

Table 5.7. 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

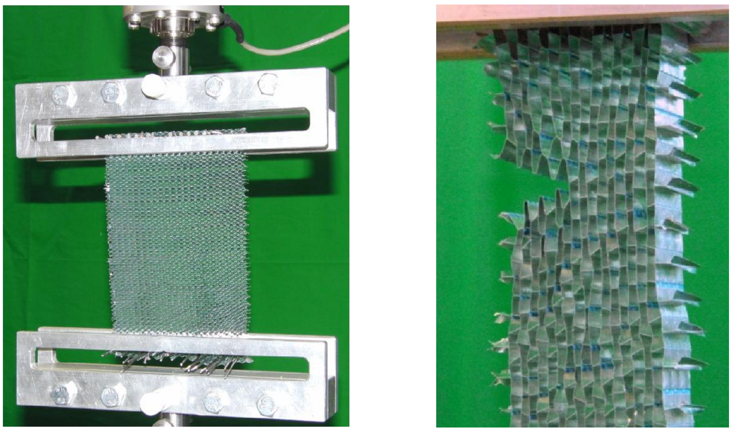


Figure 5.5. Tensile node bond strength test setup and typical failure

Table 5.8. Core tensile node bond strength

HC 6.4/20mm (thick foil)

Specimen label	σ_{node} MPa	*b*, mm	*h*, mm
HC 6.4/20mm_1	0.176	120	200
HC 6.4/20mm_2	0.199	120	200
HC 6.4/20mm_3	0.192	120	200
HC 6.4/20mm_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

HC 3.2/10mm (thick foil)

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

6 Bonding strength of adhesives

6.1 Climbing drum peel test

Climbing drum peel test can be carried out by using ASTM D1781 or EN2243 DIN53295 test methods. The climbing drum peel test should be performed on sandwich panels with relatively thin skins. The maximum thicknesses should be approximately 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. Test parameters of climbing drum peel test are gathered in Table 6.1., test set-up shown in Figure 6.1. and specimens in Figure 6.2. This test had critical impact on choosing appropriate adhesive for whole research. Results are presented in Table 6.2. numerically and in Figure 6.3. graphically. It is obvious that absolute leader is epoxy based *Permabond ET538* adhesive and it is the only one strong enough to cause cohesive failure of skin plate which indicates that skin to honeycomb bond is stronger than skin's interlaminar bonds. Difference between cohesive and adhesive failure shown in Figure 6.4.

Table 6.1. Test parameters of climbing drum peel tests

Testing method	ASTM D1718
Equipment	ZWICK Z100
Operator ID	Guntis Japins
Test type	Climbing drum peel
Crosshead movement speed	25 mm/min

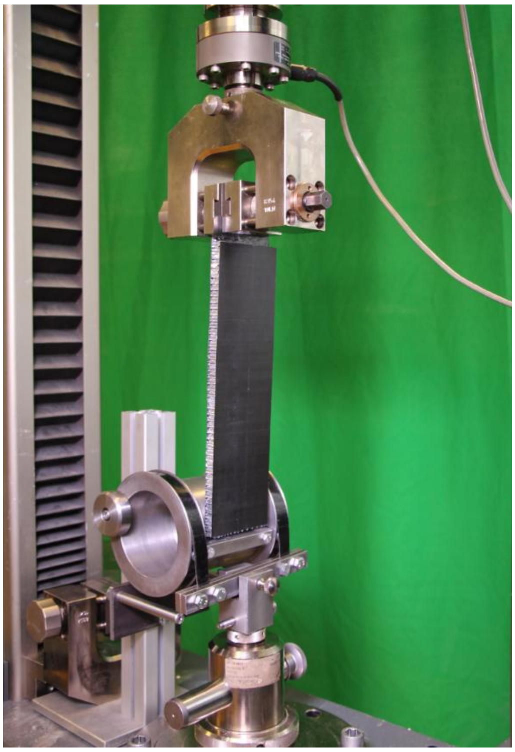


Figure 6.1. Climbing drum peel test setup

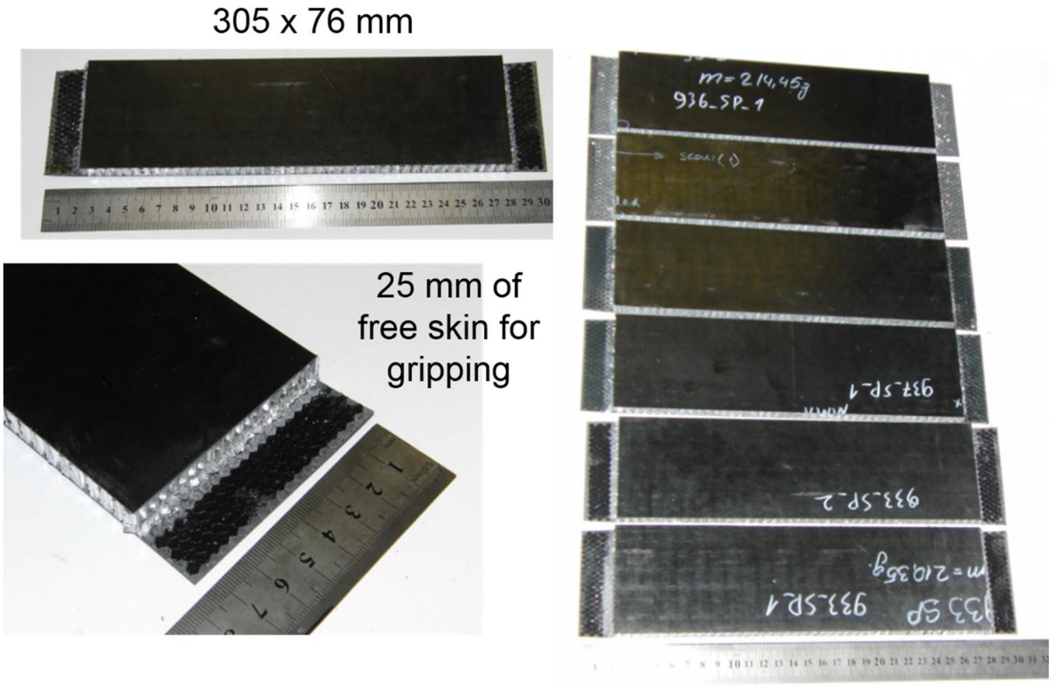


Figure 6.2. Specimens for climbing drum peel tests

Table 6.2. Peel strength for different adhesives

Specimen	Adhesive	Skin thickness, mm	Honeycomb	Peel torque (T_p) N·m/m
1	PU UT-100	0.26	3.2/10mm	21.9
2		0.27		23.5
			Mean peel strength	**22.7**
1	PU18	0.26	3.2/10mm	14.2
2		0.26		12.2
			Mean peel strength	**13.2**
1	Permabond ET538	0.27	3.2/10mm	60.3
2		0.26		58.2
			Mean peel strength	**59.2**
1	VM100 Black	0.26	3.2/10mm	5.1
2		0.26		6.7
			Mean peel strength	**5.9**

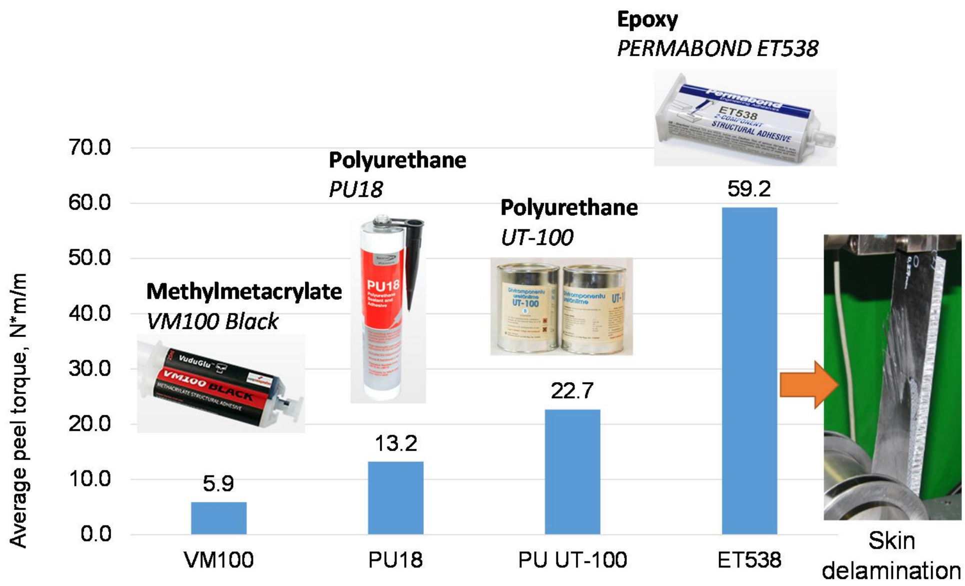
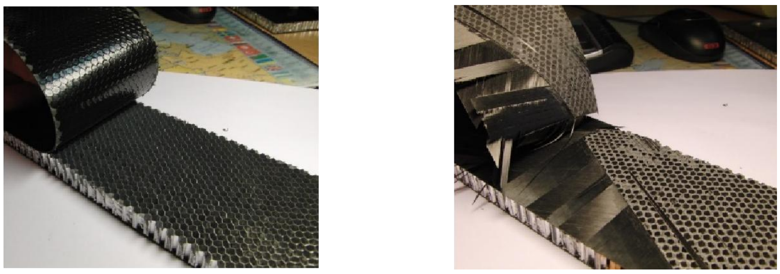


Figure 6.3. Peel strength for different adhesives



a b

Figure 6.4. Skin adhesive (a) and cohesive (b) peel

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

7.1 Introduction in testing of sandwich panels

There are several tests to determinate properties of honeycomb sandwich panels. Flatwise tension and climbing drum peel test are good ways to evaluate the integrity of a honeycomb sandwich panel and how well the skins are bonded to the honeycomb. Other tests which characterise sandwich panels are: flatwise compression, plate shear, flexural shear, edgewise compression and long beam flexure. Table 7.1. contains tests methods used to investigate CFRP skin and aluminium honeycomb sandwich panels.

Table 7.1. Test methods applied for sandwich panels

Coupons	Properties	Standard
Flatwise compression	F_z^{fcu}, E_z^{fc}, $\sigma_z^{fc0.02}$	ASTM C365
Flatwise tension	F_z^{ftu}	ASTM C297
Climbing drum peel test	T_p	ASTM D1781
Flatwise compression-tension	F_z^{fcu}, E_z^{fc}, F_z^{ftu}	custom from ASTM C365, C297

7.2 Flatwise compression test

Test parameters are listed in Table 7.2. In Figure 5.4. is shown test setup. Test results are presented in Table 7.3.

Table 7.2. Test parameters of flatwise compression tests

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

Table 7.3. Core flatwise compressive chord modulus, ultimate flatwise compressive strength

Specimen	Adhesive's trade name	Honeycomb	E_z^{fc}, GPa	F_z^{fcu} MPa
1	Pearn STC	3.2/10mm (thick foil)	-	4.35
2		3.2/10mm (thick foil)	-	3.67
		Mean	-	4.01
		SD	-	0.48
		Median	-	4.01
		Minimum	-	3.67

Maximum	-	4.35
CV	-	11.99
Mean+ 2 SD	-	4.97
Mean - 2 SD	-	3.05

Specimen	Adhesive's trade name	Honeycomb	E_z^{fc}, GPa	F_z^{fcu} MPa
1	PU 18	3.2/10mm (thick foil)	2.58	2.73
2		3.2/10mm (thick foil)	2.3	2.8
3		3.2/10mm (thick foil)	2.17	2.45
		Mean	2.35	2.66
		SD	0.21	0.19
		Median	2.30	2.73
		Minimum	2.17	2.45
		Maximum	2.58	2.80
		CV	8.92	6.96
		Mean+ 2 SD	2.77	3.03
		Mean - 2 SD	1.93	2.29

Specimen	Adhesive's trade name	Honeycomb	E_z^{fc}, GPa	F_z^{fcu} MPa
1	ET538	6.4/20mm (thin foil)	0.66	0.21
2		6.4/20mm (thin foil)	0.8	0.2
3		6.4/20mm (thin foil)	0.76	0.16
4		6.4/20mm (thin foil)	0.71	0.13
5		6.4/20mm (thin foil)	0.66	0.13
6		6.4/20mm (thin foil)	0.78	0.16
7		6.4/20mm (thin foil)	0.234	3.56
		Mean	0.66	0.65
		SD	0.19	1.28
		Median	0.71	0.16
		Minimum	0.23	0.13
		Maximum	0.80	3.56
		CV	29.63	197.47
		Mean+ 2 SD	1.05	3.22
		Mean - 2 SD	0.27	-1.92

Specimen	Adhesive's trade name	Honeycomb	E_z^{fc}, GPa	F_z^{fcu} MPa
1	ET538	3.2/20mm (thin foil)	0.476	2.04
2	ET538	3.2/20mm (thin foil)	0.582	2.16
3	ET538	3.2/20mm (thin foil)	0.604	2.1
4	ET538	3.2/20mm (thin foil)	0.63	2.33
5	ET538	3.2/20mm (thin foil)	0.574	2.06
		Mean	0.57	2.14
		SD	0.06	0.12
		Median	0.58	2.10
		Minimum	0.48	2.04
		Maximum	0.63	2.33
		CV	10.21	5.46
		Mean+ 2 SD	0.69	2.37
		Mean - 2 SD	0.46	1.90

7.3 Flatwise tension test

In this method sandwich construction is subjected to 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 7.4., Figure 7.1. shows test setup. Test results are presented inTable 7.5.

Table 7.4. 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

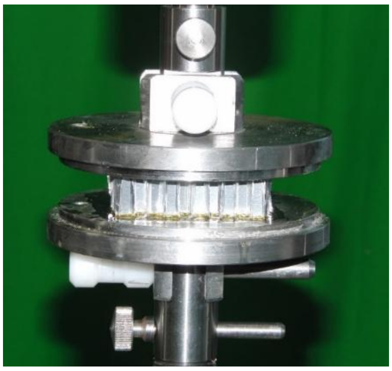


Figure 7.1. Flatwise tension test setup

Table 7.5. Results of ultimate flatwise tensile strength

Specimen	Adhesive's trade name	Honeycomb	F_z^{ftu}, MPa	Failure type
1	Pearn STC	3.2/10mm (thick foil)	0.476	Facing to core adhesive failure
2		3.2/10mm (thick foil)	0.582	
		Mean	**1.06**	
		SD	0.37	
		Median	1.06	
		Minimum	0.79	
		Maximum	1.32	
		CV	35.52	
		Mean+ 2 SD	1.80	
		Mean - 2 SD	0.31	

Specimen	Adhesive's trade name	Honeycomb	F_z^{ftu}, MPa	Failure type
1	PU 18	3.2/10mm (thick foil)	1.01	Facing to core adhesive failure
2		3.2/10mm (thick foil)	0.63	
3		3.2/10mm (thick foil)	0.41	
4		3.2/10mm (thick foil)	0.63	
5		3.2/10mm (thick foil)	0.69	
		Mean	**0.67**	
		SD	0.22	
		Median	0.63	
		Minimum	0.41	
		Maximum	1.01	
		CV	32.06	
		Mean+ 2 SD	1.11	
		Mean - 2 SD	0.24	

Specimen	Adhesive's trade name	Honeycomb	F_z^{ftu}, MPa	Failure type
1	Permabond ET538	3.2/10mm (thick foil)	5.57	Inappropriate facing to steel block failure
2		3.2/10mm (thick foil)	5.85	
3		3.2/10mm (thick foil)	5.33	
4		3.2/10mm (thick foil)	6.17	
5		3.2/10mm (thick foil)	5.51	
		Mean	**5.69**	

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SD	0.33
Median	5.57
Minimum	5.33
Maximum	6.17
CV	5.78
Mean+ 2 SD	6.34
Mean - 2 SD	5.03

8 Residual strength estimation

8.1 Variables

A vital necessity before manufacturing panels and planning test matrix was to determine variables to be investigated. Reviewing literature was found that damage tolerance is affected by a multitude of factors from panel construction to boundary conditions. These factors could be divided in two groups: intrinsic and extrinsic. Table 8.1. summarizes all intrinsic and extrinsic variables mentioned in other researches.

Table 8.1. Main intrinsic and extrinsic variables in damage tolerance tests

Influence on damage tolerance	Intrinsic variables	Extrinsic variables
Have been investigated in current research	skin layup skin thickness honeycomb cell size honeycomb thickness honeycomb wall thickness	indenter diameter impact type damage size, impact energy
Have not been investigated in current research	specimen's dimensions skin and core materials fiber type matrix type fiber volume	indenter stiffness indenter shape temperature specimen support conditions indenter geometry loading speed impact location drop-weight

8.2 Definition of barely visible damage

8.2.1 Definition of appropriate damage size

There is need to set reasonable range of damage sizes, which is based on specific sandwich panel properties. During literature review was found that smallest damage could be defined as hardly detectable by unarmed eye. In opposite, the highest energy threshold could the border behind which cracks in the skin. Every author used own criteria of BVID estimation, like dent depth, impact energy, drop height and others. Use of dent depth only as a measure of the extent of damage in an impacted structure might not always be reliable or realistic [1], although this method is suitable for quasi-static indentation tests, which is proven by other researchers. For example, as BVID criteria Czabaj et al. [2] used load and permanent depth, McGowan et al. [3] used dent depth. In drop-weight impact is quite hard to control specific indentation depth, so the popular criteria for damage size is impact energy, for example Klaus et al. [4] used this approach.

Three different damage sizes for each method were defined. For quasi-static indentation tests damage size was controlled by the depth of the indent, which was 1 mm, 1.5 mm, and 2 mm. Unfortunately in some cases rupture occurred near 2 mm indentation (Table 8.2.), which points to that 2 mm is possibly to much. In Figure 8.1. rapid force fall indicates about skin cracking. For low velocity impact as damage criteria was taken an impact energy, with lowest value 0.3 J, which is minimal possible to be set on machine. Upper limit for impact energy was 0.7 for 20 mm diameter indenter and 1 J for 150 mm diameter indenter. On some specimens impact with 20 mm diameter indenter and impact energy of 0.7 J caused skin cracks. This became a reason not to increase energy anymore for 20 mm diameter indenter. All cases of cracked skins during impact tests are shown in Table 8.3. For 150 mm indenter upper impact energy was increased to 1 J, because its radius is larger and energy distributes on larger surface, preventing appearance of larger stress. Main artificial damage introduction types and sizes are gathered in diagram (Figure 8.2.)

Interesting to notice, that skin cracks occurred mostly on four ply skins. Two ply skins at the same indentation depth didn't cracked (in Table 8.2. and Table 8.3. highlighted in bold).

Table 8.2. Quasi static indentation. Specimens with unacceptable failure mode – skin cracked during indentation

Specimen ID	Layup	Honeycomb	Indenter ∅, mm	Indentation threshold, mm	Failure
ESA_045_4	[-60/+60/0]	3.2/20mm	20	2	Dent/crack
ESA_032_1	[0/-60/+60/0]			2	Dent/crack
ESA_032_2				2	Dent/crack
ESA_034_6		6.4/30mm		2	Dent/invisible crack
ESA_041_4, ESA_041_5	**[90/0]**	**3.2/20mm**	**20**	**2**	**Dent**

Table 8.3. Low velocity drop-weight impact. Specimens with unacceptable failure mode – skin cracked during impact

Specimen ID	Layup	Honeycomb	Indenter ∅, mm	Impact energy, J	Failure
ESA_029_3	[0/-60/+60/0]	3.2/20mm	20	0.50	Dent/skin crack
ESA_031_3					Dent/skin crack
ESA_030_2				0.60	Dent/skin crack
ESA_030_3					Dent/skin crack
ESA_029_6				0.70	Dent/skin crack
ESA_031_5					Dent/skin crack
ESA_031_6					Dent/skin crack
ESA_036_5	[-60/+60/0]	6.4/30mm			Dent/skin crack
ESA_036_6					Dent/skin crack
ESA_044_3	**[90/0]**	**3.2/30mm**		**0.70**	**Dent**

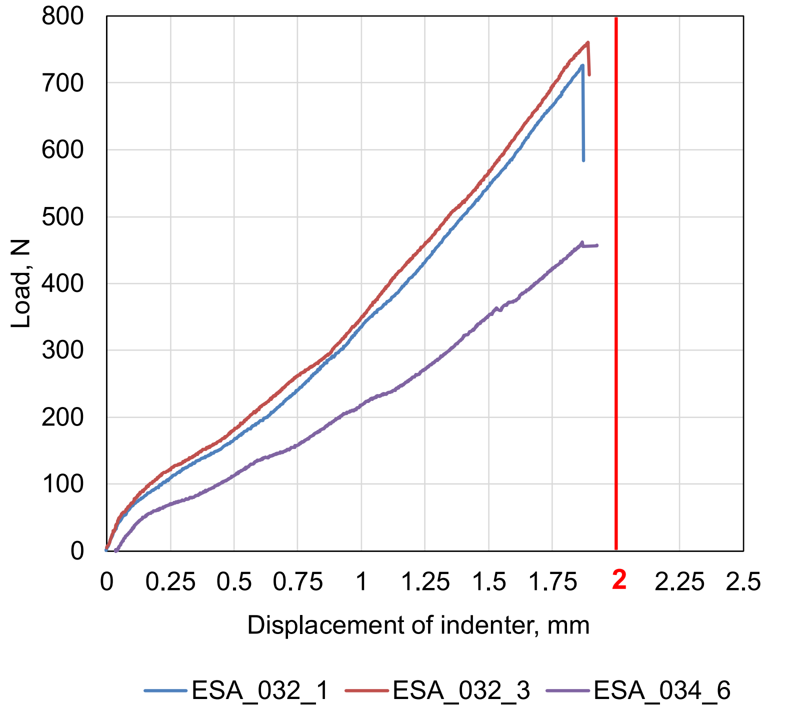

Figure 8.1. Quasi-static indentation load/displacement curves

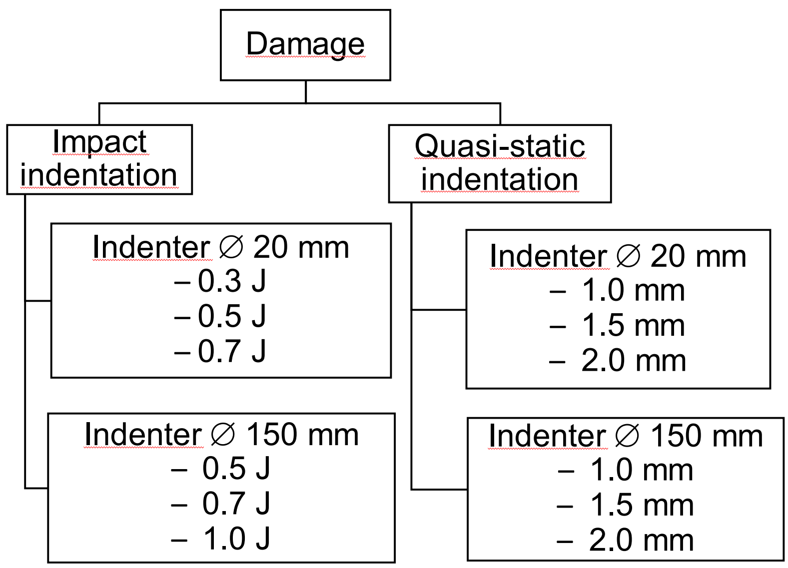

Figure 8.2. Main artificial damage introduction types and sizes

8.3 Damage introduction

8.3.1 Basic parameters and indenters for damage introduction

Artificial damage introduction in sandwich panel was carried out by using two alternative methods: quasi-static indentation and low velocity drop-weight impact. Impact test is more close to real accidental dropping of an object on panel, but quasi-static indentation have one significant advantage instead – it can be easier simulated with numerical model. As found in literature review, most commonly used are hemispherical indenters. Most popular indenter diameters were are 12.7 mm and 25.4 mm, furthermore the smallest one was 5.25 mm and largest – 76.2 mm.

Hemispherical indenters also used in both quasi-static indentation and low velocity drop-weight impact tests. Test parameters of damage introduction tests are gathered in Table 8.4. In order to compare the influence of indenter's diameter on damage tolerance, two different diameter indenters were used in the tests (Figure 8.3).

