2023

Use of biomimicry model for the design of perforated composite plates

Modica-Cliff, G.

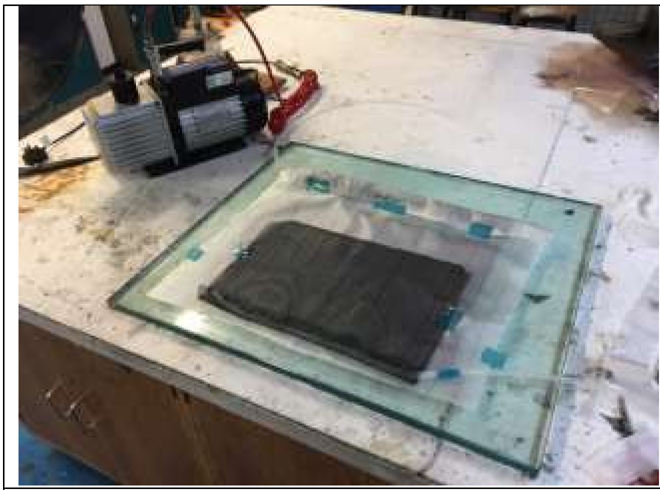
Modica-Cliff, G. (2023) 'Use of biomimicry model for the design of perforated composite platesl',
The Plymouth Student Scientist, 16(1), pp. 49-85.
https://pearl.plymouth.ac.uk/handle/10026.1/21078