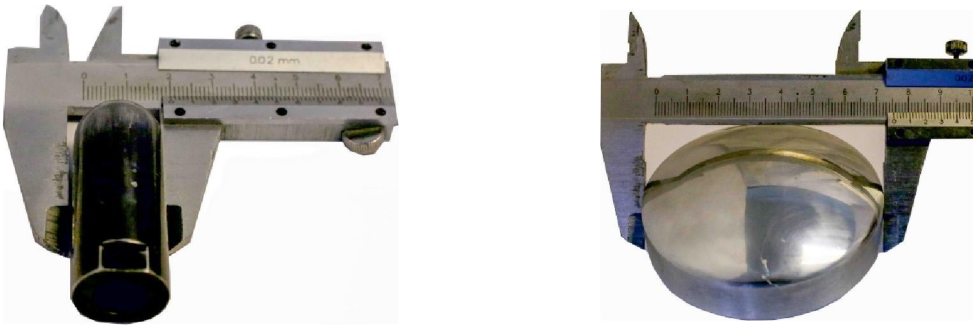

Figure 8.3. 20 mm and 150 mm diameter indenters used in quasi-static and low velocity drop-weight indentation

Table 8.4. Test parameters of quasi-static indentation tests

Quasi-static indentation	
Testing method	custom from ASTM D6264
Equipment	Instron E3000
Operator ID	Guntis Japins
Test type	quasi-static indentation test
Indent depth measurement by:	crosshead travel
Opposite side deflection measurement by:	Digital video gauge system
Testing speed, mm/min	1
Indenter type	Hemispherical
Indenter r diameters, mm	20; 150
Depth of indentation, mm	1; 1.5; 2
Low velocity impact	
Testing method	ASTM D7766 and custom from ASTM D7136
Equipment	Intron Dynatup 9250HV
Operator ID	Guntis Japins
Test type	impact test
Drop weight, kg	0.95 for 20 mm indenter, 0.99 for 150 mm indenter
Indenter type	Hemispherical
Indenter diameters, mm	20; 150
Impact energies, J	1; 1.5; 2

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8.3.2 Quasi-static indentation

Quasi-static indentation is performed on basic principles of ASTM D6264, where a flat, square composite plate is subjected to an out-of-plane, concentrated in one point force by pressing a hemispherical indenter into the surface. Specimen is placed on steel frame, with inner dimensions 125 x 75 mm, and fixed with 4 rubber pads (Figure 8.4.). Then hemispherical indenter is evenly pushed into specimen's skin with constant, 1 mm/min, speed until is reached predetermined threshold. In early tests was used load threshold, it means that test ended when indenter's load on panel reached specific value. Indenter's displacement is measured by testing machine as crosshead travel and deflection on opposite side is measured with digital video gauge system (Figure 8.5.). After making several tests it became clear that load controlled test is incorrect because panels with different skin layup and different honeycombs will also have different, incomparable damage sizes. For example: panel with two layer skin and honeycomb with cell size 6.4 mm will have significantly deeper dent than panel with four layer skin and honeycomb with cell size 3.2 mm at the same load.

8.3.3 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 indenter. Test setup is presented in Figure 8.6. For specimen fixation during impact also used the same frame as for quasi-static indentation (Figure 8.4.).

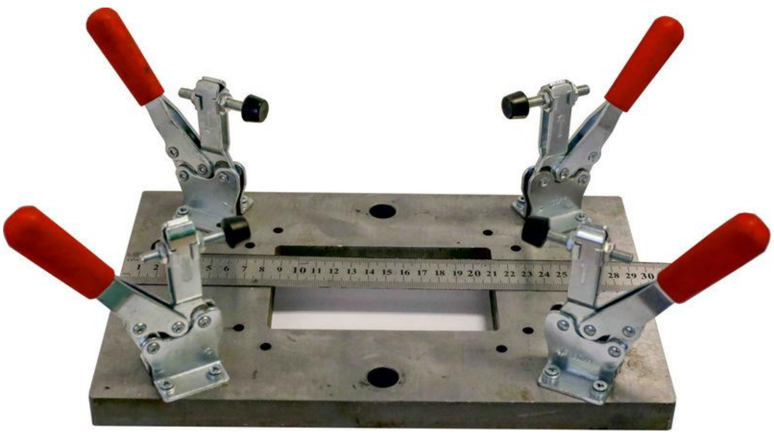

Figure 8.4. Specimen clamping device for impact and quasi-static tests according to ASTM D7136, D6264

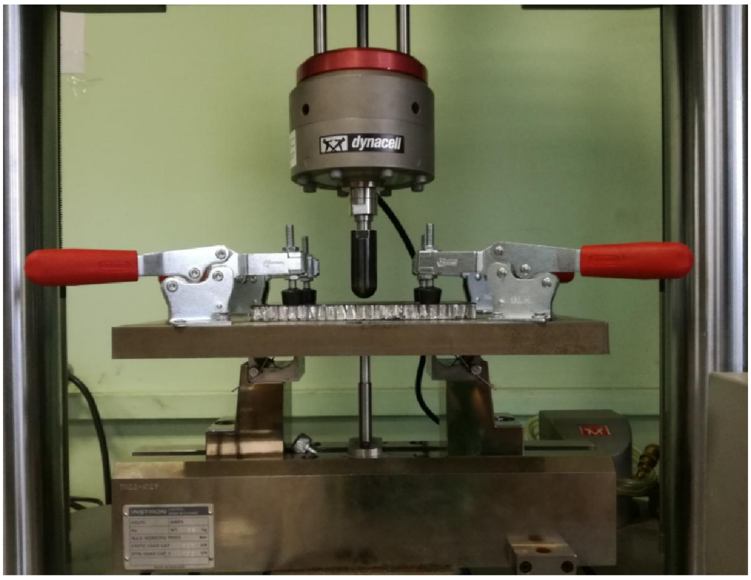

Figure 8.5. Quasi-static indentation test setup for artificial damage introduction

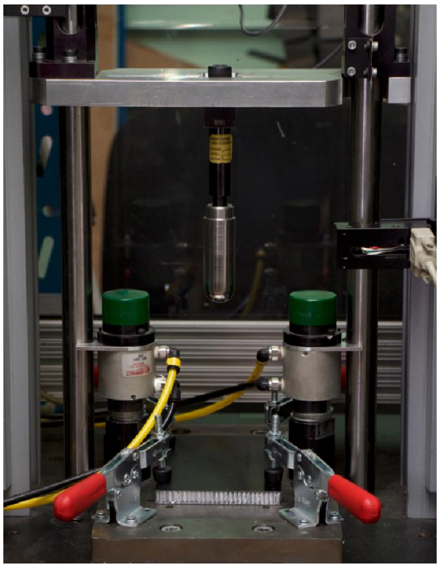

Figure 8.6. Low velocity drop-weight impact test setup for artificial damage introduction

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8.3.4 Damage introduction test matrix

There is need for great amount of specimens to cover all field of different variations of variables. In tables below are shown test matrixes of completed load controlled (Table 8.5.), debonding (Table 8.6.) and deflection controlled (Table 8.7.) indentations tests for all specimens. Number in shaded cells shows the number of specific specimens tested with specific conditions.

Table 8.5.Test matrix of completed load controlled indentations for panels with different constructions

		Lay-up																						
Honeycomb size, mm	Honeycomb height, mm	[90/0]								[-60/60/0]						[-60/0/+60]							[0/-60/+60/0]	
		Quasi-static, kN							NO DAMAGE	Quasi-static, kN														
		indenter Ø20					indenter Ø150			indenter Ø20						indenter Ø20			indenter Ø150				Ø20	Ø150
		75	100	125	500	750	500	1000		100	125	150	500	750	1000	500	750	1000	500	750	1000	1400	500	1400
3.2 thick foil	10															10	1	1	2	1	1	1		
	15												2	2	1									
	20				4	2	2	2								6							6	1
6.4 thin foil	20	2	2	3					2	2	2	2												
																						Specimens total:		**60**

Table 8.6.Test matrix of completed artificial debonding cases for panels with different constructions

		Lay-up						
Honeycomb size, mm	Honeycomb height, mm	3 ply [-60/0/+60]						
		Quasi-static indentation on honeycomb with no skin				Diameter of debonding area, mm		
		12	20	30	50	20	35	48
3.2	10					2	2	2
	15	3	3	3	3			
						Total specimens:		**18**

Table 8.7.Test matrix of completed deflection controlled indentations for panels with different constructions

Honeycomb size, mm	Honeycomb height, mm	Lay-up: 2 ply 90/0 — indenter ∅20, Impact, J			Quasi-static, mm			indenter ∅150, Impact, J			Quasi-static, mm			no damage
		0.3	0.5	0.7	1	1.5	2	0.5	0.7	1.0	1	1.5	2	
3.2	20				1	2	2				1	2	2	2
	30	1	1	1	1	2	2	1	1	1				1
6.4	20													
	30				2	1	2				2	1	2	2

Honeycomb size, mm	Honeycomb height, mm	3 ply -60/+60/0 — indenter ∅20, Impact, J			Quasi-static, mm			indenter ∅150, Impact, J			Quasi-static, mm			no damage
		0.3	0.5	0.7	1	1.5	2	0.3	0.5	0.7	1	1.5	2	
3.2	20		2	1	1	2	2	1	1	1				1
	30	1	1	1		2	1	1	1	1	1	1	1	
6.4	20							1		1			1	
	30	2	2	2	2	2	1							1

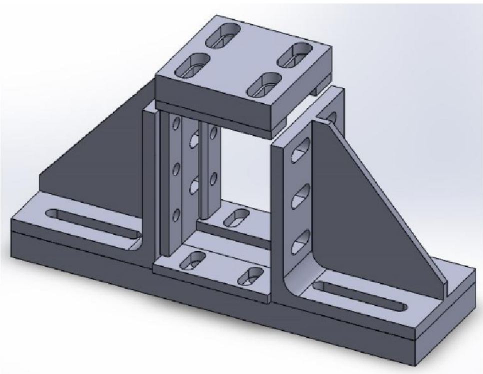
Honeycomb size, mm	Honeycomb height, mm	4 ply 0/-60/+60/0 — indenter ∅20, Impact, J			Quasi-static, mm					indenter ∅150, Impact, J			Quasi-static, mm			no damage
		0.3	0.5	0.7	0.5	1	1.5	2	2.5	0.5	1	1.0	1	1.5	2	
3.2	20	2	3	4			2	2						2		3
	30	1	1	1		1	1	1		1	1	1	1	1	1	
6.4	20	2	2	2	2	2	3	3	2							
	30					2	2	2					2	2	2	
															Total specimens:	**135**

8.4 Testing of damaged specimens

8.4.1 Testing of damaged specimens

After artificial damage is introduced in specimen, appropriate and robust method for residual strength estimation must be applied. In literature review it was found that most popular method used by other researches was the compression after impact [5]. A uniaxial compression test is performed using a balanced, symmetric sandwich plate, 150 × 100 mm, which has been damaged and inspected prior to the application of compressive force. The damage state is imparted through out-of-plane loading caused by quasi-static indentation or drop-weight impact. Basing on literature review currently the most popular method for the compression after impact of monolithic laminates is SACMA SRM 2-88 (Suppliers of Advanced Composite Materials Association). It is the basis of the Airbus Industries test method and ASTM D7137 [6] (Figure 8.7.). Although this method is designed for laminates, not for sandwich panels. Specimens was mechanically clamped form all sides. Clamping force was high enough to prevent skin crushing to outside – end-brooming failure. In very first attempts to perform test, specimens failed at ends, by skins crushing inside or buckling near specimen ends, showing inappropriate and premature failure.

During literature review was found, that for thin metallic facings and non-metallic skins the ends or core should be potted [7]. To solve the problem all specimens were reinforced by ends potting into epoxy/sand mixture. To make it possible a special potting stand was designed and manufactured (Figure 8.8.). When the specimens are ready they are placed between two steel plates in testing machine for compression test as shown in Figure 8.9. Extension measurement was performed by using two LVDTs in opposite sides. Lower compression plate was placed on hemisphere to provide uniform distribution of the load. Compression after impact test parameters are show in Table 8.8.

a) 

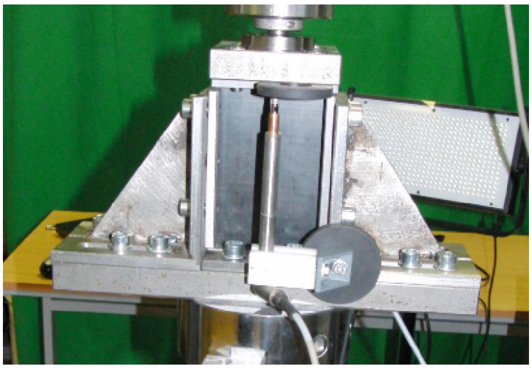
b) 

Figure 8.7. SACMA compression after impact test rig: a – model, b – the rig with specimen placed inside and equipped with LVDT

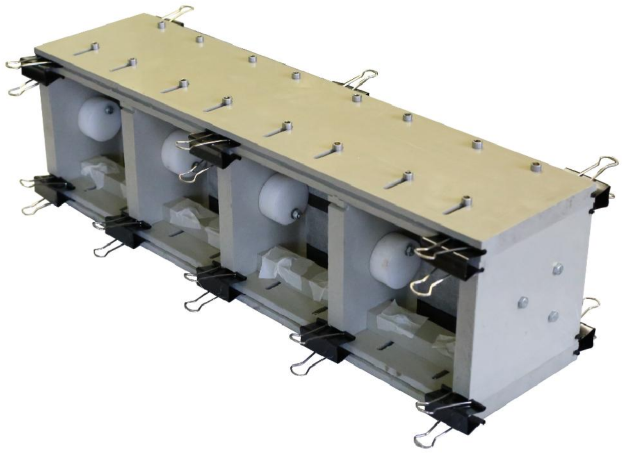


Figure 8.8. Potting stand for ends reinforcement

Figure 8.9. Edgewise compression test

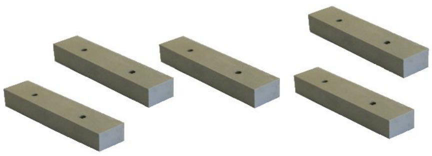
Table 8.8. Test parameters of edgewise compression (compression after impact)

Testing method	custom from ASTM C364
Equipment	ZWICK Z100 (100 kN)
Operator ID	Guntis Japins
Test type	edgewise compression
Testing speed, mm/min	0.5
Extension measurement devices	LVDT pair

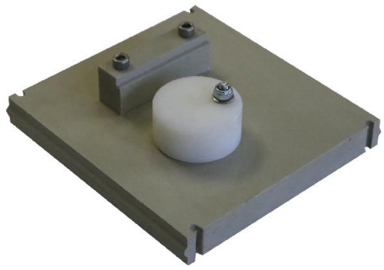
8.4.2 Procedure of end reinforcement

In Figure 8.10. are shown components of potting stand and assembly sequence in Figure 8.11. Stand contains several components: two base plates, 16 side formworks, 5 vertical walls which are separating specimens and holding them in straight vertical position. Four specimens can be potted simultaneously in one stand. In total three stands were manufactured. Potting process starts with cleaning of each part. Then every surface which will have direct contact to epoxy resin is coated with mold release agent. After that parts are assembled together as shown in Figure 8.11. Finally epoxy and sand are mixed with ratio about 1:3 by mass and filled around one end of each specimens. After resin is cured stand is turned upside down and potting procedure is repeated. Depending on specimen’s thickness each of them needed from 520 to 560 grams of epoxy/sand mixture. Potting provided effective ends reinforcing and stabilization (Figure 8.12.).

Baseplate (2 in total)



Side formworks (16 in total)

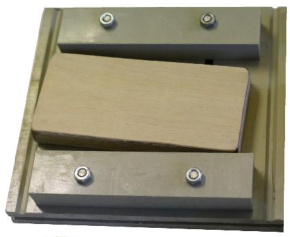


Vertical wall with specimen positioner and fixator (5 in total)

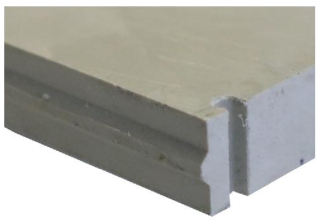
Figure 8.10. Components of one potting stand

a) Baseplate with side formworks

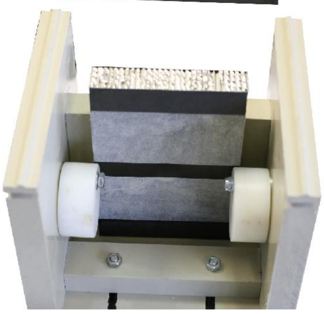
b) Plywood stencil for positioning of side formworks



c) Sidewalls with longitudinal protrusion are placed in special slots on baseplates



d) Specimens are placed in all four cells and fixed with round fixators



e) second baseplate is attached on the top, assembly bonded together with clips

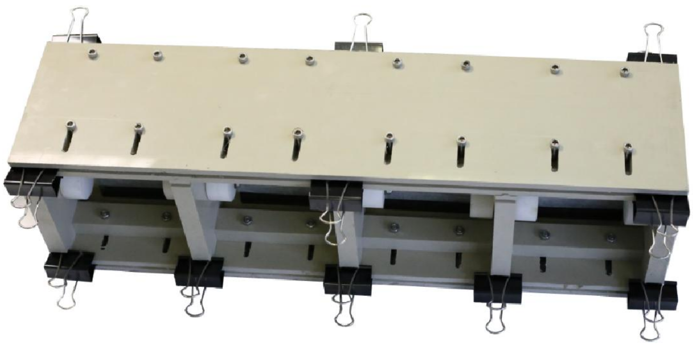


Figure 8.11. Potting stand assembly

Figure 8.12. Sandwich panel specimen with reinforced ends for edgewise compression

8.5 Test results

All test results related to damage introduction, specimens response to damage, compression after impact are gathered in table which can be found in website (http://bnm4eks.rtu.lv) [8] of this research. Also there is lot of many other information, including photos and videos.

8.5.1 Residual strength

As mentioned before, residual strength was estimated through edgewise compression test results. None of specimens with honeycombs made of 0.0381 mm foil had satisfactory failure, it means that they never failed due to artificially introduced damage. This led to the idea that the damage did not provoke destruction until the delamination is occurred, because otherwise crushed honeycomb continue to stabilize the skin. To prove this hypothesis, few specimens with artificial skin debonding were manufactured and tested. Under compression load facing skin started to buckle until it failed giving satisfactory result. Also increment of debonding area leaded to decrease of compression strength (Figure 8.18.).

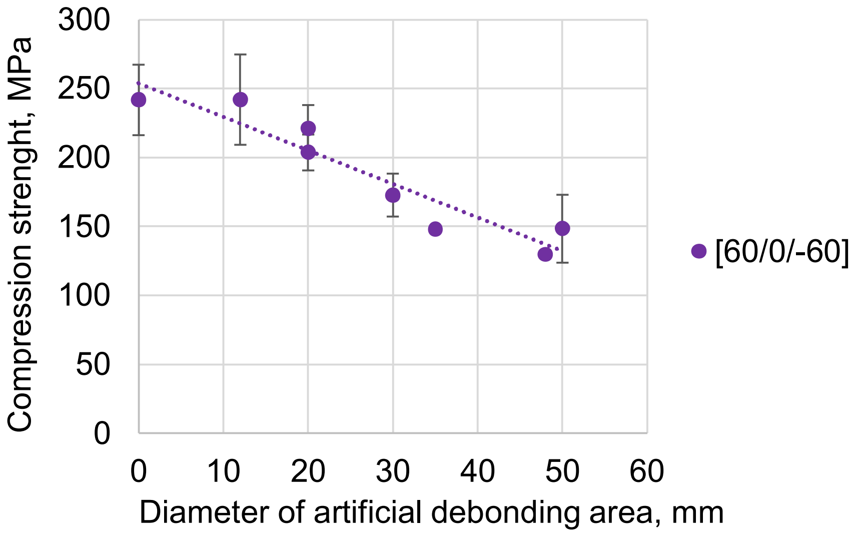


Figure 8.13. Residual compression strength depending on diameter of debonding area

Possibly honeycombs with cell wall foil thickness 0.0381 mm are too dense and stable to let skin to buckle into specimen. This means that under the compression load, the dent damage will not be able to grow and deepen by crushing honeycomb. Therefore, next panels were made from honeycomb with thinner foil – 0.0178 mm. Second prerequisite is thicker skins which also leads to catastrophic inward growth and propagation of the residual indentation [6].

In Figure 8.14., Figure 8.15., Figure 8.16., Figure 8.17. shown residual compression strength dependence on impact energy, indentation depth and layup. Honeycomb core for all reviewed results have the same density, cell size (3.2 mm) and foil thickness (0.0178 mm). With red circle marked all cases where specimens had inappropriate failure mode. Only samples with thickest skin showed a desirable tendency.

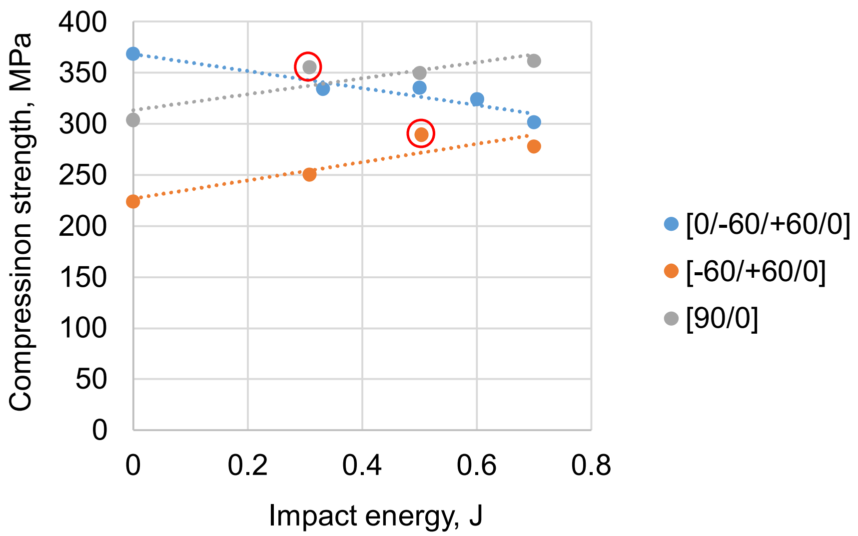


Figure 8.14. Residual compression strength depending on impact energy with 20 mm indenter

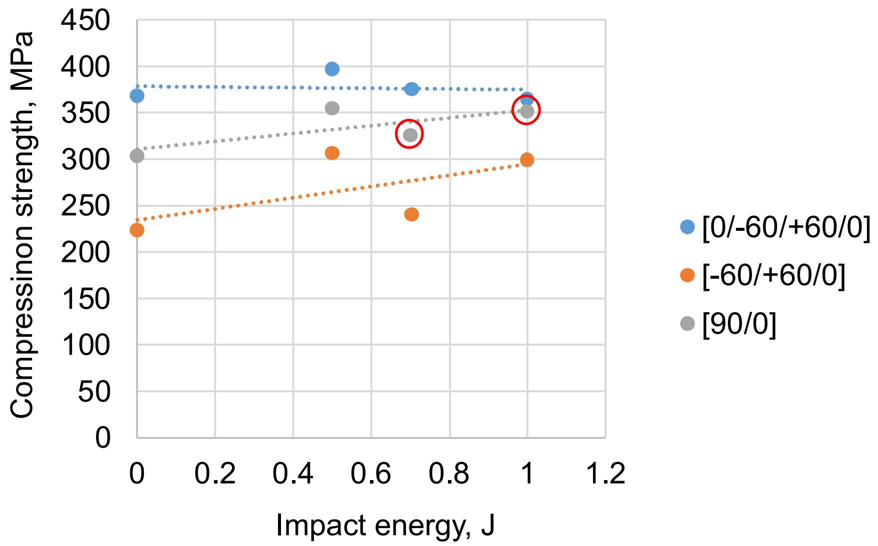


Figure 8.15. Residual compression strength depending on impact energy with 150 mm indenter

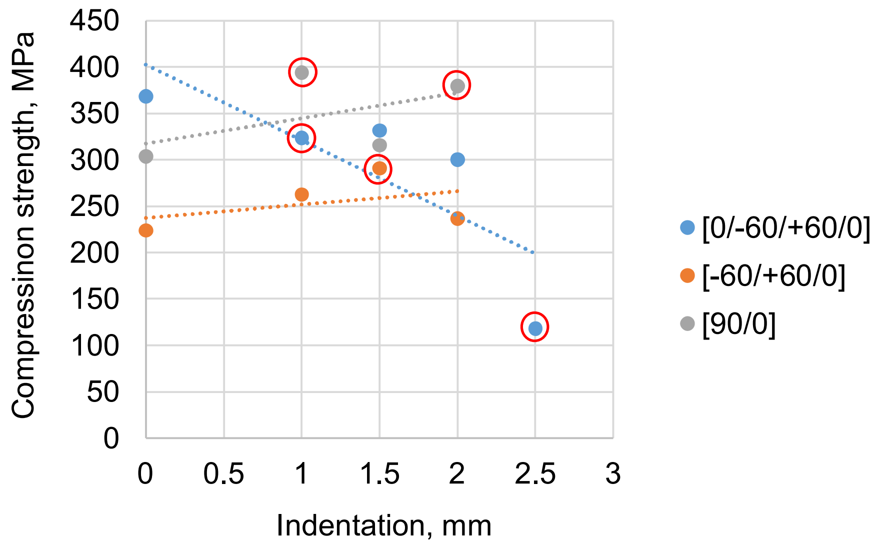


Figure 8.16. Residual compression strength depending on quasi-static indentation depth with 20 mm indenter

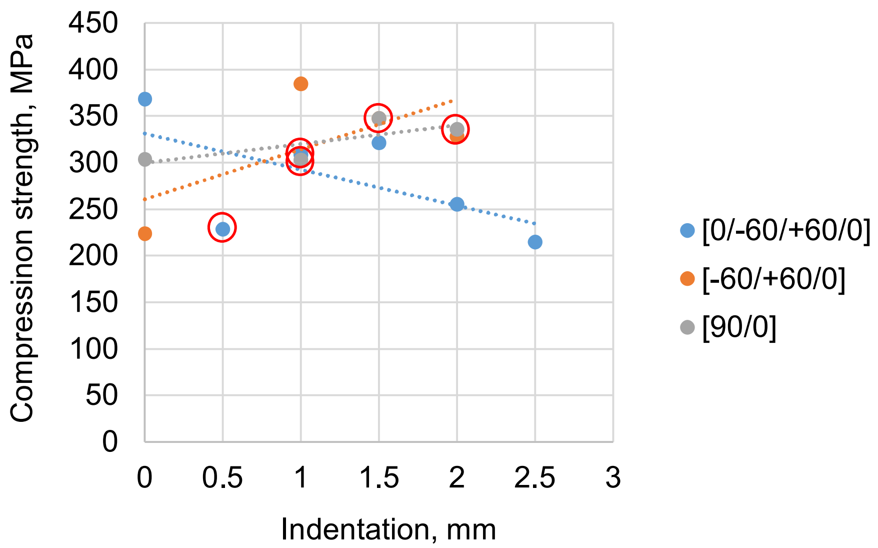


Figure 8.17. Residual compression strength depending on quasi-static indentation depth with 150 mm indenter

8.5.2 Failure types depending on sandwich panel construction

In several 3D graphics shown the failure type dependence on panel construction and damage size. All dots marked with circles shows failures caused by artificial damage, with triangles – inappropriate failures and crosses represents undamaged specimens.

Table 8.9. Edgewise compression failure types

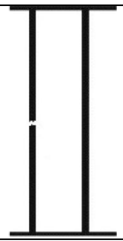
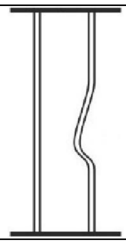
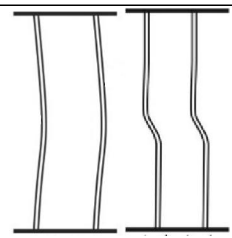
Skin crack	Skin buckling: Core crushing	Skin buckling: Skin debonding	Global (general) buckling. Shear crimping
a	b	d	e
			

Table 8.8. Test results of impact and quasi-static indentations, and compression after impact

Foil thickness	Lay-up	Honeycomb	Damage type	Indenter diameter	Damage size criteria	Max Load I & QS	Indent Failure	Deflection in QS test		Compression after impact				
								A skin	B skin	Load	σ_{skins}	E_{skins}	Deflection	Failure
				mm		N		mm	mm	kN	MPa	GPa	mm	mm
Thick foil,	[60/0/-60]	3.2/10mm	D	20	20 mm	-	-	-	-	10.7	203.7	38.3	0.60	D, A+
				35	35 mm	-	-	-	-	7.7	147.7	34.4	0.49	D, A+

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				48	48	mm	-	-	-	-	6.8	129.6	31.8	0.59	D, A+
			QS	20	500	N	500	Dent	1.24	0.21	11.8	224.8	41.2	0.62	D, A-
					500	N	500	Dent	1.12	-	11.7	221.4	39.8	0.89	D, A-
				150	750	N	749	Dent	0.78	0.27	11.2	213.7	41.9	0.63	D, A-
					1000	N	999	Dent	1.18	0.45	10.1	193.1	40.8	0.52	D, A-
					1400	N	1316	Dent	1.61	0.62	9.6	183.8	40.1	0.52	D, A-
			-	-	-	-	-	-	-	-	12.7	241.6	38.9	0.79	D, A+
		3.2/15mm	D	12	12	N	-	-	-	-	12.7	241.9	35.6	0.77	D, A+
				20	20	N	-	-	-	-	11.6	221.1	35.4	0.80	D, A+
				30	30	N	-	-	-	-	9.1	172.6	38.1	0.46	D, A+
				50	50	N	-	-	-	-	7.8	148.4	31.7	0.51	D+
		3.2/20mm	QS	20	500 frame	N	500	Dent	1.51	0.19	14.1	269.6	39.3	0.77	A-
					500 plate	N	500	Dent	1.49	-	11.0	209.0	39.7	0.63	A-
			-	-	-	-	-	-	-	-	11.4	217.9	42.6	0.57	D, A+
	[0/60/-60/0]	3.2/20mm	QS	20	500	N	500	Dent	1.14	0.19	35.6	494.5	52.7	1.47	A-
				150	1400	N	1399	Dent	1.77	0.7	-	-	-	-	A-
			-	-	-	-	-	-	-	-	37.9	526.7	48.2	1.67	A+
	[-60/60/0]	3.2/15mm	QS	20	500	N	496	Dent	1.31	0.16	19.1	364.9	41.5	1.01	A-
					750	N	686	crack	1.60	0.22	18.3	348.9	42.1	0.95	A-
				150	1000	N	998	Dent	1.14	0.26	18.4	351.5	39.4	1.04	D, A-
			-	-	-	-	-	-	-	-	16.8	319.4	41.5	0.89	D, A+
	[90/0]	3.2/20mm	QS	20	500	N	502	Dent	1.59	0.21	8.1	163.5	39.3	0.55	D, A-
					750	N	748	Dent	2.26	0.33	8.7	165.8	32.4	0.88	D, A-
				150	500	N	499	Dent	0.40	0.11	7.5	189.8	48.1	0.52	D, A-
					1000	N	1002	Dent	1.16	0.31	7.5	188.3	44.3	0.48	D, A-
Thin foil, 0.0178 mm	[0/-60/+60/0]	3.2/20mm	I	20	0.33	J	462	Dent	-	-	21.3	306.3	44.4	0.92	A, B+
					0.50	J	580	Dent	-	-	22.3	311.2	47.9	0.77	B, A+
					0.60	J	670	Dent/crack	-	-	22.9	324.3	46.4	0.83	B, A+
					0.70	J	630	Dent/crack	-	-	19.3	276.3	48.2	0.71	B, A+
			QS	20	1.00	mm	198	Dent	1.02	0.149	17.6	230.3	39.5	0.68	B-
					1.50	mm	443	Dent	1.52	0.17	23.1	309.2	44.6	0.78	B, A+
					2.00	mm	606	Dent/crack	1.95	0.25	20.9	278.8	42.3	0.83	B, A+
					2.5	mm	567	Dent/crack	2.55	0.32	9.0	118.1	39.6	0.34	D, E
				150	0.50	mm	196	Dent	0.50	0.08	16.1	228.7	45.7	0.56	B, A+
					1.00	mm	318	Dent	1.01	0.13	15.3	217.3	43.6	0.50	D
					1.50	mm	831	Dent	1.51	0.28	21.9	300.4	42.6	0.83	B, A+
					2.00	mm	684	Dent	1.98	0.27	18.0	255.3	45.8	0.62	B, E+
					2.50	mm	864	Dent	2.46	0.41	15.2	214.9	43.5	0.53	B, E+
			-	-	-	-	-	-	-	-	28.9	368.4	46.9	0.95	B, A+
		3.2/30mm	I	20	0.31	J	513	Dent	-	-	28.9	447.2	54.6	1.00	A, B+
					0.50	J	653	Dent	-	-	29.4	455.0	52.5	1.05	A, B+
					0.70	J	766	Dent	-	-	26.1	403.8	54.6	0.91	A, B+

				150	0.50	J	614	Dent	-	-	25.6	397.1	55.6	0.86	A, B+
					0.70	J	744	Dent	-	-	24.3	375.6	51.5	0.83	A, B+
					1.00	J	897	Dent	-	-	23.6	364.9	54.3	0.80	A, B+
			QS	20	1.00	mm	383	Dent	0.97	0.06	29.0	417.1	46.7	1.34	end fail-
					1.50	mm	569	Dent	1.46	0.24	29.3	421.4	48.3	1.07	A, B+
					2.00	mm	596	Dent	2.04	0.41	26.9	386.8	51.4	0.94	A, B+
				150	1.00	mm	764	Dent	1.02	0.10	27.8	399.9	49.8	0.99	A-
					1.50	mm	1033	Dent	1.50	0.29	26.7	383.5	50.1	0.91	A, B+
					2.00	mm	1379	Dent	1.98	0.28	22.7	326.7	47.5	0.77	A, B+
		6.4/30mm	QS	20	1.00	mm	215	Dent	0.95	0.07	22.0	291.5	49.0	0.67	B+
					1.50	mm	335	Dent	1.43	0.11	20.3	268.9	49.5	0.78	B+
					2.00	mm	471	Dent	1.90	0.13	18.7	248.0	49.5	0.57	B, E+
				150	1.00	mm	332	Dent	0.96	0.09	20.2	282.9	49.7	0.65	B+
					1.50	mm	494	Dent	1.44	0.13	16.2	226.1	49.9	0.51	B+
					2.00	mm	689	Dent	1.93	0.22	15.0	209.9	51.2	0.47	B+
	[-60/+60/0]	3.2/20mm	I	20	0.50	J	650	Dent	-	-	16.5	297.3	37.8	0.94	A-
					0.70	J	658	Dent	-	-	18.8	338.5	37.5	1.12	A, B+
				150	0.50	J	614	Dent	-	-	17.0	305.2	37.0	0.99	A, B+
					0.70	J	726	Dent	-	-	12.6	227.1	36.9	0.70	A, B+
					1.00	J	795	Dent	-	-	16.3	293.1	37.2	0.96	A, B+
			QS	20	100	N	100	Dent	0.58	0.06	9.4	162.9	30.6	0.60	D-
					125	N	126	Dent	0.75	0.07	12.0	208.1	31.6	0.76	B-
					150	N	151	Dent	0.90	0.08	12.3	214.2	31.9	0.79	B-
					1	mm	291	Dent	1.00	0.16	14.6	262.5	37.4	0.81	A, B+
					1.50	mm	519	Dent	1.49	0.16	16.1	288.8	37.1	0.92	A, B+
					2.00	mm	689	Dent	1.98	0.20	12.3	220.5	37.6	0.71	A, B+
			-	-	-	-	-	-	-	-	12.5	224.0	37.1	0.65	A, B+
		3.2/30mm	I	20	0.31	J	487	Dent	-	-	13.4	250.4	40.4	0.72	A, B+
					0.50	J	649	Dent	-	-	14.7	273.3	36.9	0.79	A, B+
					0.70	J	804	Dent	-	-	14.9	278.2	37.7	0.83	A, B+
				150	0.50	J	634	Dent	-	-	16.5	308.5	40.0	0.88	A, B+
					0.70	J	744	Dent	-	-	13.7	254.5	40.2	0.83	A, D-
					1.00	J	913	Dent	-	-	16.4	305.3	40.1	0.89	A-
			QS	20	1.50	mm	512	Dent	1.45	0.12	15.4	292.7	40.5	0.85	A, B+
					2.00	mm	759	Dent	1.88	0.17	14.2	269.4	40.1	0.82	A, B+
				150	1.00	mm	648	Dent	1.02	0.11	20.3	384.7	41.3	1.14	A, B+
					1.50	mm	1028	Dent	1.50	0.17	18.3	347.5	40.0	1.04	A-
					2.00	mm	1304	Dent	1.99	0.23	17.3	328.0	39.8	1.34	A, B+
		6.4/20mm	I	150	0.37	J	410	Dent	-	-	11.5	218.9	39.9	0.62	A, B-
					0.70	J	583	Dent	-	-	8.7	164.9	39.6	0.53	D-
			QS	150	2	mm	617	Dent	-	-	11.1	211.1	39.2	0.62	E+
			-	-	-	-	-	-	-	-	10.7	202.9	39.1	0.57	B-

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		6.4/30mm	I	20	0.39	J	1177	Dent	-	-	9.6	175.7	39.0	0.53	B+
					0.49	J	2028	Dent	-	-	11.4	208.7	35.2	0.62	B+
					0.68	J	2405	Dent/crack	-	-	9.3	170.5	38.4	0.51	B+
			QS	20	1.00	mm	187	Dent	0.99	0.06	10.7	193.1	37.7	0.58	A, B-
					1.50	mm	282	Dent	1.48	0.10	9.4	169.8	36.9	0.51	D-
					2	mm	414	Dent	1.98	0.12	10.3	185.2	38.3	0.55	B-
			-	-	-	-	-	-	-	-	10.3	185.8	38.9	0.54	B, D+
	[90/0]	3.2/20mm	QS	20	75	N	76	Dent	0.53	0.06	6.7	168.4	53.2	0.42	A
					100	N	101	Dent	0.82	0.07	7.9	200.0	43.5	0.52	B, A-
					125	N	126	Dent	0.93	0.07	9.9	249.5	44.7	0.64	B, A-
					150	N	150	Dent	-	-	7.2	181.4	43.0	0.51	B, A-
					1	mm	241	Dent	1.00	0.11	12.1	382.2	63.7	0.74	A-
					1.50	mm	384	Dent	1.50	0.13	10.1	317.9	64.6	0.61	B, A+
					2.00	mm	544	Dent	2.06	0.23	12.6	397.7	66.4	0.71	A, B-
					no	-	946	Dent	-	1.280	4.8	130.1	40.7	0.47	A, B-
				150	1	mm	597	Dent	0.98	0.21	9.6	302.9	62.9	0.54	A-
					1.50	mm	868	Dent	1.45	0.25	11.1	347.6	59.8	0.71	A-
					2.00	mm	1132	Dent	1.96	0.39	10.7	335.6	62.3	0.69	A, D-
			-	-	-	-	-	-	-	-	10.2	297.9	51.1	0.66	A+
		3.2/30mm	I	20	0.31	J	466	Dent	-	-	12.0	355.7	14.1	0.73	A-
					0.50	J	606	Dent	-	-	11.8	350.1	59.2	0.72	A, B+
					0.70	J	727	Dent	-	-	12.2	361.7	1.1	0.68	A, B+
				150	0.50	J	625	Dent	-	-	12.0	354.8	62.3	0.66	A, B+
					0.70	J	731	Dent	-	-	11.0	325.8	58.0	0.65	A, B+
					1.00	J	924	Dent	-	-	11.9	351.5	31.1	0.68	A-
			QS	20	1	mm	259	Dent	1.02	0.09	13.7	405.5	57.8	0.75	A-
					1.50	mm	404	Dent	1.51	0.10	10.6	314.0	58.5	0.65	A, B+
					2.00	mm	547	Dent	2.00	0.14	12.2	361.2	59.8	0.69	A, B-
			-	-	-	-	-	-	-	-	11.1	327.2	60.1	0.61	A, D-
		6.4/30mm	QS	20	1.00	mm	131	Dent	1.00	0.06	7.3	204.0	51.0	0.47	A, B-
					1.50	mm	207	Dent	1.49	0.08	7.0	194.4	49.1	0.45	A+
					2.00	mm	293	Dent	1.99	0.12	7.3	203.9	48.3	0.45	A+
				150	1.00	mm	235	Dent	1.00	0.10	8.3	238.7	54.9	0.50	A, B+
					1.50	mm	391	Dent	1.55	0.15	7.4	212.6	49.0	0.45	A-
					2.00	mm	530	Dent	2.05	0.21	6.5	186.6	50.4	0.41	A, B-
			-	-	-	-	-	-	-	-	8.1	229.4	37.4	0.49	A, B+

Table 8.9. After CAI test ESA_026 panel.

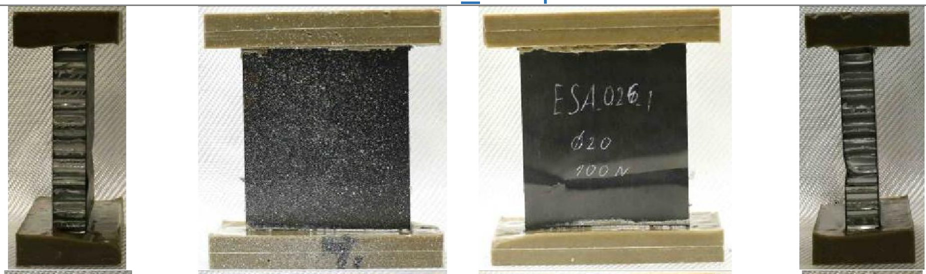
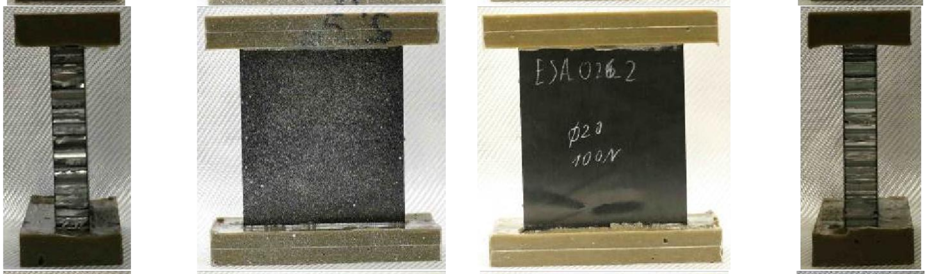
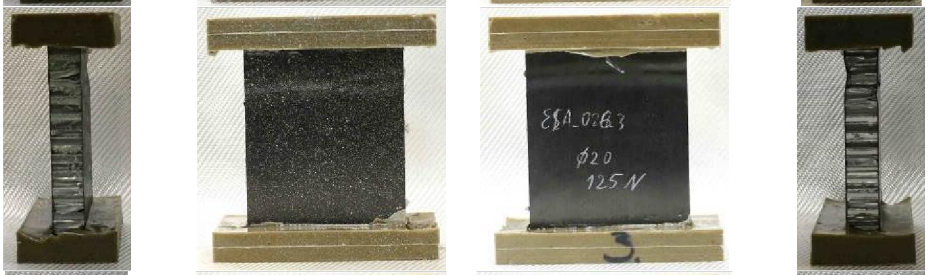
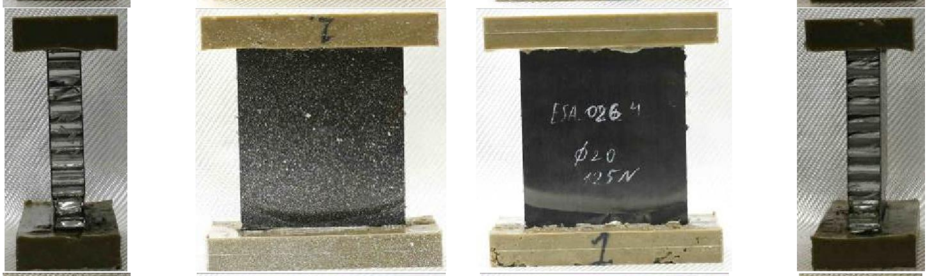
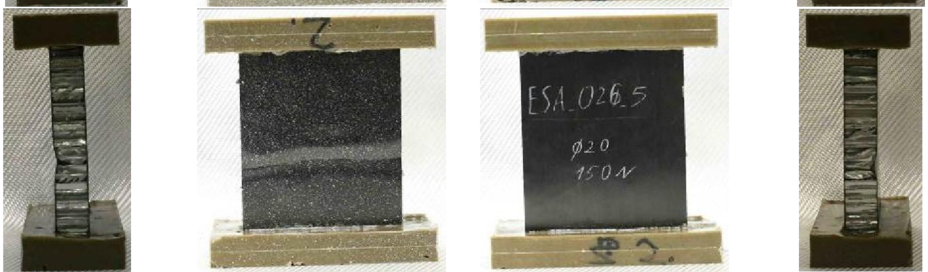
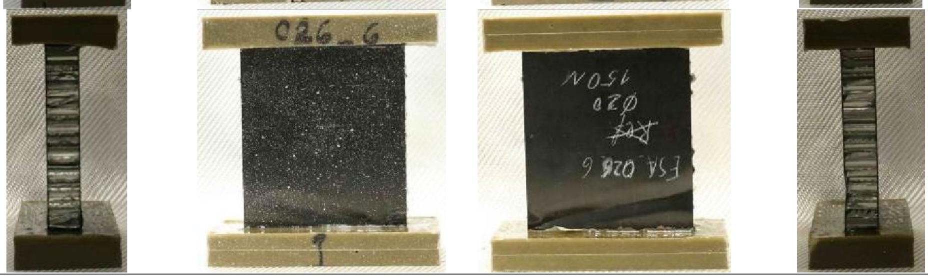
ESA_026_1	
ESA_026_2	
ESA_026_3	
ESA_026_4	
ESA_026_5	
ESA_026_6	

Table 8.10. After CAI test ESA_027 panel.

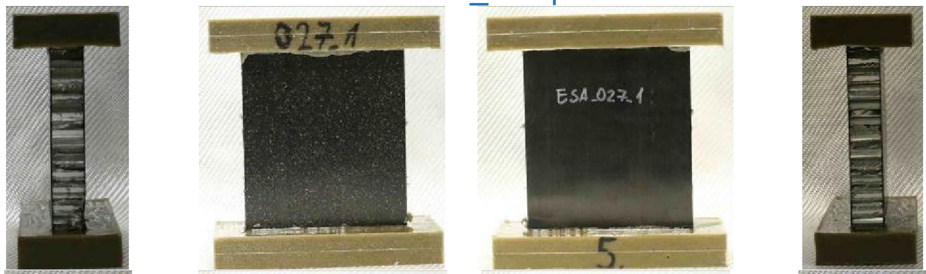
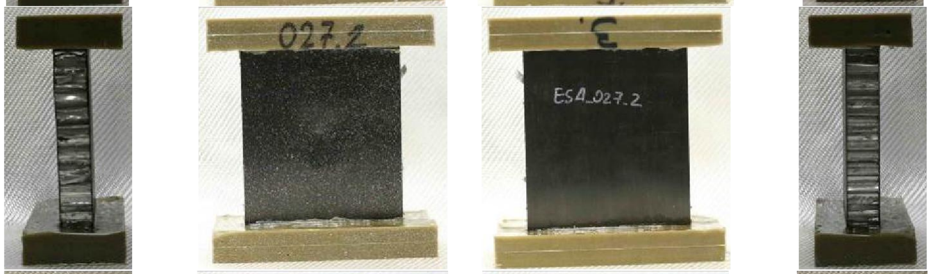
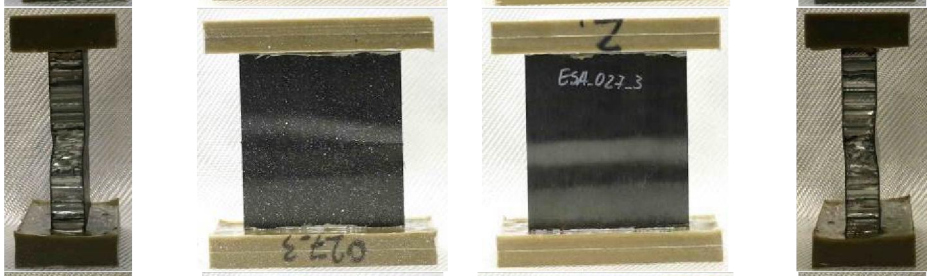
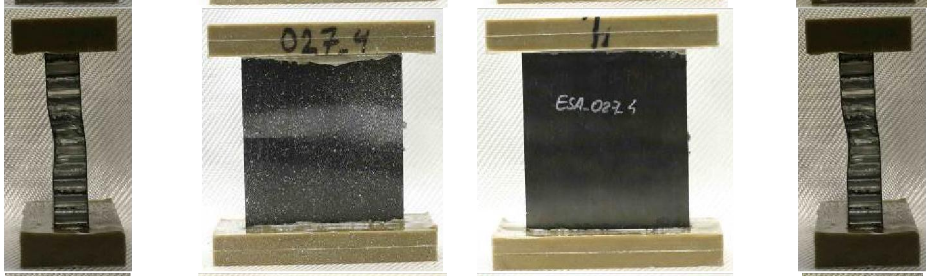
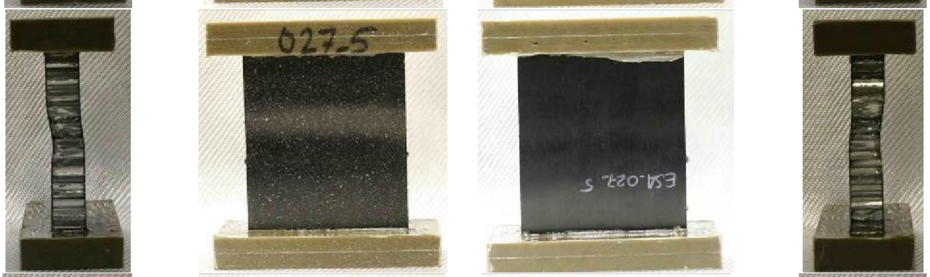
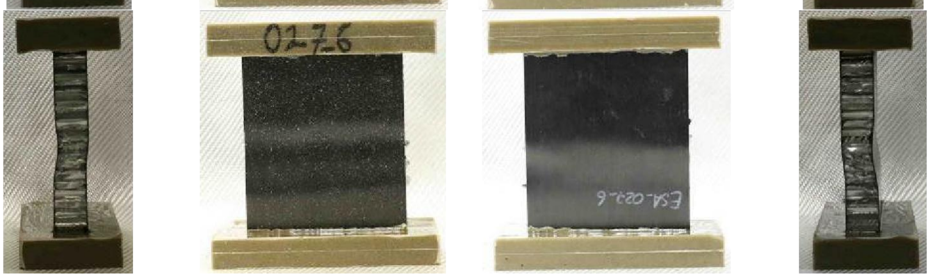
ESA_027_1	
ESA_027_2	
ESA_027_3	
ESA_027_4	
ESA_027_5	
ESA_027_6	

Table 8.11. After CAI test ESA_028 panel.

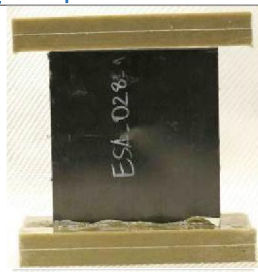
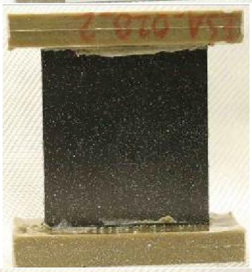
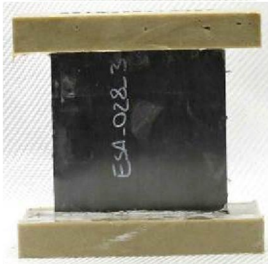
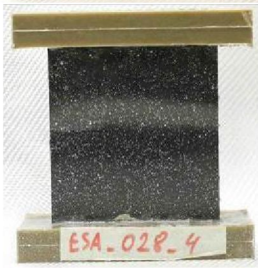
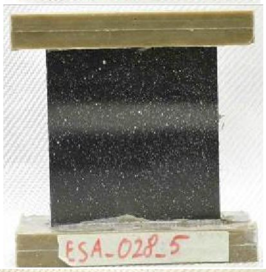
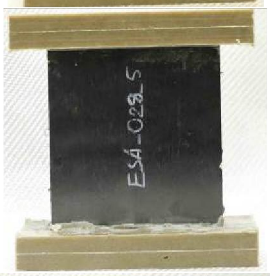
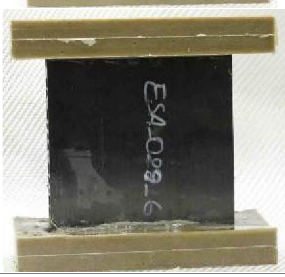
ESA_028_1				
ESA_028_2				
ESA_028_3				
ESA_028_4				
ESA_028_5				
ESA_028_6				

Table 8.12. After CAI test ESA_029 panel.

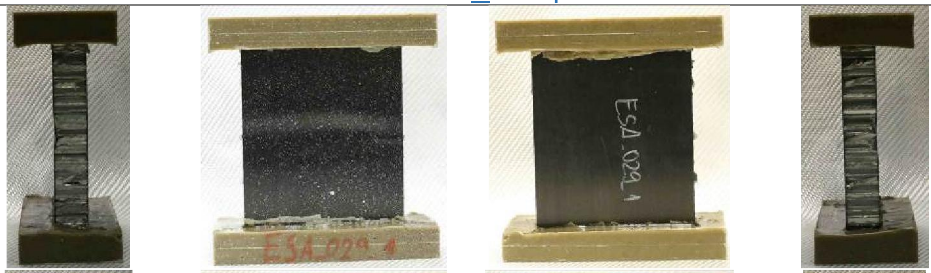
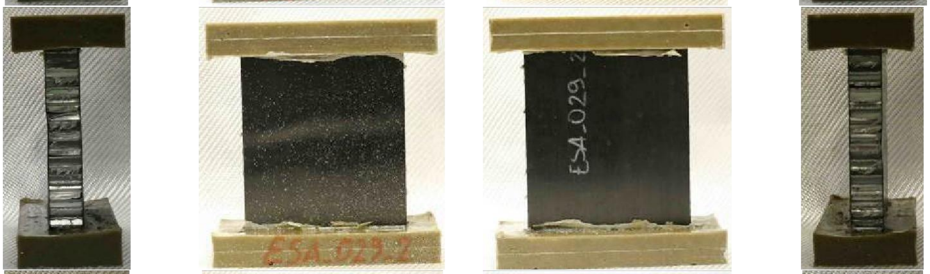
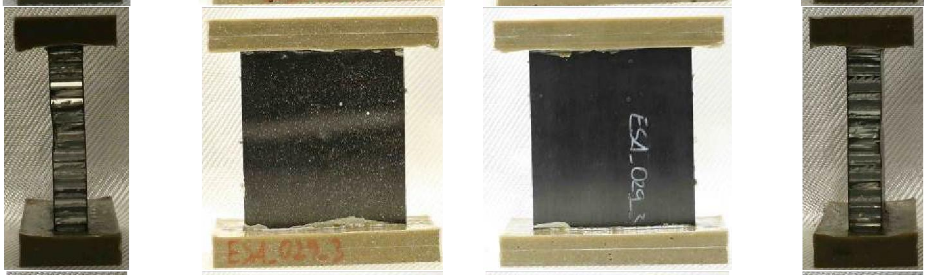
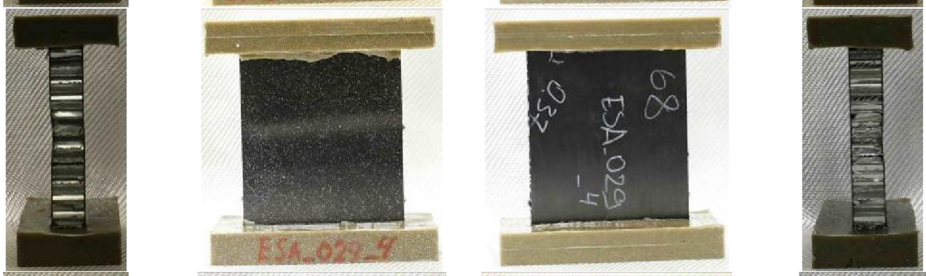
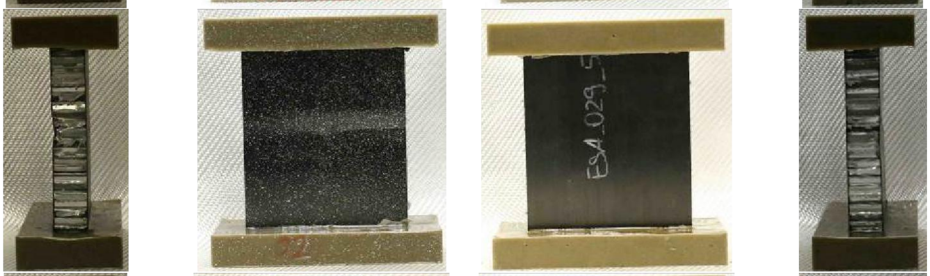
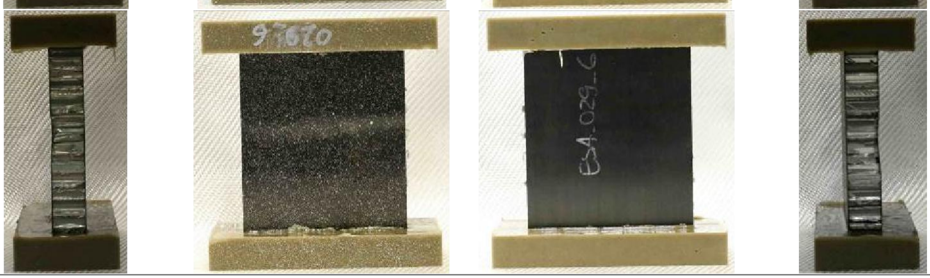
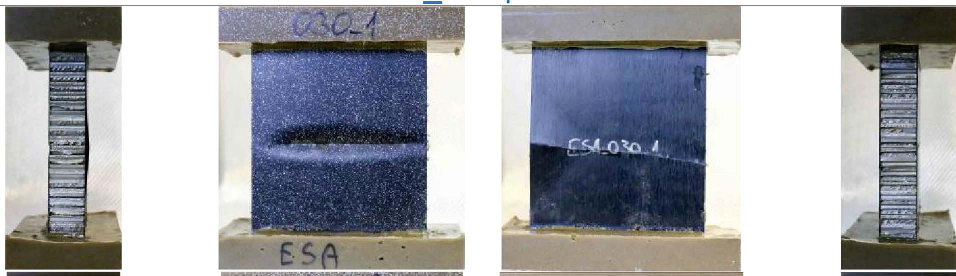
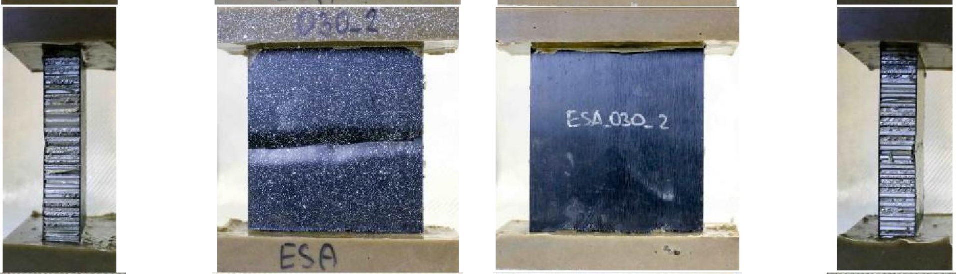
ESA_029_1	
ESA_029_2	
ESA_029_3	
ESA_029_4	
ESA_029_5	
ESA_029_6	

Table 8.13. After CAI test ESA_030 panel.

ESA_030_1



ESA_030_2



ESA_030_3

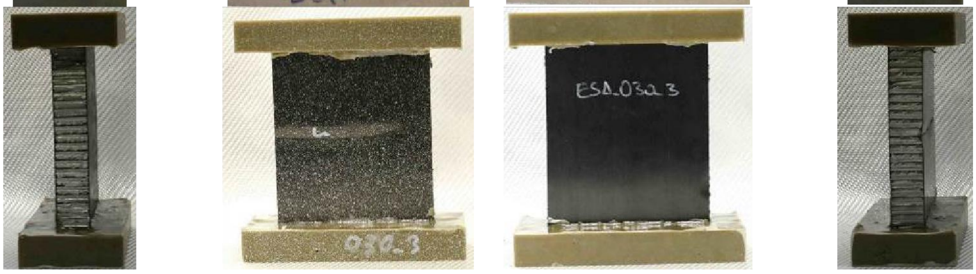


Table 8.14. After CAI test ESA_031 panel.

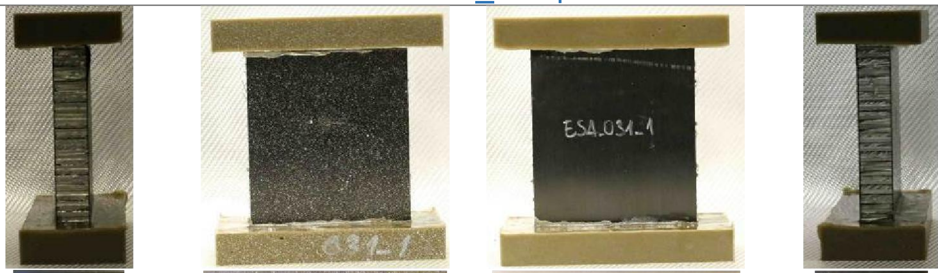
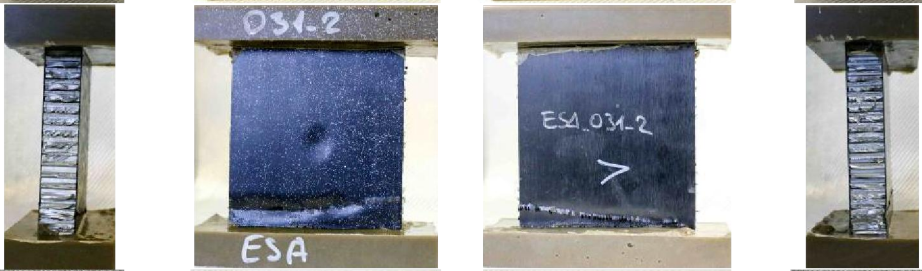
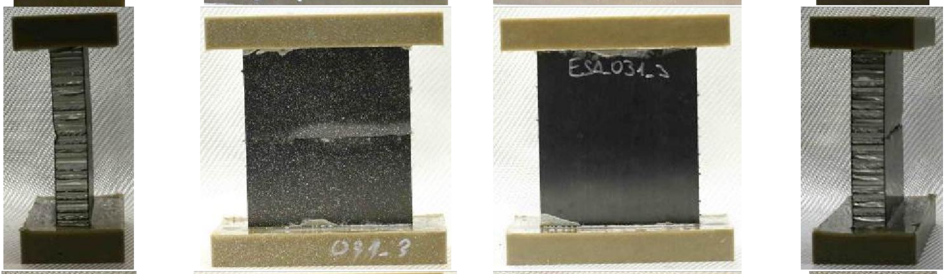
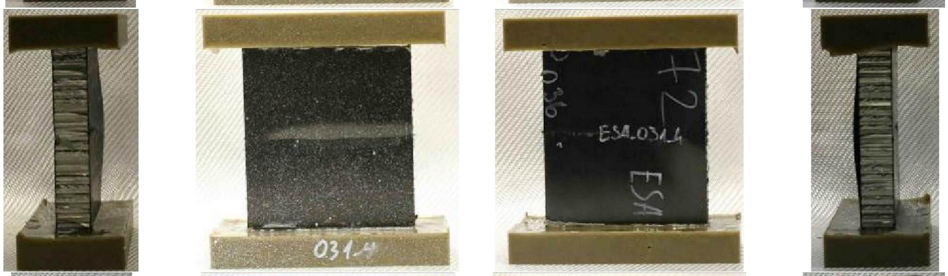
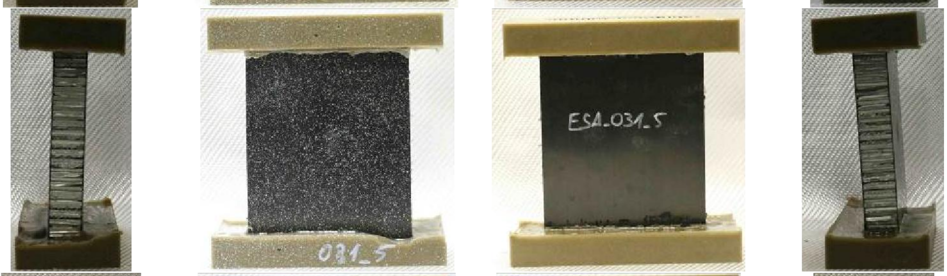
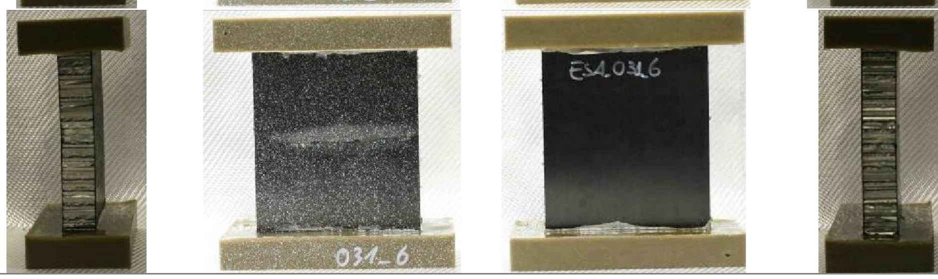
ESA_031_1	
ESA_031_2	
ESA_031_3	
ESA_031_4	
ESA_031_5	
ESA_031_6	

Table 8.15. After CAI test ESA_032 panel.

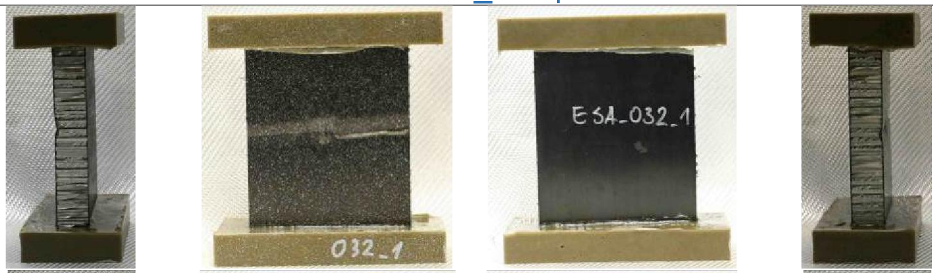
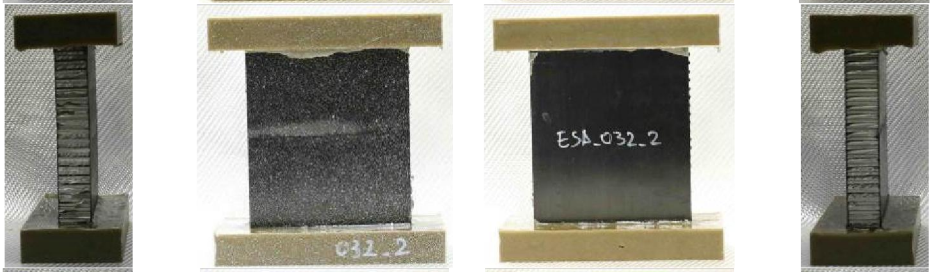
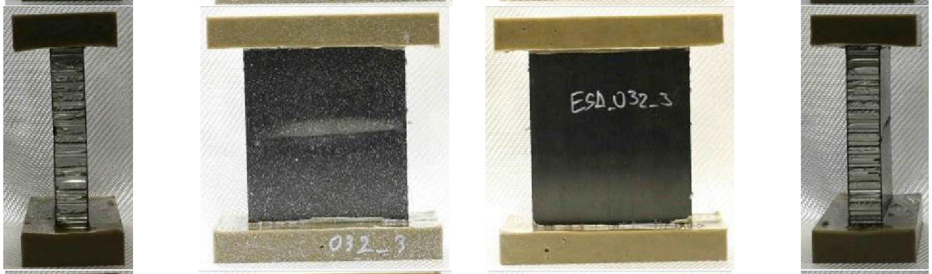
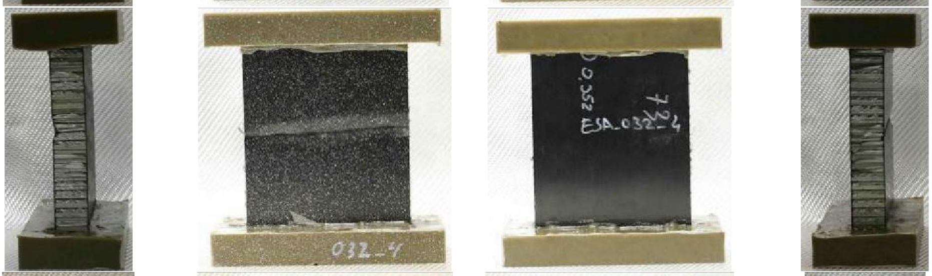
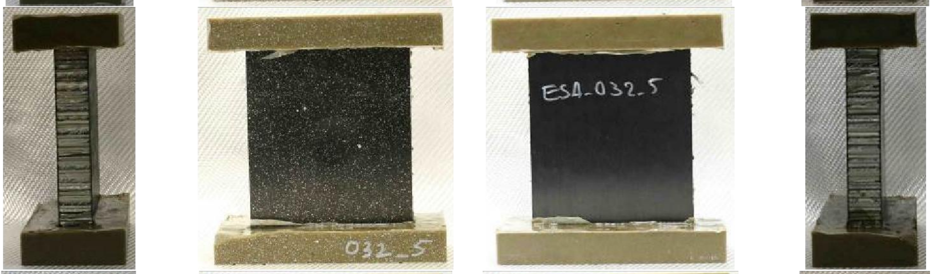
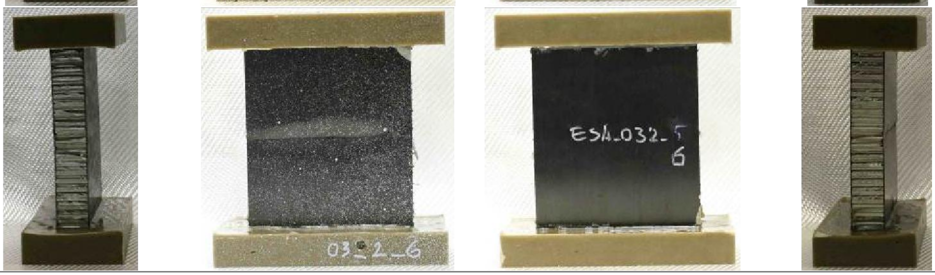
ESA_032_1	
ESA_032_2	
ESA_032_3	
ESA_032_4	
ESA_032_5	
ESA_032_6	

Table 8.16. After CAI test ESA_033 panel.

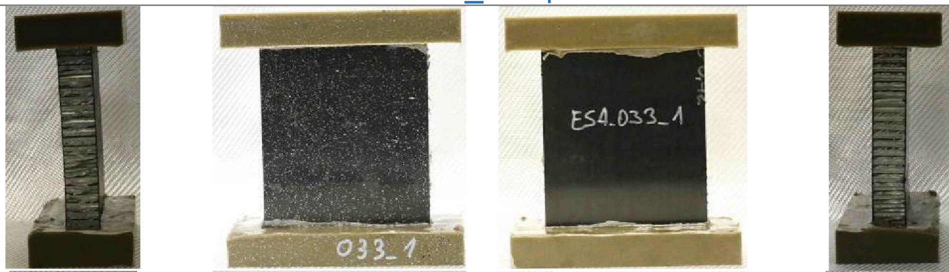
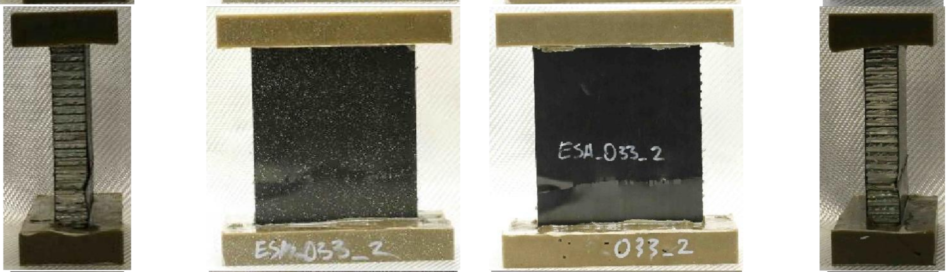
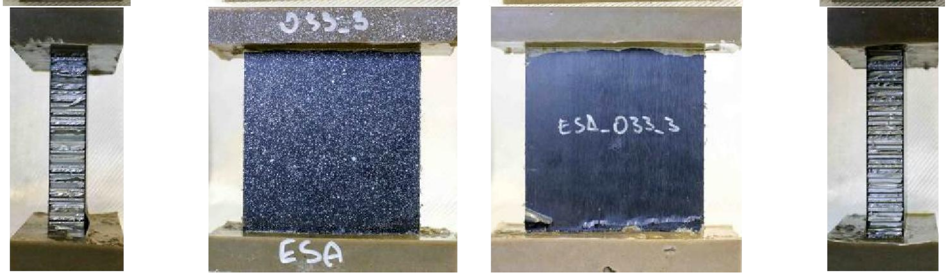
ESA_033_1	
ESA_033_2	
ESA_033_3	

Table 8.17. After CAI test ESA_034 panel.

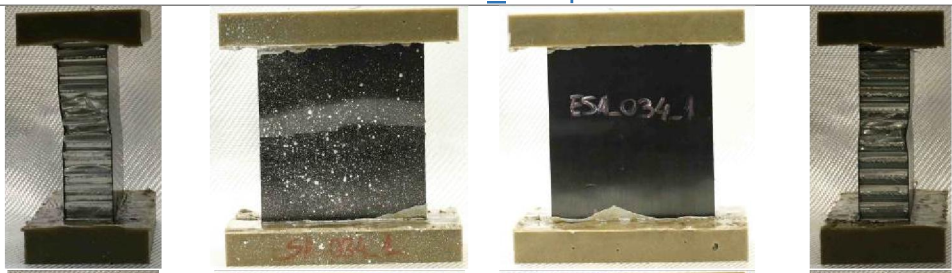
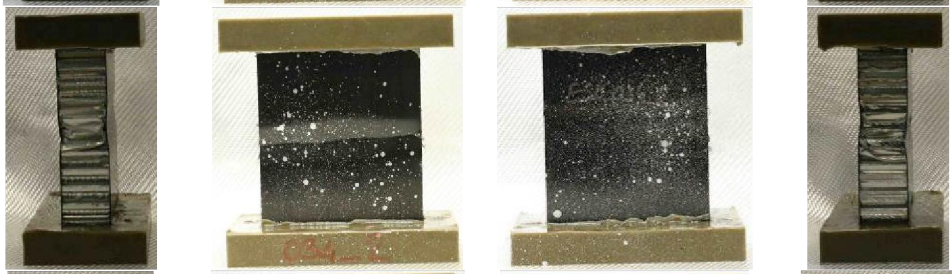
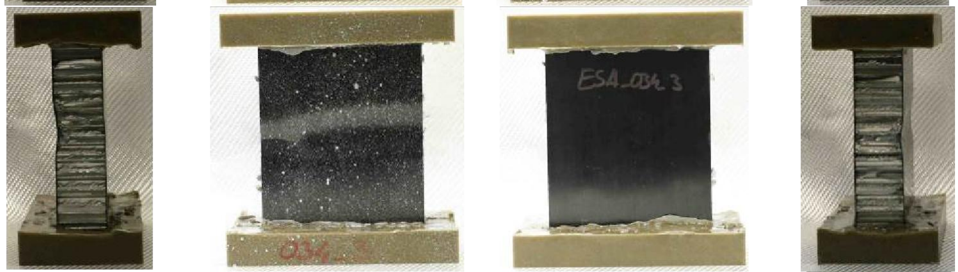
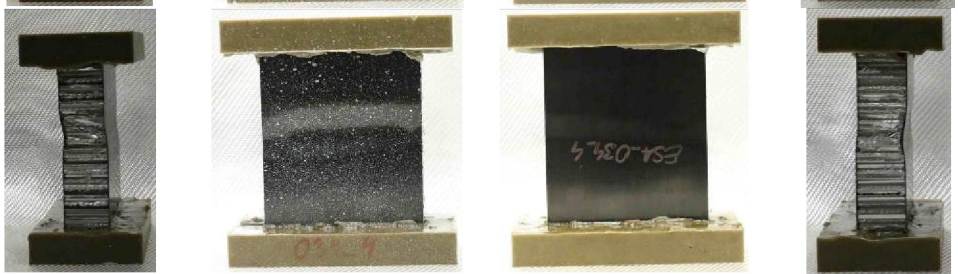
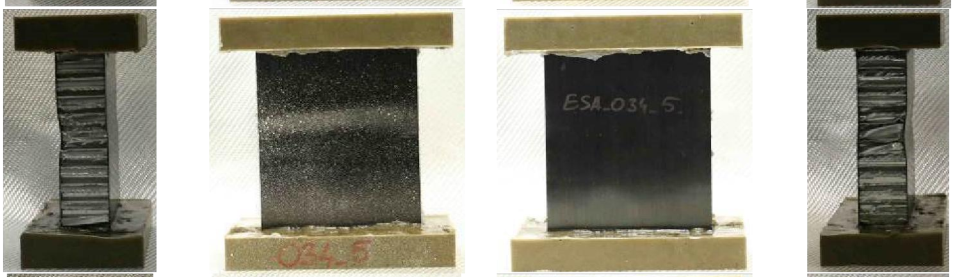
ESA_034_1	
ESA_034_2	
ESA_034_3	
ESA_034_4	
ESA_034_5	
ESA_034_6	

Table 8.18. After CAI test ESA_035 panel.

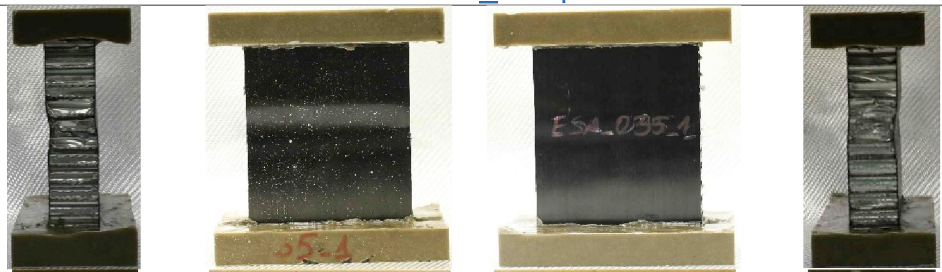
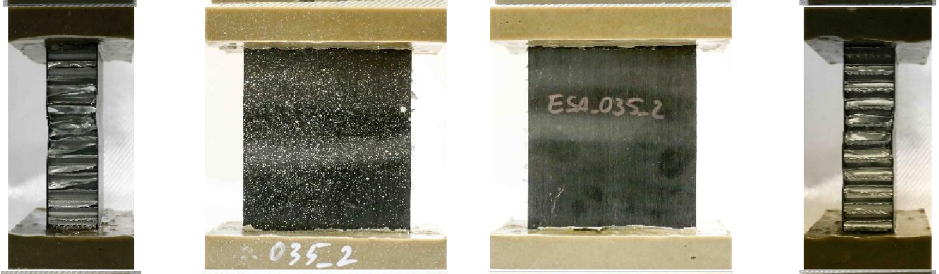
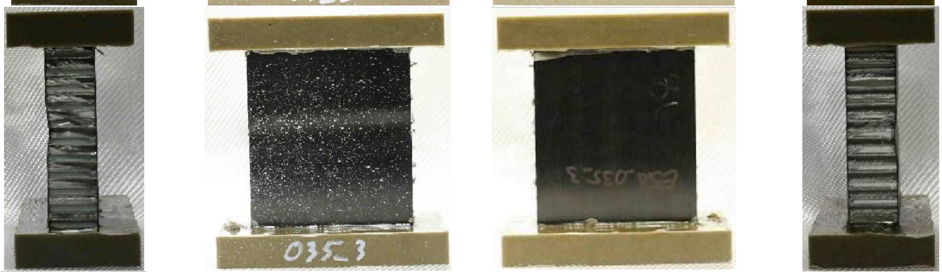
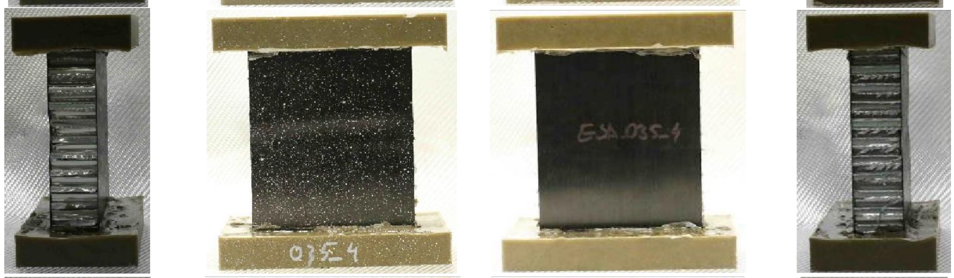
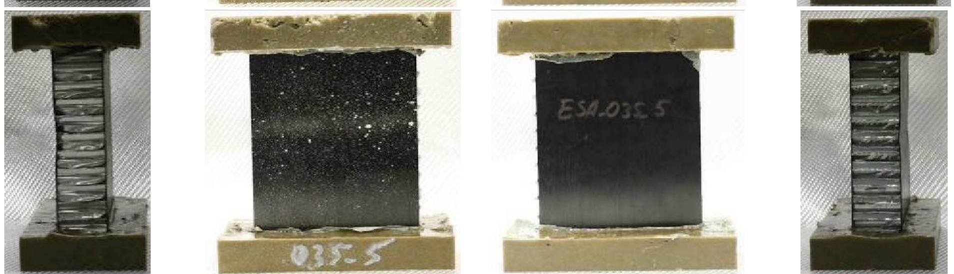
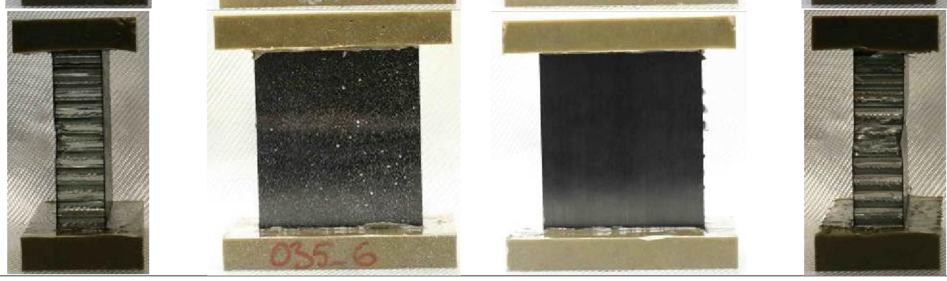
ESA_035_1	
ESA_035_2	
ESA_035_3	
ESA_035_4	
ESA_035_5	
ESA_035_6	

Table 8.19. After CAI test ESA_036 panel.

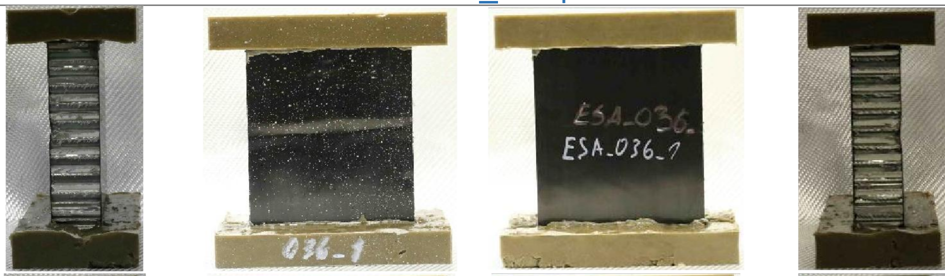
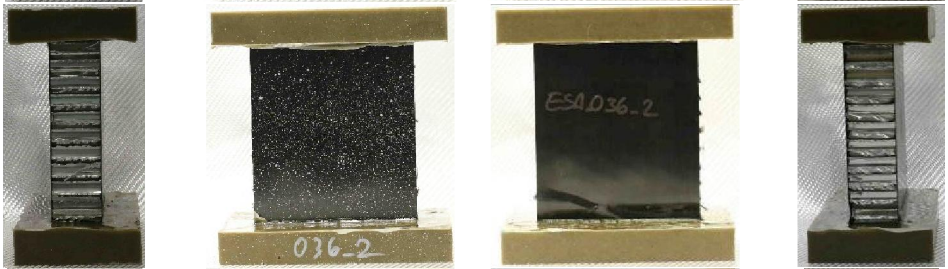
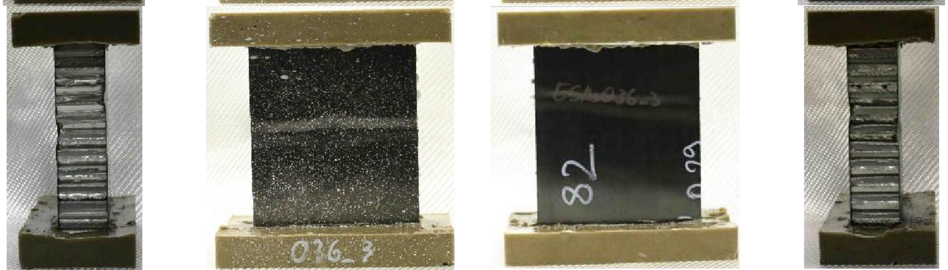
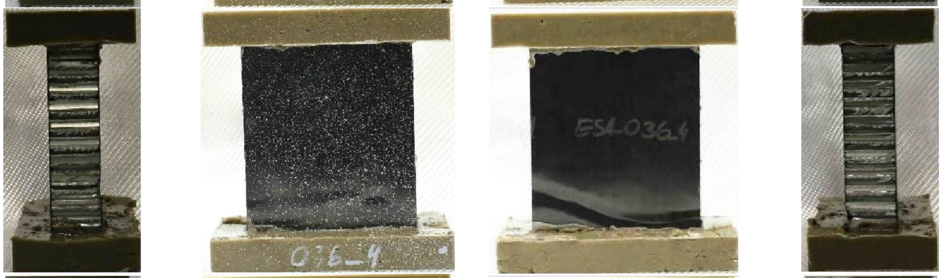
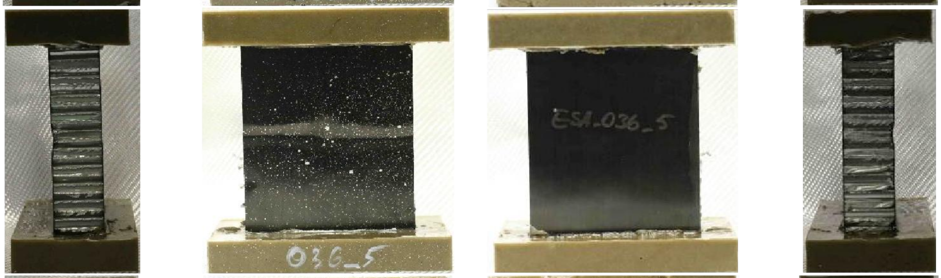
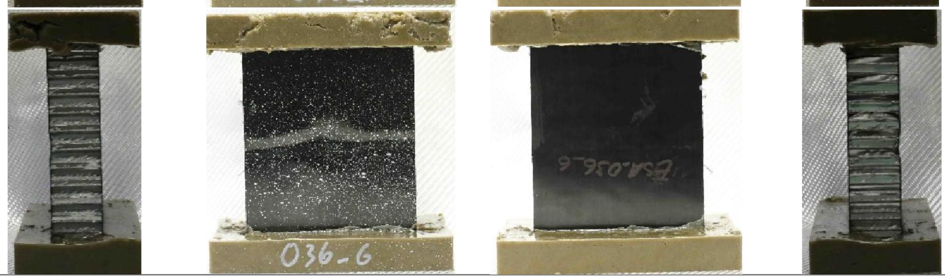
ESA_036_1	
ESA_036_2	
ESA_036_3	
ESA_036_4	
ESA_036_5	
ESA_036_6	

Table 8.20. After CAI test ESA_037 panel.

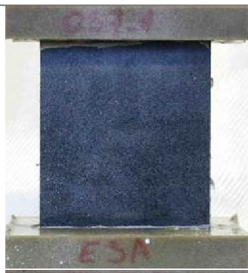
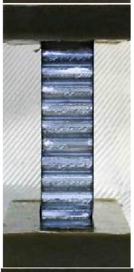
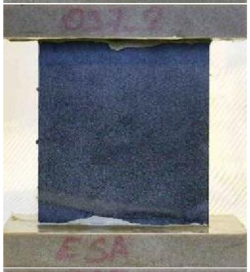
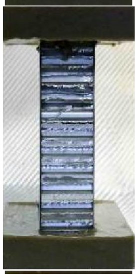
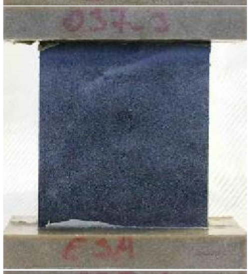
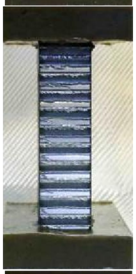
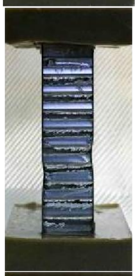
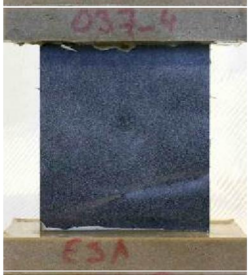
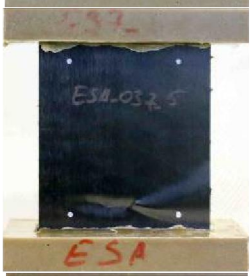
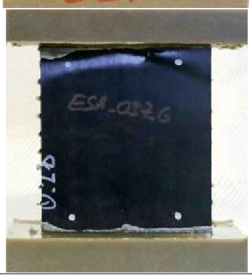
ESA_037_1				
ESA_037_2				
ESA_037_3				
ESA_037_4				
ESA_037_5				
ESA_037_6				

Table 8.21. After CAI test ESA_038 panel.

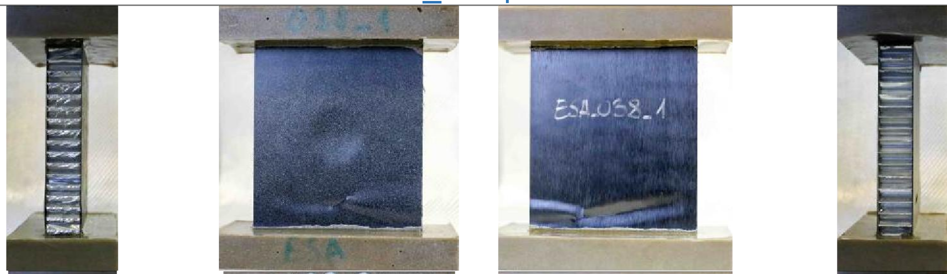
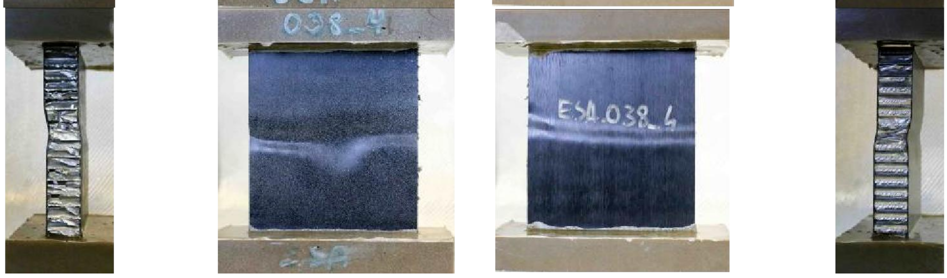
ESA_038_1	
ESA_038_2	
ESA_038_3	
ESA_038_4	

Table 8.22. After CAI test ESA_039 panel.

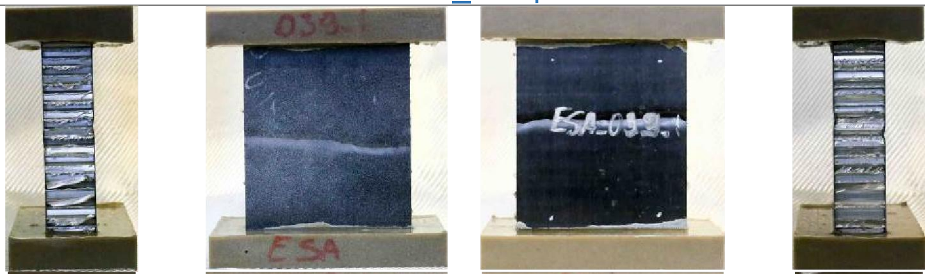
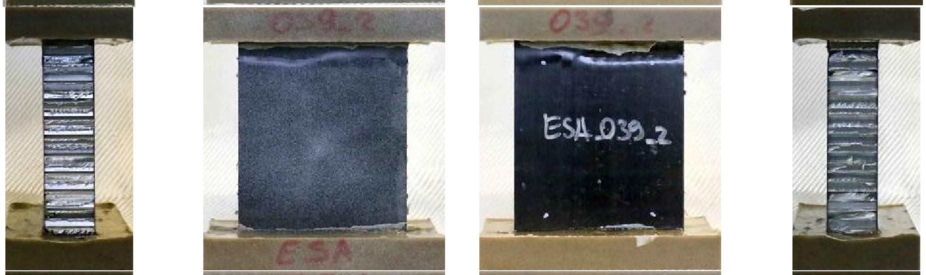
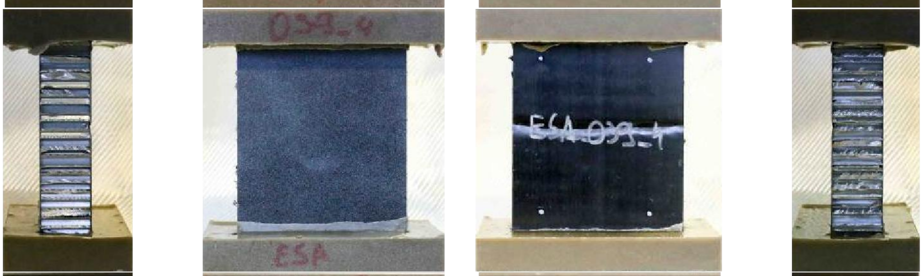
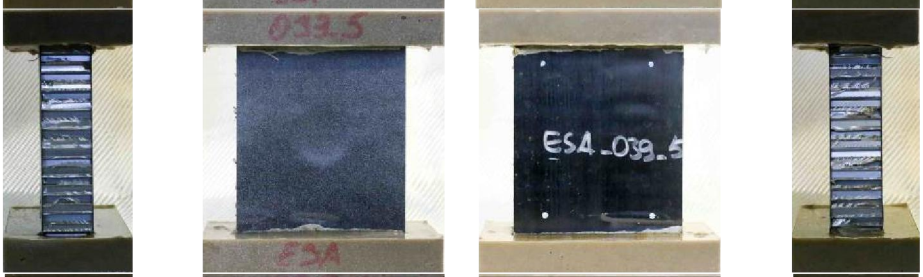
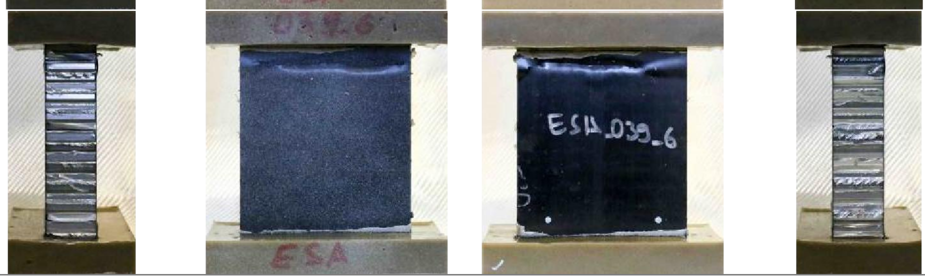
ESA_039_1	
ESA_039_2	
ESA_039_3	
ESA_039_4	
ESA_039_5	
ESA_039_6	

Table 8.23. After CAI test ESA_040 panel.

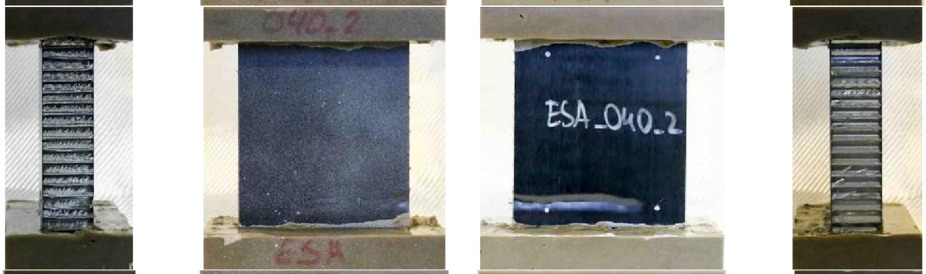
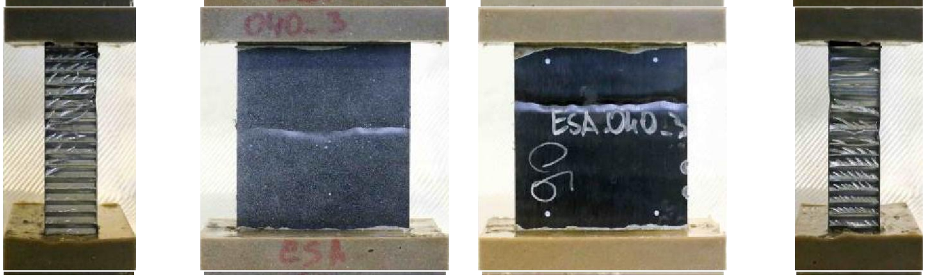
ESA_040_1	
ESA_040_2	
ESA_040_3	
ESA_040_4	
ESA_040_5	
ESA_040_6	

Table 8.24. After CAI test ESA_041 panel.

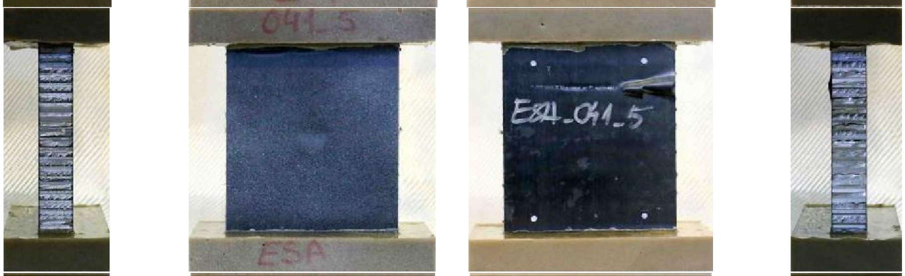
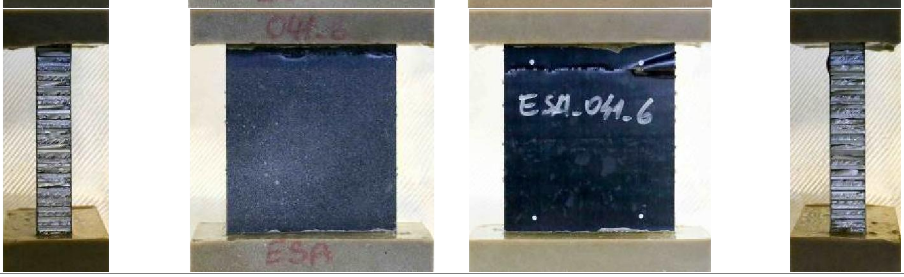
ESA_041_1	
ESA_041_2	
ESA_041_3	
ESA_041_4	
ESA_041_5	
ESA_041_6	

Table 8.25. After CAI test ESA_042 panel.

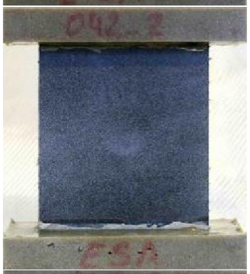
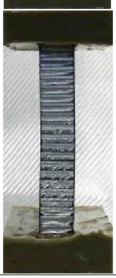
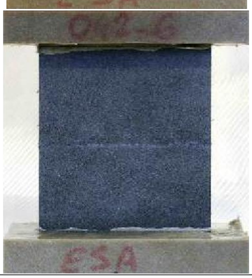
ESA_042_1				
ESA_042_2				
ESA_042_3				
ESA_042_4				
ESA_042_5				
ESA_042_6				

Table 8.26. After CAI test ESA_043 panel.

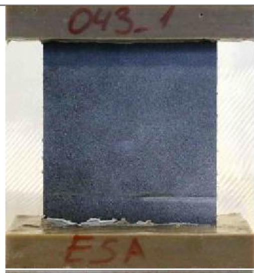
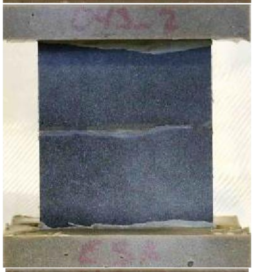
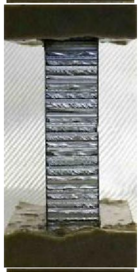
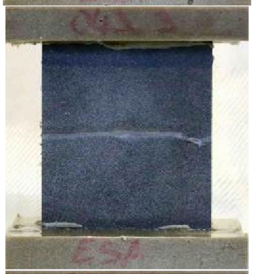
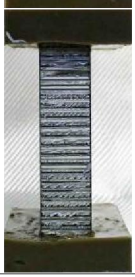
ESA_043_1				
ESA_043_2				
ESA_043_3				
ESA_043_4				
ESA_043_5				
ESA_043_6				

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Table 8.27. After CAI test ESA_044 panel.

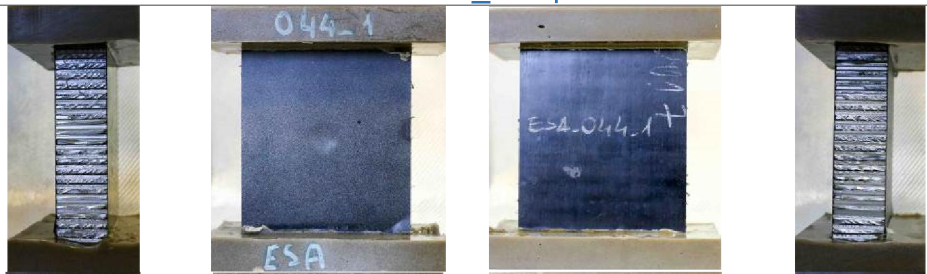
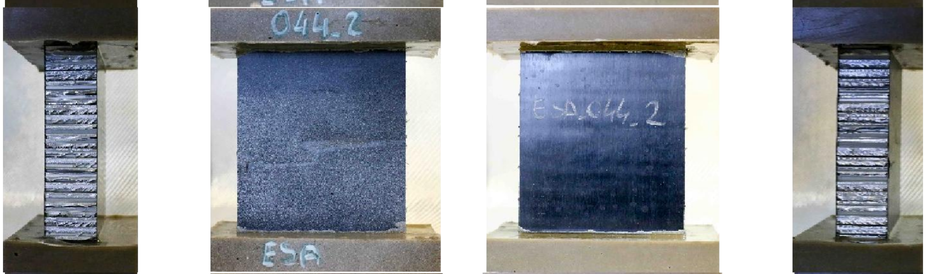
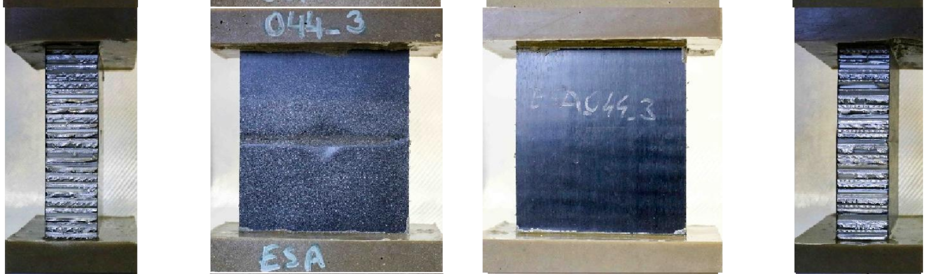
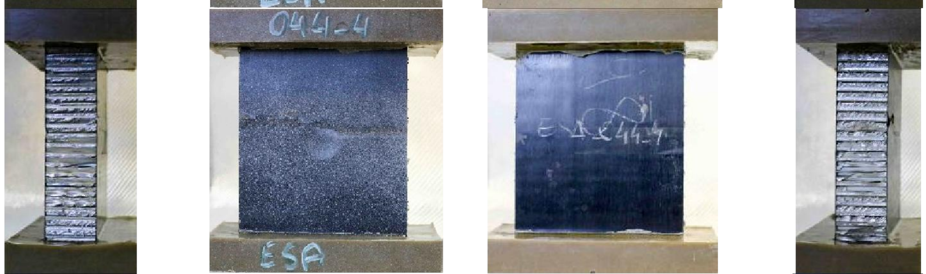
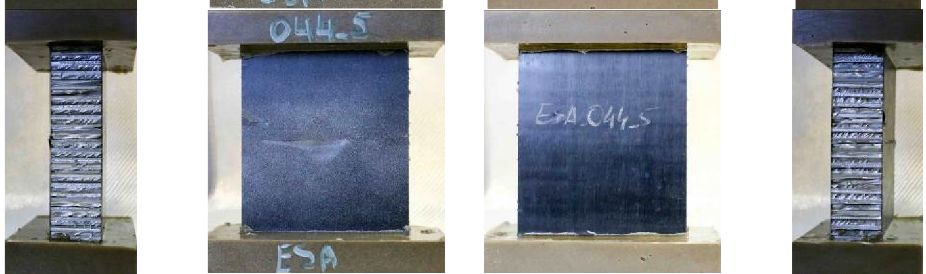
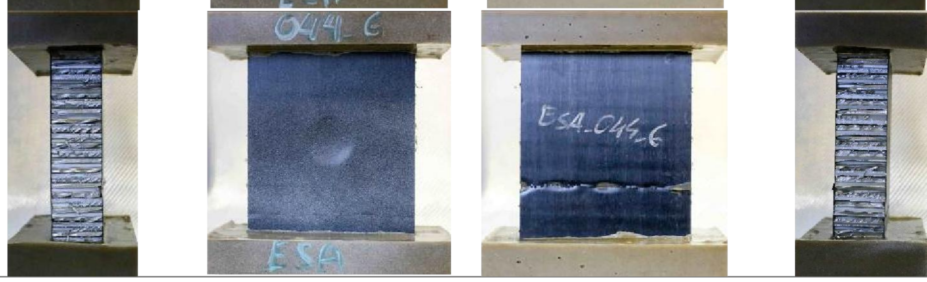
ESA_044_1	
ESA_044_2	
ESA_044_3	
ESA_044_4	
ESA_044_5	
ESA_044_6	

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Table 8.28. After CAI test ESA_045 panel.

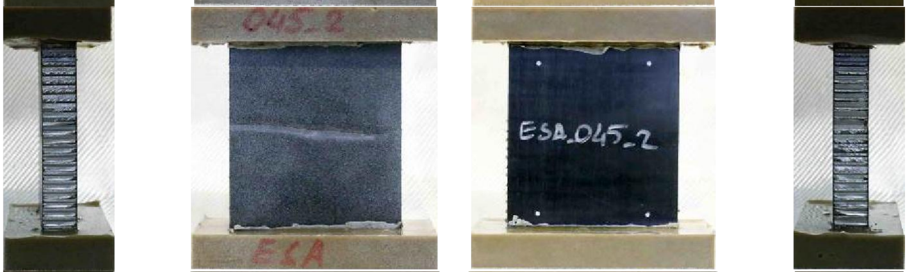
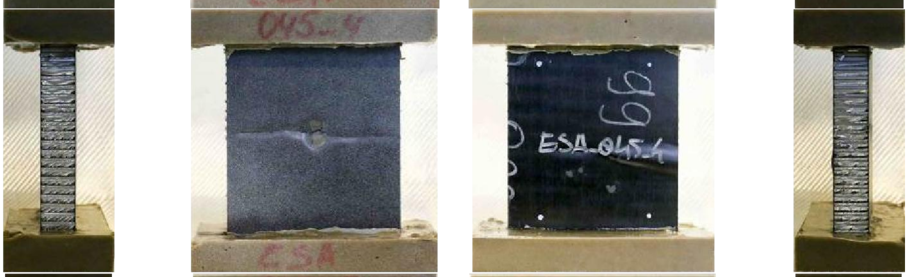
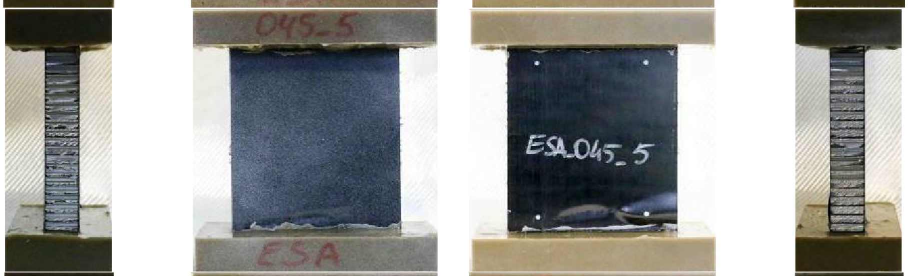
ESA_045_1	
ESA_045_2	
ESA_045_3	
ESA_045_4	
ESA_045_5	
ESA_045_6	

Table 8.29. After CAI test ESA_046 panel.

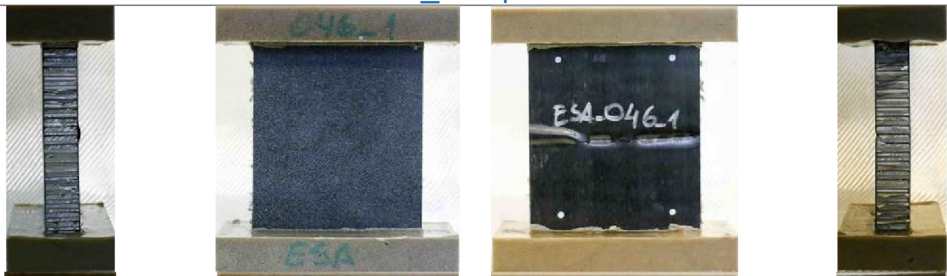
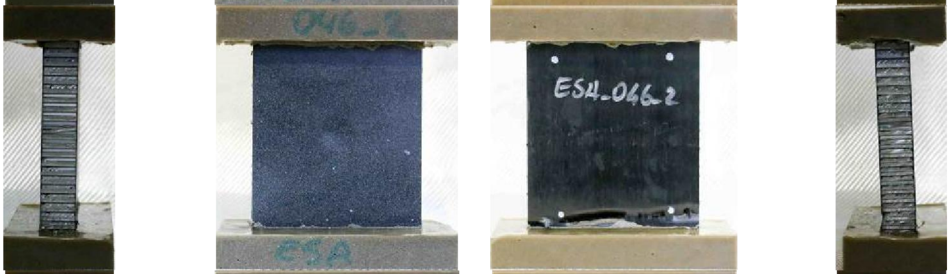
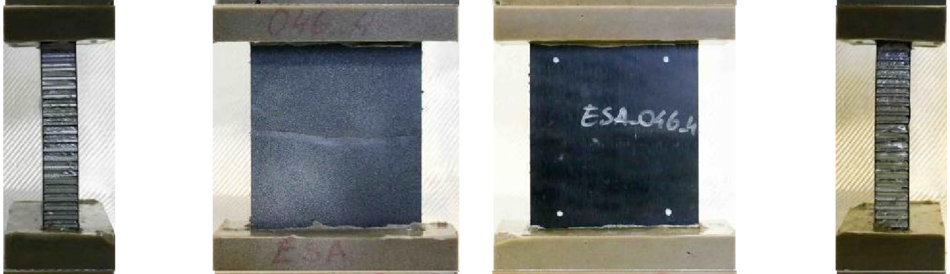
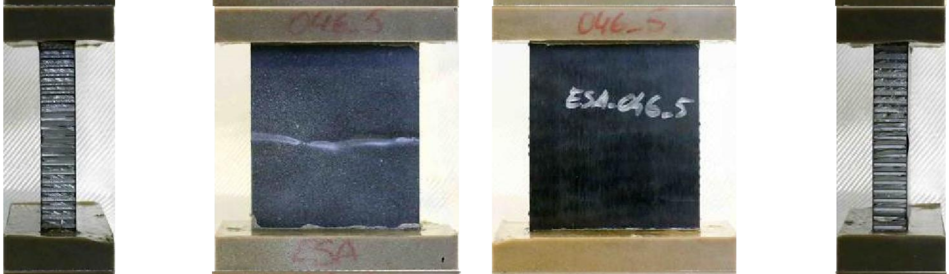
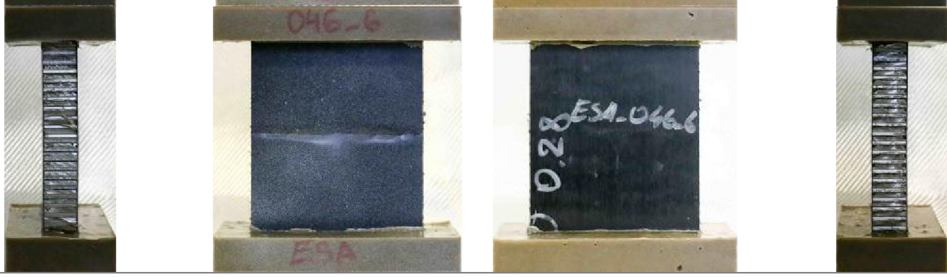
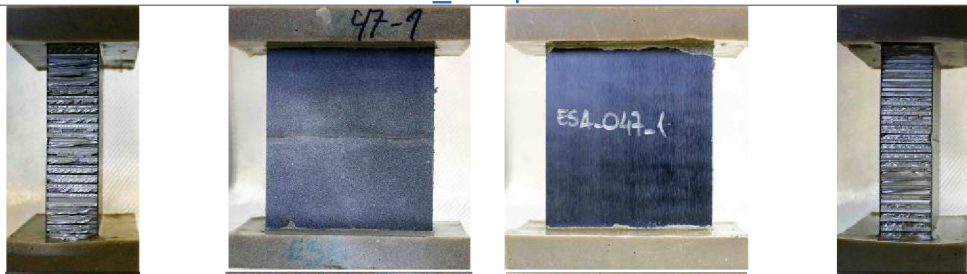
ESA_046_1	
ESA_046_2	
ESA_046_3	
ESA_046_4	
ESA_046_5	
ESA_046_6	

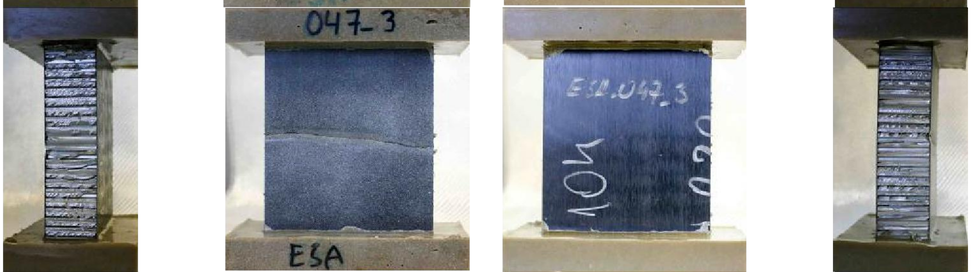
Table 8.30. After CAI test ESA_047 panel.

ESA_047_1

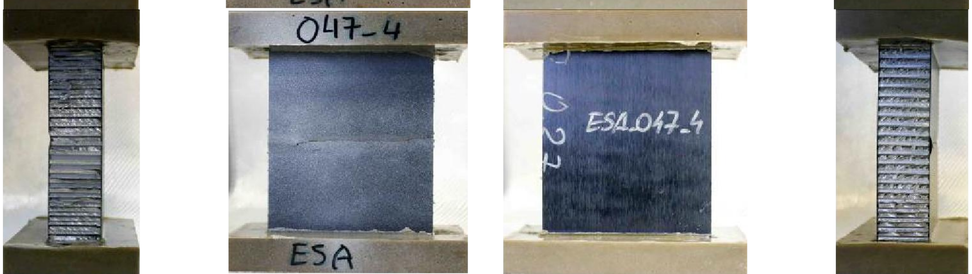


ESA_047_2

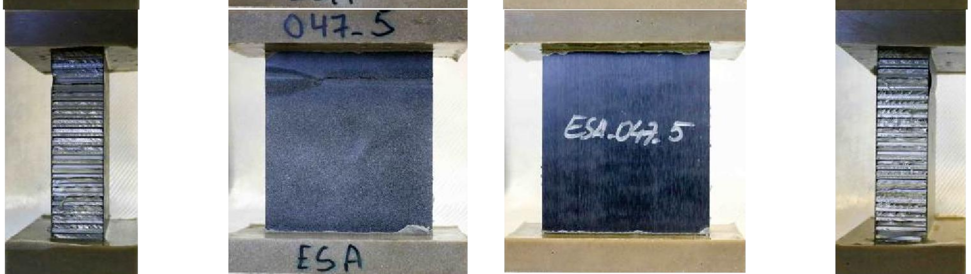
ESA_047_3



ESA_047_4



ESA_047_5



ESA_047_6

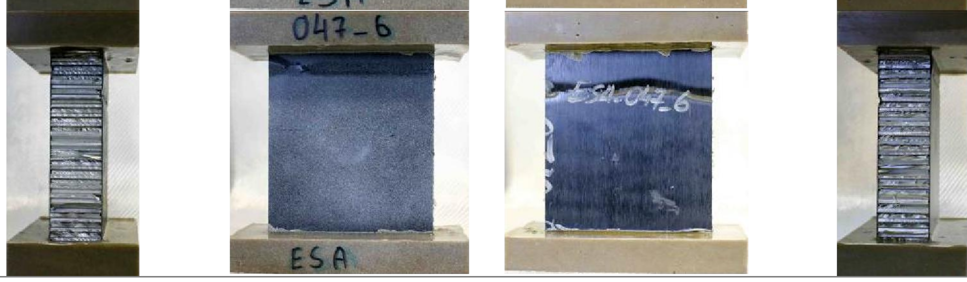


Table 8.31. After CAI test ESA_048 panel.

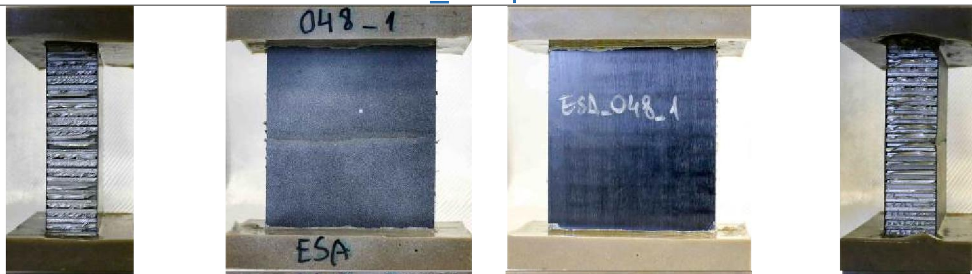
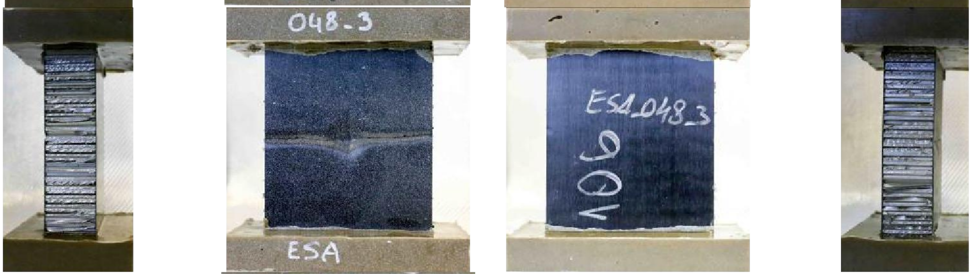
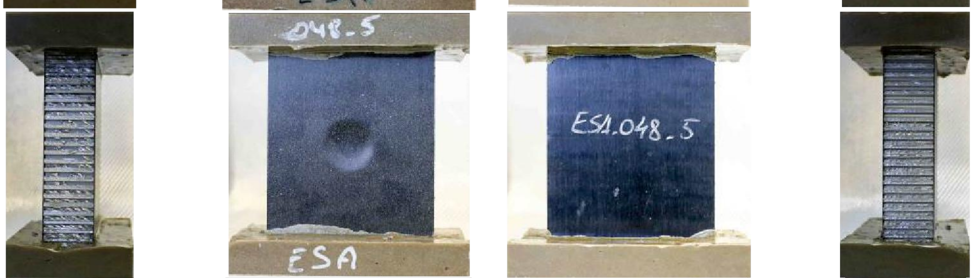
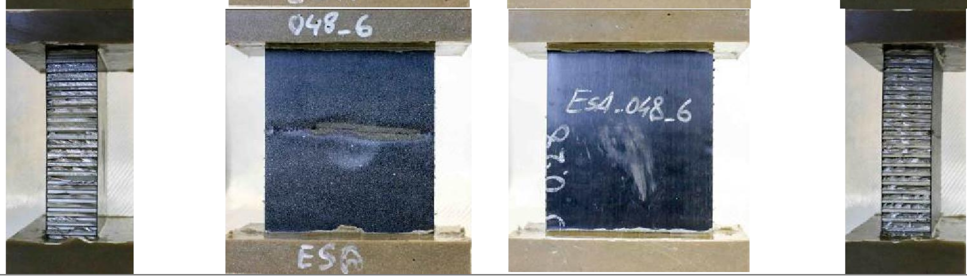
ESA_048_1	
ESA_048_2	
ESA_048_3	
ESA_048_4	
ESA_048_5	
ESA_048_6	

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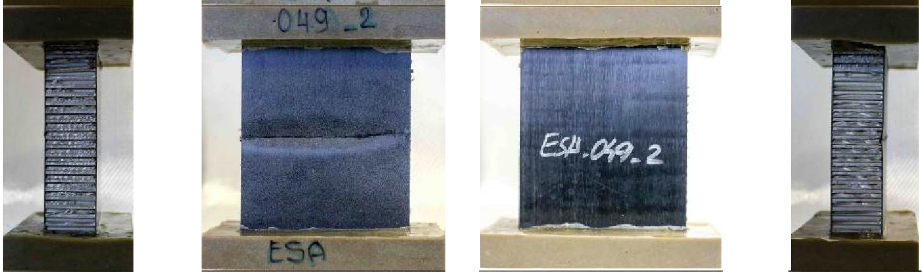
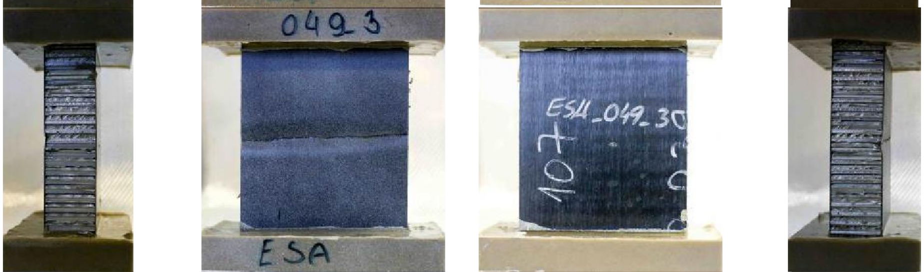
Table 8.32. After CAI test ESA_049 panel.

ESA_049_1

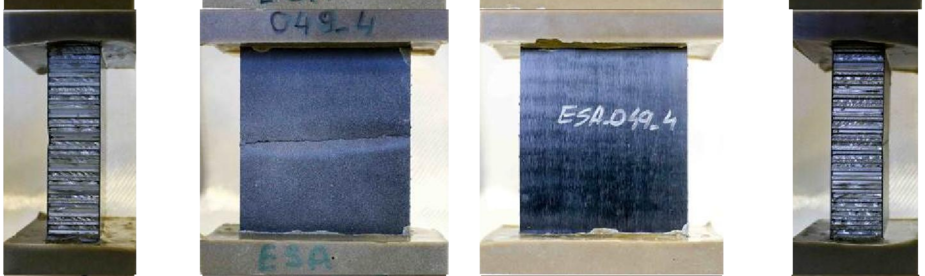
ESA_049_2



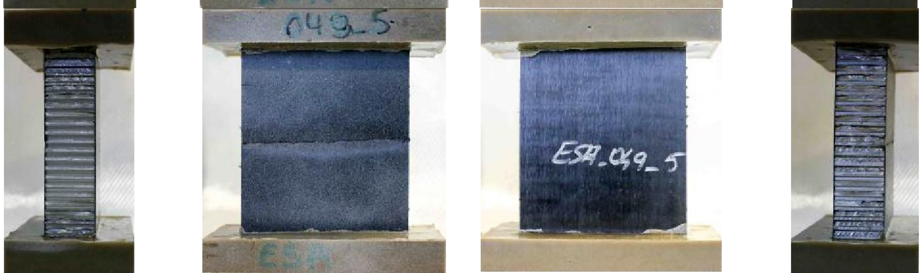
ESA_049_3



ESA_049_4



ESA_049_5



ESA_049_6

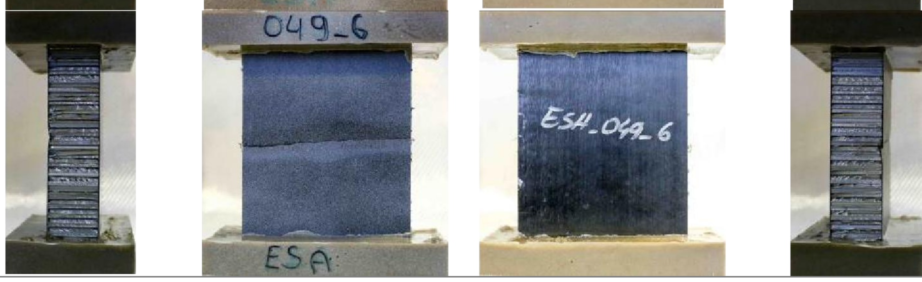
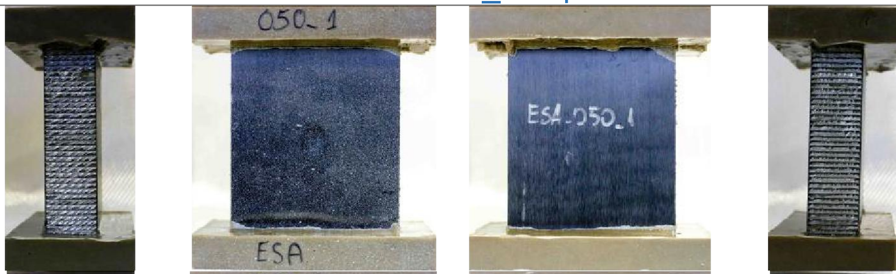
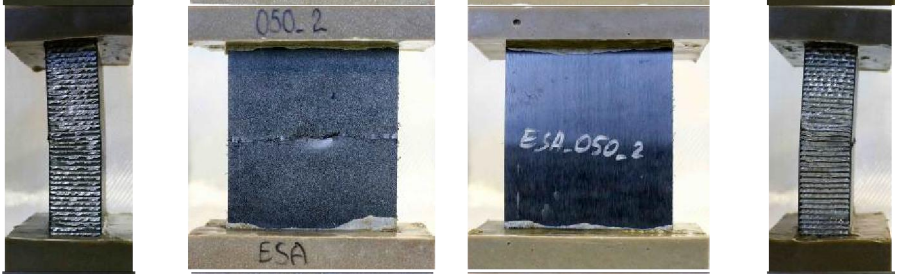
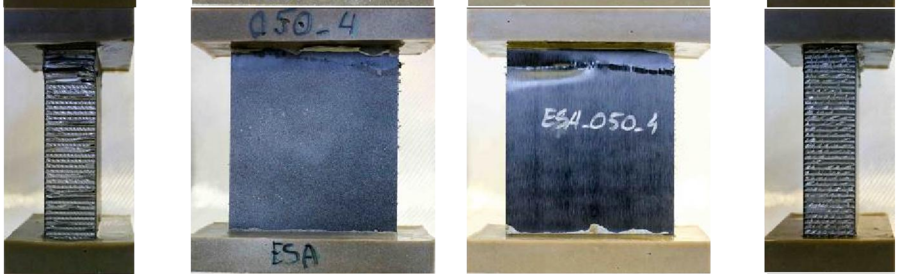
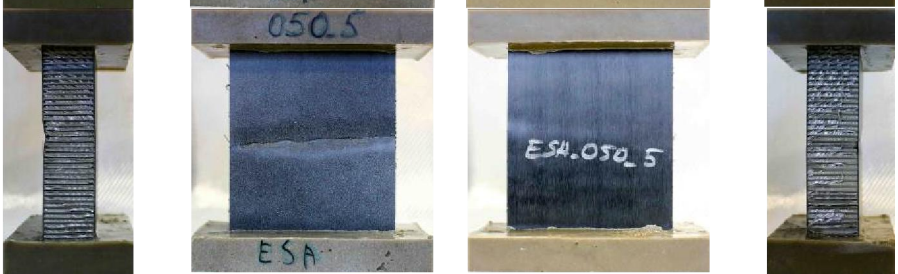
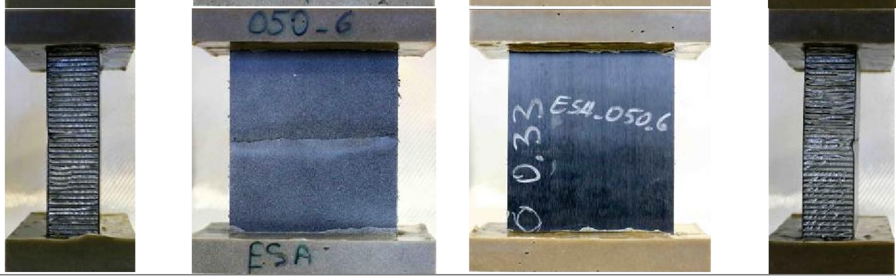


Table 8.33. After CAI test ESA_050 panel.

ESA_050_1	
ESA_050_2	
ESA_050_3	
ESA_050_4	
ESA_050_5	
ESA_050_6	

A list of specimens collapsed not at the middle of section:
ESA_026_1; ESA_026_2; ESA_026_3; ESA_026_4; ESA_026_5; ESA_026_6;
ESA_027_1; ESA_027_2;
ESA_029_1; ESA_028_2; ESA_028_3;
ESA_031_1; ESA_031_2; ESA_031_5;
ESA_035_5;
ESA_033_1; ESA_033_2; ESA_033_3;
ESA_036_2; ESA_036_4;
ESA_037_1; ESA_037_2; ESA_037_3; ESA_037_4; ESA_037_5; ESA_037_6;
ESA_038_1; ESA_038_2; ESA_038_3;
ESA_039_2; ESA_039_3; ESA_039_5; ESA_039_6;
ESA_040_1; ESA_040_2; ESA_040_6
ESA_041_1; ESA_041_2; ESA_041_3; ESA_041_4; ESA_041_5; ESA_041_6;
ESA_042_1; ESA_042_2; ESA_042_3; ESA_042_4; ESA_042_5;
ESA_043_1; ESA_043_4; ESA_043_5;
ESA_044_1; ESA_044_2; ESA_044_6;
ESA_045_5;
ESA_046_2;
ESA_047_5; ESA_047_6;
ESA_048_5;
ESA_050_1; ESA_050_4;

A list of specimens collapsed at the middle of section:
ESA_027_3; ESA_027_4; ESA_027_5; ESA_027_6;
ESA_028_4; ESA_028_5; ESA_028_6;
ESA_029_1; ESA_029_2; ESA_029_3; ESA_029_4; ESA_029_5; ESA_029_6;
ESA_030_1; ESA_030_2; ESA_030_3;
ESA_031_3; ESA_031_4; ESA_031_6;
ESA_032_1; ESA_032_2; ESA_032_3; ESA_032_4; ESA_032_6;
ESA_034_1; ESA_034_2; ESA_034_3; ESA_034_4; ESA_034_5 ESA_034_6;
ESA_035_1; ESA_035_2; ESA_035_3; ESA_035_4; ESA_035_5; ESA_035_6;
ESA_036_1; ESA_036_3; ESA_036_5; ESA_036_6;
ESA_038_4;
ESA_039_1; ESA_039_4
ESA_040_3; ESA_040_4; ESA_040_5;
ESA_042_6;
ESA_043_2; ESA_043_3; ESA_043_6;
ESA_044_3; ESA_044_4; ESA_044_5;
ESA_045_1; ESA_045_2; ESA_045_3; ESA_045_4; ESA_045_6;
ESA_046_1; ESA_046_3; ESA_046_4; ESA_046_5; ESA_046_6;
ESA_047_1; ESA_047_2; ESA_047_3; ESA_047_4;
ESA_048_1; ESA_048_2; ESA_048_3; ESA_048_4; ESA_048_6;
ESA_049_1; ESA_049_2; ESA_049_3; ESA_049_4; ESA_049_5; ESA_049_6;
ESA_050_2; ESA_050_3; ESA_050_5; ESA_050_6;

A summary of tests are depicted in 3D graphs for clear overview and formulation of best practice/guidelines. It should be noted that it`s quite frequent that a certain exception in trend appears and more in depth study should be composed to understand the triggering mechanisms why some of set-ups are extremely sensitive and others are robust enough.

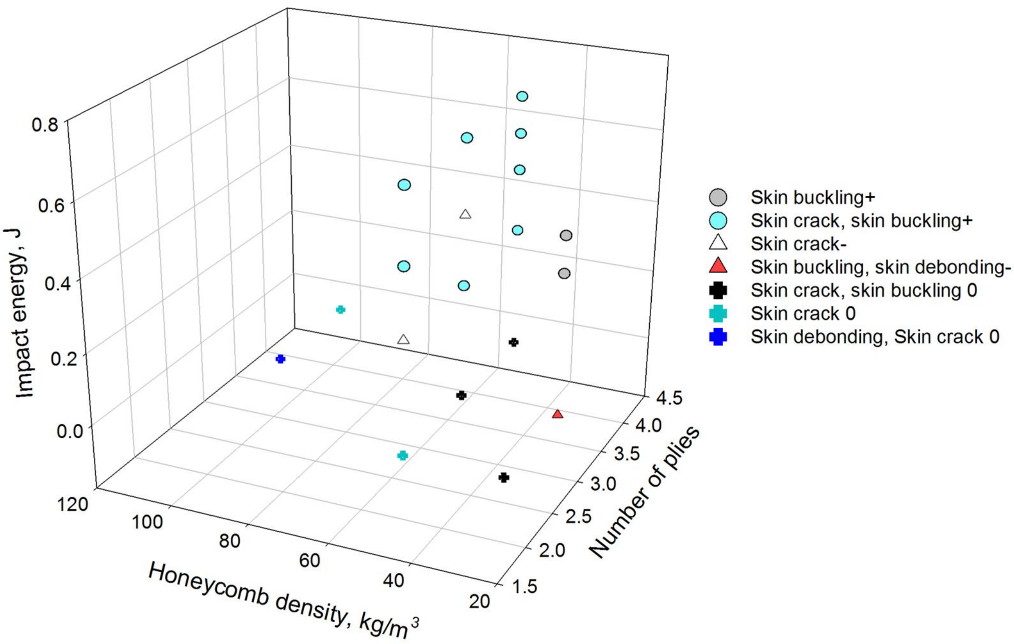


Figure 8.18. **Impact** tests with **20 mm** indenter. Distribution of failure types depending on honeycomb density, number of plies in facesheet and impact energy.

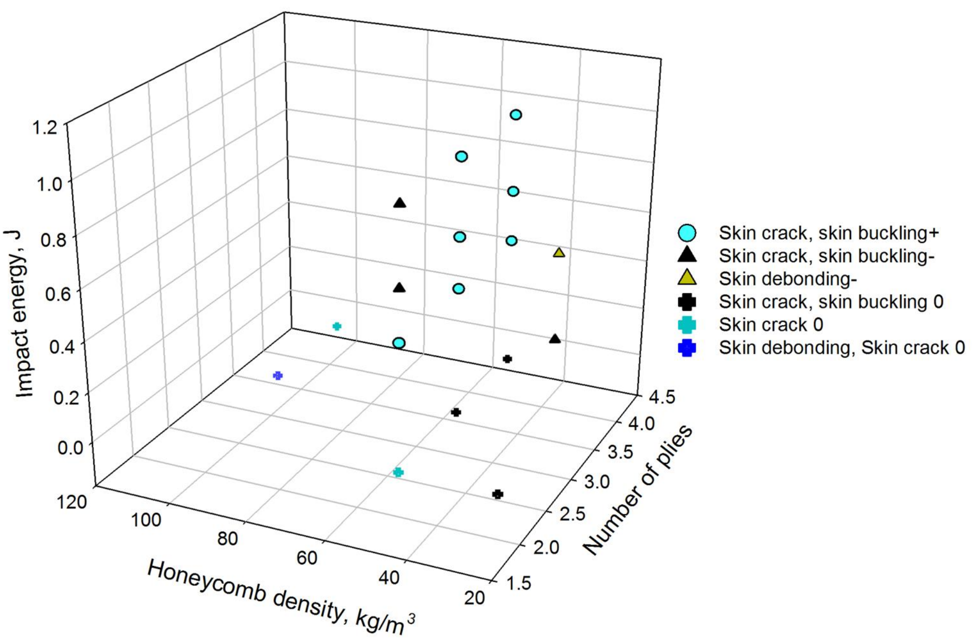


Figure 8.19. **Impact** tests with **150 mm** indenter. Distribution of failure types depending on honeycomb density, number of plies in facesheet and impact energy.

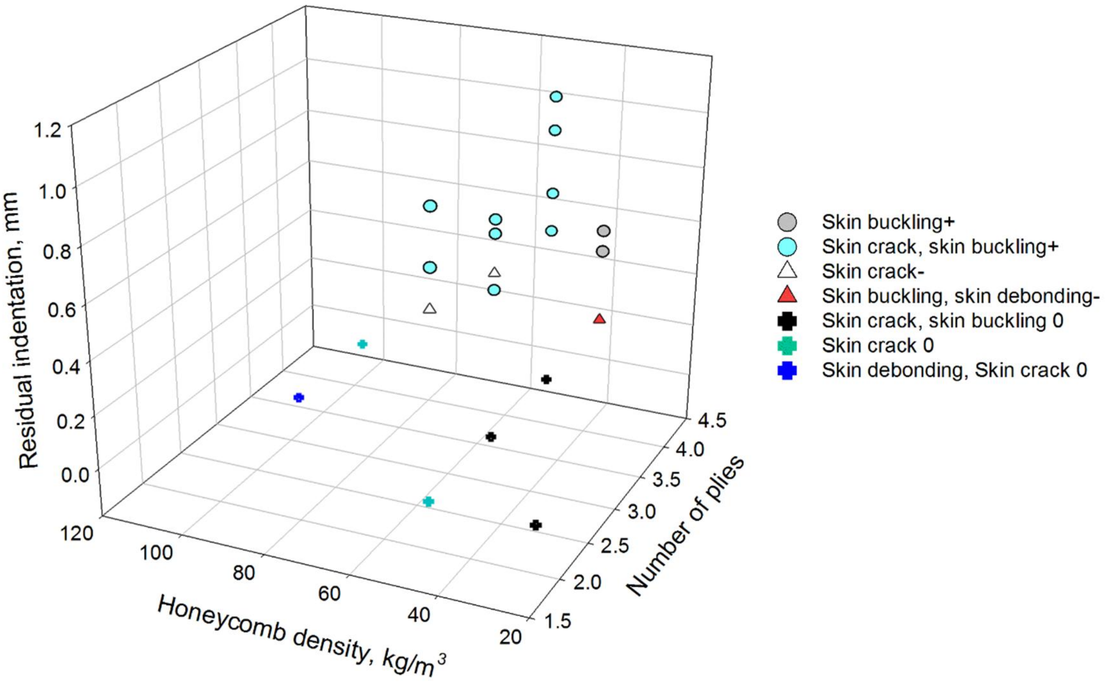


Figure 8.20. **Impact** tests with **20 mm** indenter. Distribution of failure types depending on honeycomb density, number of plies in facesheet and residual indent after impact.

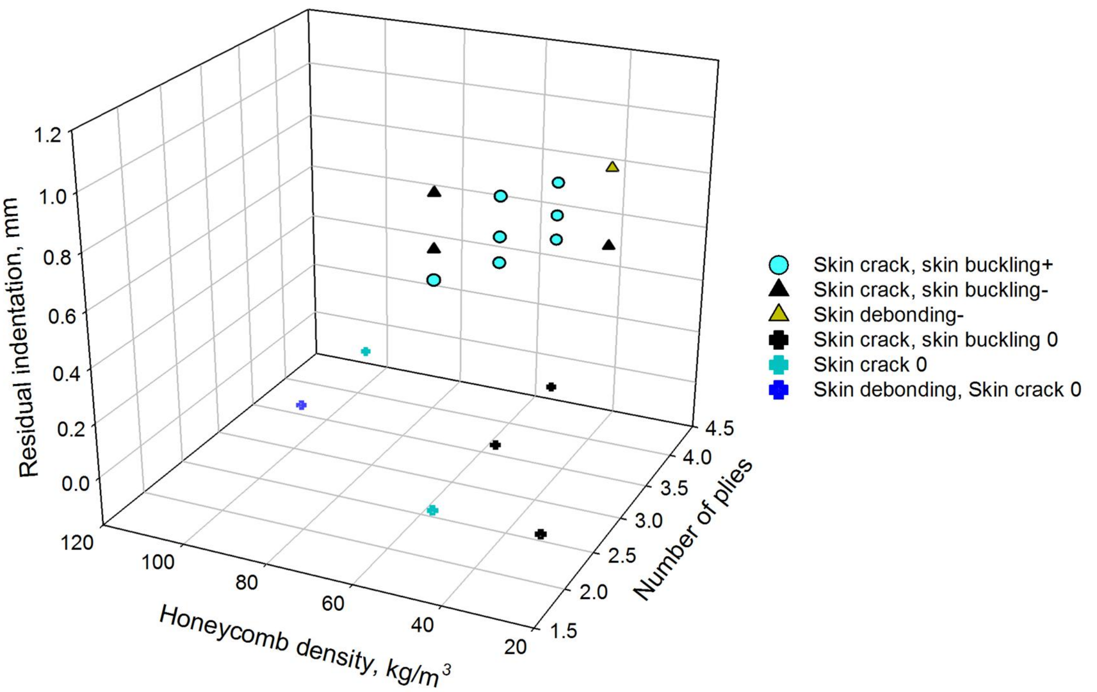


Figure 8.21. **Impact** tests with **150 mm** indenter. Distribution of failure types depending on honeycomb density, number of plies in facesheet and residual indent after impact.

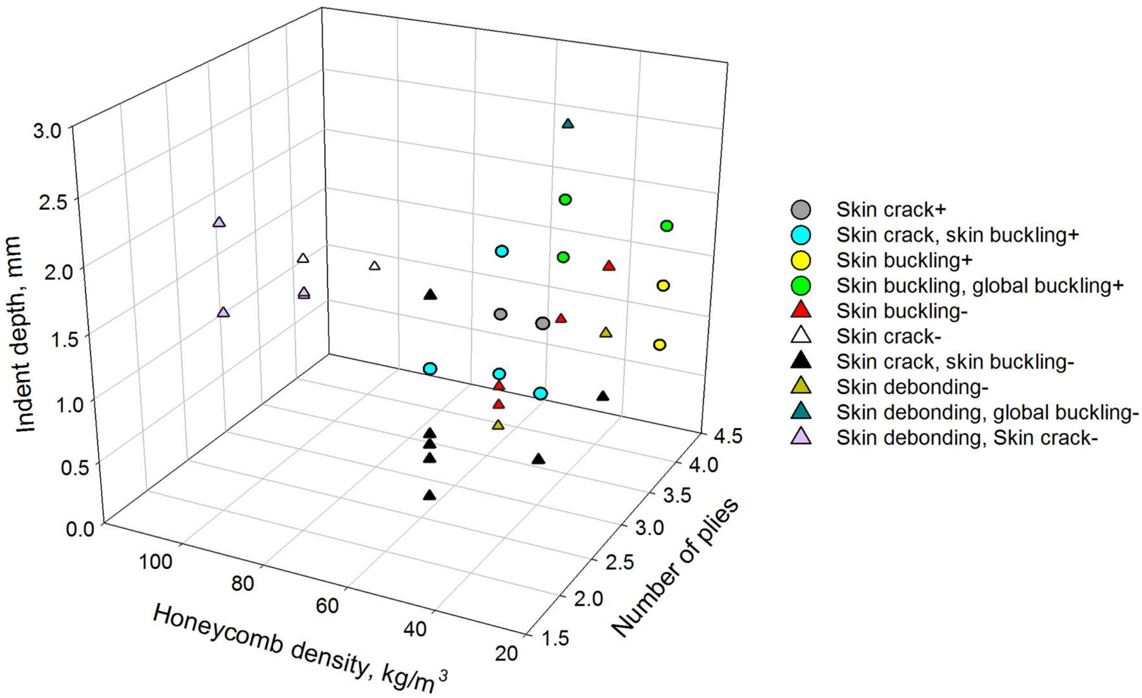


Figure 8.22. **Quasi-static indentation** tests with **20 mm** indenter. Distribution of failure types depending on honeycomb density, number of plies in facesheet and indent depth.

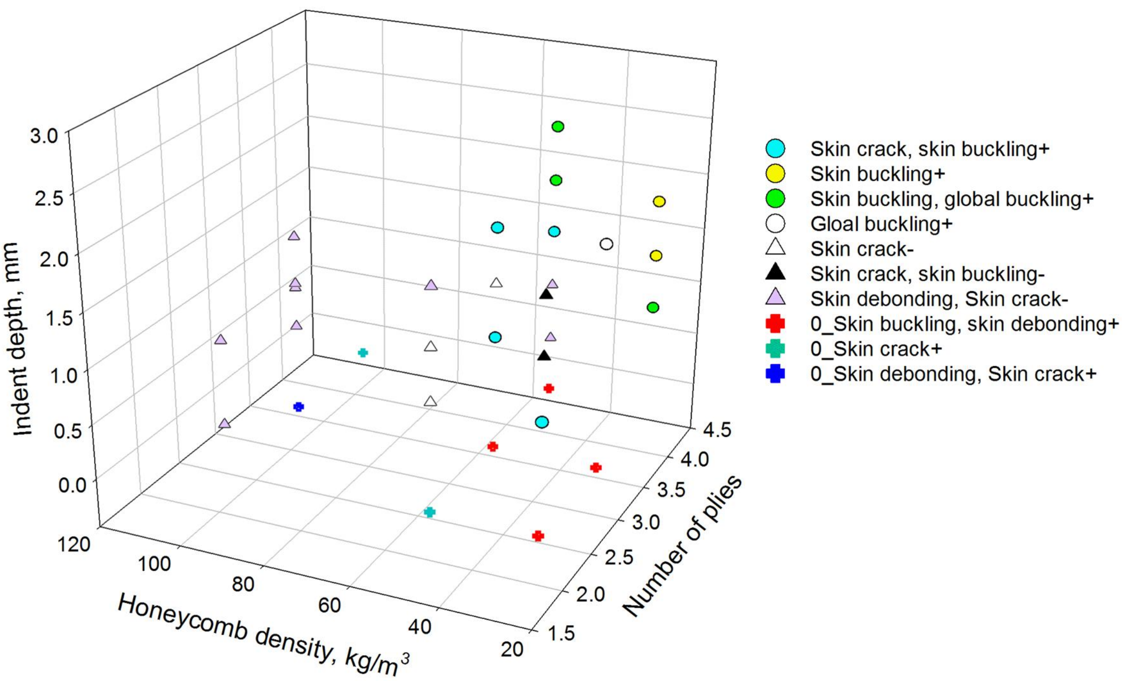


Figure 8.23. **Quasi-static indentation** tests with **150 mm** indenter. Distribution of failure types depending on honeycomb density, number of plies in facesheet and indent depth.

9 References

1. Tomblin J, Lacy T, Smith B, Hooper S, Vizzini A, Lee S. Review of Damage Tolerance for Composite Sandwich Airframe Structures. 1999:71. doi:DOT/FAA/AR-99/49.
2. Czabaj MW, Zehnder AT. Compression After Impact of Sandwich Composite Structures : Experiments and Modeling. 2010;(April):1-16.
3. McGowan DM, Ambur DR. Damage characteristics and residual strength of composite sandwich panels impacted with and without compression loading. In: *39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. ; 1998.
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5. 40011445215NLNDe _deliverable_D_1.1
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Honeycomb foil thickness	Lay-up	Honeycomb cell size	Damage type	Indenter diameter	Damage size criteria		Max Load Impact & Quasi-Static	Impact velocity	Indent Failure	Deflection in Quasi-Static test		Surface Inspection. Experimental					Surface Inspection. Analytical				Surface Inspection. FEM					Compression After Impact				
					value	unit				Deflection A skin	Deflection B skin	Depth	Mean Ø	Max Ø	Area	Volume	Depth	Mean Ø	Area	Volume	Depth	Mean Ø	Max Ø	Area	Volume	Load	σskins	Eskins	Deflection	Failure
		mm		mm			N	m/s		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	kN	MPa	GPa	mm	mm
Thick foil, 0.0381 mm	[60/0/-60]	3.2	Debonding I	20	20	mm	-	-	-	-	-	0.87	30.10	32.80	710.00	242.00	-	-	-	-	-	-	-	-	-	10.69	203.73	38.30	0.60	Skin debonding, skin crack+
				35	35	mm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.75	147.75	34.37	0.49	Skin debonding, skin crack+
				48	48	mm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.80	129.62	31.80	0.59	Skin debonding, skin crack+
			Debonding II	12	12	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12.69	241.86	35.60	0.77	Skin debonding, skin crack+
				20	20	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11.60	221.15	35.35	0.80	Skin debonding, skin crack+
				30	30	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9.05	172.56	38.10	0.46	Skin debonding, skin crack+
				50	50	N	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.79	148.43	31.67	0.51	Skin debonding+
			Quasi-static	20	500	N	500	-	Dent	1.33	0.20	0.44	17.08	18.92	247.60	34.80	0.62	23.10	418.80	47.00	0.44	17.90	18.40	252.00	20.00	12.23	232.80	40.26	0.71	Skin debonding, skin crack-
				150	750	N	749	-	Dent	0.78	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11.21	213.67	41.93	0.63	Skin debonding, skin crack-
					1000	N	999	-	Dent	1.18	0.45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10.13	193.13	40.76	0.52	Skin debonding, skin crack-
					1400	N	1316	-	Dent	1.61	0.62	1.04	32	33.4	795	340	1.08	35.7	1001	304	-	-	-	-	-	9.64	183.83	40.14	0.52	Skin debonding, skin crack-
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12.70	241.63	38.85	0.79	Skin debonding, skin crack+
	[0/60/-60/0]		Quasi-static	20	500	N	500	-	Dent	1.14	0.19	0.40	16.78	17.52	228.40	31.80	0.56	23.10	418.00	43.00	0.36	16.70	17.70	222.00	17.00	35.60	494.46	52.71	1.47	Skin crack-
				150	1400	N	1399	-	Dent	1.77	0.7	1.09	34.7	36.3	979	433	1.02	37.1	1081	293	-	-	-	-	-	-	-	-	-	-
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	37.92	526.71	48.20	1.67	Skin crack+
	[-60/60/0]		Quasi-static	20	500	N	496	-	Dent	1.31	0.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	19.14	364.95	41.49	1.01	Skin crack-
					750	N	686	-	Skin crack	1.60	0.22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.30	348.93	42.14	0.95	Skin crack-
				150	1000	N	998	-	Dent	1.14	0.26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.43	351.46	39.35	1.04	Skin debonding, skin crack-
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16.75	319.38	41.55	0.89	Skin debonding, skin crack+
	[90/0]		Quasi-static	20	500	N	502	-	Dent	1.59	0.21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8.05	163.48	39.34	0.55	Skin debonding, skin crack-
					750	N	748	-	Dent	2.26	0.33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8.70	165.79	32.43	0.88	Skin debonding, skin crack-
				150	500	N	499	-	Dent	0.40	0.11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.54	189.77	48.15	0.52	Skin debonding, skin crack-
					1000	N	1002	-	Dent	1.16	0.31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.48	188.33	44.32	0.48	Skin debonding, skin crack-
Thin foil, 0.0178 mm	[0/-60/+60/0]	3.2	Impact	20	0.33	J	472	0.77	Dent	-	-	0.58	27.32	28.92	620.00	143.80	0.74	35.46	1030.60	135.80	-	-	-	-	-	22.81	334.49	46.42	0.94	Skin buckling, skin crack+
					0.50	J	592	0.95	Dent	-	-	0.72	28.72	30.72	672.17	160.00	0.86	39.03	1245.00	192.33	-	-	-	-	-	23.46	335.18	48.68	0.81	Skin buckling, skin crack+
					0.60	J	670	1.07	Dent/skin crack	-	-	0.95	25.55	27.05	520.00	129.50	0.89	35.20	972.00	153.00	-	-	-	-	-	22.87	324.26	46.36	0.83	Skin buckling, skin crack+
					0.70	J	657	1.12	Dent, crack	-	-	1.07	33.24	37.00	915.20	311.80	1.00	44.24	1603.80	283.20	-	-	-	-	-	20.62	301.84	49.48	0.75	Skin buckling, skin crack+
				150	0.50	J	614	0.9007	Dent	-	-	0.57	25.6	25.9	534	132	0.91	37.1	1078	255	-	-	-	-	-	25.64	397.15	55.60	0.86	Skin buckling, skin crack+
					0.70	J	744	1.0578	Dent	-	-	0.66	30.5	31.3	773	186	1.04	40.8	1309	341	-	-	-	-	-	24.25	375.56	51.53	0.83	Skin buckling, skin crack+
					1.00	J	897	1.2765	Dent	-	-	0.78	33.3	34.1	866	266	1.19	45.3	1609	467	-	-	-	-	-	23.56	364.90	54.32	0.80	Skin buckling, skin crack+
			Quasi-static	20	1.00	mm	198	-	Dent	1.02	0.149	0.28	22	23.5	386	38	0.48	30.7	742	62	0.52	19.2	21.9	295	79	17.62	230.33	39.50	0.68	Skin buckling-
					1.50	mm	468	-	Dent	1.51	0.18	0.53	26.00	28.20	544.00	98.60	0.70	33.70	906.00	109.80	0.94	25.40	27.40	523.50	169.50	24.33	331.61	45.33	0.84	Skin buckling, global buckling+
					2.00	mm	604	-	Dent/crack	1.97	0.28	1.22	31.40	33.80	796.00	241.40	0.84	38.84	1219.60	180.00	1.38	32.10	33.95	833.50	327.00	22.06	300.39	44.15	0.85	Skin buckling, global buckling+
					2.5	mm	567	-	Dent/invisible crack	2.55	0.32	0.95	42.3	44.9	1416	407	0.97	51.6	2095	348	1.75	46.5	49	1708	878	9.04	118.15	39.65	0.34	Debonding, global buckling-
				150	0.50	mm	196	-	Dent	0.50	0.08	0.20	20.50	22.10	335.50	25.50	0.44	30.15	714.50	72.00	-	-	-	-	-	16.13	228.73	45.67	0.56	Skin debonding, skin crack -
					1.00	mm	318	-	Dent	1.01	0.13	0.51	30.5	32.2	724	135	0.62	38.7	1177	158	-	-	-	-	-	15.32	217.25	43.64	0.50	Skin debonding, skin crack -
					1.50	mm	882	-	Dent	1.51	0.28	0.85	35.03	36.40	979.25	323.50	0.95	41.48	1365.50	306.75	1.26	38.30	38.80	1156.00	481.00	23.06	321.18	44.45	0.85	Skin buckling, skin crack+
					2.00	mm	684	-	Dent	1.98	0.27	0.99	44.6	45.8	1563	587	1.04	57.3	2582	551	-	-	-	-	-	18.00	255.26	45.82	0.62	Skin buckling, global buckling+
					2.50	mm	864	-	Dent	2.46	0.41	1.17	50.8	53.5	2069	944	1.23	64.6	3275	808	-	-	-	-	-	15.16	214.87	43.47	0.53	Skin buckling, global buckling+
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28.91	368.41	46.95	0.95	Skin buckling, skin crack+
		6.4	Quasi-static	20	1.00	mm	215	-	Dent	0.95	0.07	0.30	23.45	26.10	451.00	46.50	0.51	32.00	806.00	71.00	0.48	21.00	24.00	353.00	71.00	22.01	291.51	49.04	0.67	Skin buckling+
					1.50	mm	335	-	Dent	1.43	0.11	0.52	29.70	32.45	702.50	124.50	0.69	39.85	1247.50	147.00	0.84	29.70	32.80	706.00	197.00	20.30	268.92	49.50	0.78	Skin buckling+
					2.00	mm	471	-	Dent	1.90	0.13	0.75	35.80	40.10	1005.50	268.50	0.86	47.15	1745.50	257.50	1.27	38.10	39.90	1153.00	391.00	18.72	247.99	49.47	0.57	Skin buckling, global buckling+
				150	1.00	mm	332	-	Dent	0.96	0.09	0.53	29.70	32.35	673.00	148.50	0.64	39.65	1233.00	169.50	0.68	25.40	26.80	515.00	185.00	20.23	282.88	49.74	0.65	Skin buckling, global buckling+
					1.50	mm	494	-	Dent	1.44	0.13	0.79	35.80	39.95	1030.50	341.00	0.84	48.50	1850.50	323.00	1.10	36.30	38.00	1045.00	513.00	16.17	226.06	49.94	0.51	Skin buckling+
					2.00	mm	689	-	Dent	1.93	0.22	0.99	42.60	44.95	1466.50	595.50	1.05	57.55	2601.00	557.50	1.51	47.40	49.10	1770.00	1048.00	15.01	209.89	51.24	0.47	Skin buckling+
	[-60/+60/0]	3.2	Impact	20	0.31	J	487	0.79	Dent	-	-	0.55	21.1	22.8	353	69	0.73	28.4	632	83	-	-	-	-	-	13.43	250.38	40.36	0.72	Skin buckling, skin crack+
					0.50	J	650	0.97	Dent	-	-	0.61	23.47	24.33	442.33	95.67	0.88	32.60	835.00	132.00	-	-	-	-	-	15.91	289.33	37.49	0.89	Skin crack-
					0.70	J	658	1.20	Dent	-	-	0.75	26.8	27.8	567	156	1.01	36	1015	182	-	-	-	-	-	18.83	338.47	37.52	1.12	Skin buckling, skin crack+
					0.70	J	804	1.19	Dent	-	-	0.8	27.6	29.6	601	163	1.01	36	1015	182	-	-	-	-	-	14.92	278.20	37.70	0.83	Skin buckling, skin crack+
				150	0.50	J	614	0.93	Dent	-	-	0.64	25	26	500	136	0.98	36.2	1032	277	-	-	-	-	-	16.76	305.16	37.00	0.99	Skin buckling, skin crack+
					0.70	J	726	1.05	Dent	-	-	0.75	28.2	29.6	624	195	1.11	39.9	1252	368	-	-	-	-	-	13.14	227.07	36.94	0.70	Skin buckling, skin crack+
					1.00	J	795	1.30	Dent	-	-	0.88	29.4	30.7	696	283	1.27	44.3	1539	502	-	-	-	-	-	16.34	293.09	37.16	0.96	Skin buckling, skin crack+
			Quasi-static	20	100	N	100	-	Dent	0.58	0.06	0.15	14.20	14.85	165.00	9.50	0.34	22.00	380.00	22.50	0.22	14.30	14.80	163.00	11.00	9.39	162.89	30.55	0.60	Skin debonding-
					125	N	126	-	Dent	0.75	0.07	0.22	15.85	16.55	203.50	17.00	0.39	24.60	474.50	32.50	0.28	16.00	16.40	204.00	16.00	11.99	208.14	31.59	0.76	Skin buckling-
					150	N	151	-	Dent	0.90	0.08	0.29	19.40	20.85	301.50	30.00	0.44	26.95	571.00	44.50	0.34	17.70	18.40	249.00	23.00	12.34	214.24	31.89	0.79	Skin buckling-
					1	mm	291	-	Dent	1.00	0.16	0.34	16.1	17.4	203	25	0.51	21.7	371	34	0.51	16.1	16.4	204	26	14.60	262.47	37.39	0.81	Skin buckling, skin crack+
					1.50	mm	516	-	Dent	1.47	0.14	0.58	22.15	23.95	388.50	77.75	0.75	28.88	654.75	89.00	1.05	23.80	24.20	438.00	69.00	15.74	290.74	38.83	0.89	Skin crack+
					2.00	mm	689	-	Dent	1.98	0.20	2.26	24.90	27.40	500.50	275.50	0.91	33.30	872.00	142.00	1.53	35.00	35.90	970.00	132.00	12.26	220.45	37.55	0.71	Skin buckling, skin crack+
				150	1.00	mm	648	-	Dent	1.02	0.11	0.72	27.7	28.8	613	174	0.79	30.9	748	173	-	-	-	-	-	20.25	384.70	41.33	1.14	Skin buckling, skin crack+
					1.50	mm	1028	-	Dent	1.50	0.17	1.01	33.1	34.7	892	368	1.09	39.3	1213	352	-	-	-	-	-	18.30	347.50	40.00	1.04	Skin crack-
					2.00	mm	1304	-	Dent	1.99	0.23	1.25	38.9	40.7	1184	636	1.28	44.5	1554	509	-	-	-	-	-	17.27	327.97	39.78	1.34	Skin buckling, skin crack+
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12.46	223.95	37.15	0.65	Skin buckling, skin crack+
		6.4	Impact	20	0.39	J	1177	0.86	Dent	-	-	0.75	34.70	36.20	967.00	258.00	0.90	45.70	1637.00	255.00	-	-	-	-	-	9.60	175.68	39.03	0.53	Skin buckling+
					0.49	J	2028	0.94	Dent	-	-	0.82	36.45	38.15	1074.50	323.50	0.99	48.80	1868.00	317.00	-	-	-	-	-	11.40	208.71	35.17	0.62	Skin buckling+
				150	0.37	J	410	0.78	Dent	-	-	0.79	35.4	37	989	333	0.95	49.7	1943	393	-	-	-	-	-	11.53	218.92	39.95	0.62	Skin buckling, skin crack-
					0.70	J	583	1.07	Dent	-	-	1.05	43	44.2	1444	638	1.21	59.8	2812	708	-	-	-	-	-	8.68	164.87	39.58	0.53	Skin debonding-
			Quasi-static	20	1.00	mm	187	-	Dent	0.99	0.06	0.32	18.70	20.05	280.50	33.50	0.51	29.95	704.50	62.50	0.51	17.50	18.10	242.00	56.00	10.74	193.07	37.69	0.58	Skin buckling, skin crack-
					1.50	mm	282	-	Dent	1.48	0.10	0.55	24.80	26.10	494.50	103.50	0.67	36.65	1054.50	122.50	0.82	25.80	26.90	525.00	166.00	9.44	169.76	36.92	0.51	Skin debonding-
					2.00	mm	414	-	Dent	1.98	0.12	0.76	31.4	34.5	788	233	0.87	44.3	1541	230	1.51	32.8	33.5	849	330	10.30	185.16	38.28	0.55	Skin buckling-
				150	2.00	mm	617	-	Dent	-	-	0.99	40.6	42	1294	566	1.06	54.2	2311	518	-	-	-	-	-	11.11	211.06	39.21	0.62	Global buckling+
			Undamaged	Undamaged	-	-	-	-	-	-	-	0.51	24.5	25.1	469	95	-	-	-	-	-	-	-	-	-	10.51	202.89	39.13	0.57	Skin buckling, debonding+
	[90/0]	3.2	Impact	20	0.31	J	466	0.80	Dent	-	-	0.68	19	21	286	72	0.8	27.5	594	86	0.8	15.2	15.3	183	112	12.01	355.68	14.14	0.73	Skin crack-
					0.50	J	606	1.01	Dent	-	-	0.82	21.6	23.4	388	115	0.96	31.6	782	136	1.26	23	23	418	353	11.82	350.05	59.21	0.72	Skin buckling, skin crack+
					0.70	J	727	1.20	Dent	-	-	1.02	25.5	28.4	504	193	1.1	34.8	951	188	1.26	23	23	418	353	12.22	361.69	1.10	0.68	Skin buckling, skin crack+
				150	0.50	J	625	0.91	Dent	-	-	0.8	25.8	25.9	530	193	1.09	35.2	971	317	1.74	29	29.2	667	713	11.98	354.76	62.28	0.66	Skin buckling, skin crack+
					0.70	J	731	1.07	Dent	-	-	0.9	27.6	28.1	593	246	1.23	38.7	1178	418	1.74	29	29.2	667	713	11.00	325.80	58.03	0.65	Skin buckling, skin crack-
					1.00	J	924	1.28	Dent	-	-	1.08	30.1	31.4	732	362	1.4	42.9	1446	563	-	-	-	-	-	11.87	351.46	31.10	0.68	Skin buckling, skin crack-
			Quasi-static	20	75	N	76	-	Dent	0.53	0.06	0.17	10.75	13.15	97.50	8.50	0.32	19.20	289.00	16.50	-	-	-	-	-	6.69	168.44	53.20	0.42	Skin buckling, skin crack-
					100	N	101	-	Dent	0.82	0.07	0.31	13.35	16.00	154.50	18.50	0.39	22.10	384.50	26.00	-	-	-	-	-	7.95	199.95	43.53	0.52	Skin buckling, skin crack-
					125	N	126	-	Dent	0.93	0.07	0.31	14.10	15.70	160.50	19.00	0.45	24.70	480.00	38.00	-	-	-	-	-	9.91	249.49	44.72	0.64	Skin buckling, skin crack-
					150	N	150	-	Dent	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.21	181.41	43.02	0.51	Skin buckling, skin crack-
					1	mm	241	-	Dent	1.00	0.11	0.37	13.5	15.4	148	20	0.51	19.8	308	29	0.61	12.7	13.2	126	24	12.92	382.20	63.70	0.74	Skin buckling, skin crack-
					1.50	mm	394	-	Dent	1.50	0.12	0.62	18.38	20.65	267.50	59.00	0.71	25.28	502.75	65.50	0.94	19.70	22.00	311.00	60.50	10.36	315.94	61.55	0.63	Skin buckling, skin crack-
					2.00	mm	545	-	Dent	2.03	0.19	0.87	21.20	23.65	350.50	117.50	0.89	29.65	692.50	111.50	1.33	34.40	36.00	946.00	143.00	12.42	397.66	66.36	0.71	Skin buckling, skin crack-
					no	-	946	-	Dent	-	1.280	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.77	130.14	40.72	0.47	0
				150	1	mm	597	-	Dent	0.98	0.21	0.72	24.5	25.7	485	146	0.86	29.3	673	189	0.83	23.6	23.9	440	175	9.63	302.91	62.93	0.54	Skin crack-
					1.50	mm	868	-	Dent	1.45	0.25	1.08	30.80	31.95	749.50	346.00	1.11	35.65	996.50	328.50	1.30	31.10	32.10	764.00	437.00	11.05	347.62	59.85	0.71	Skin crack-
					2.00	mm	1132	-	Dent	1.96	0.39	1.42	35.70	37.50	1058.50	647.50	1.32	40.95	1317.00	491.50	1.78	37.80	40.20	1146.00	829.00	10.67	335.61	62.31	0.69	Skin debonding, skin crack-
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10.36	303.77	52.94	0.65	Skin crack+
		6.4	Quasi-static	20	1.00	mm	131	-	Dent	1.00	0.06	0.35	16.40	18.95	223.50	28.50	0.46	25.15	496.00	40.50	0.56	16.50	17.40	217.00	42.00	7.29	203.97	51.02	0.47	Skin buckling, skin crack-
					1.50	mm	207	-	Dent	1.49	0.08	0.56	21	22.6	356	66	0.62	31.5	780	85	0.86	22	24.9	378	102	6.95	194.36	49.14	0.45	Skin buckling, skin crack+
					2.00	mm	293	-	Dent	1.99	0.12	0.78	29.50	31.00	684.50	176.50	0.79	37.40	1100.00	150.50	1.20	31.10	39.30	803.00	225.00	7.29	203.89	48.28	0.45	Skin crack+
				150	1.00	mm	235	-	Dent	1.00	0.10	0.63	27.30	29.30	609.00	139.50	0.62	32.75	844.00	128.00	0.78	24.20	24.60	463.00	181.00	8.30	238.73	54.91	0.50	Skin buckling, skin crack+
					1.50	mm	391	-	Dent	1.55	0.15	0.92	32.9	33.9	866	322	0.88	42.7	1431	289	1.22	34	35.5	917	475	7.39	212.63	49.00	0.45	Skin buckling, skin crack-
					2.00	mm	530	-	Dent	2.05	0.21	1.20	39.05	41.10	1221.50	601.00	1.09	49.90	1954.50	470.50	1.67	43.40	46.20	1509.00	926.00	6.49	186.58	50.41	0.41	Skin buckling, skin crack-
			Undamaged	Undamaged	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8.08	229.42	37.44	0.49	Skin buckling, skin crack+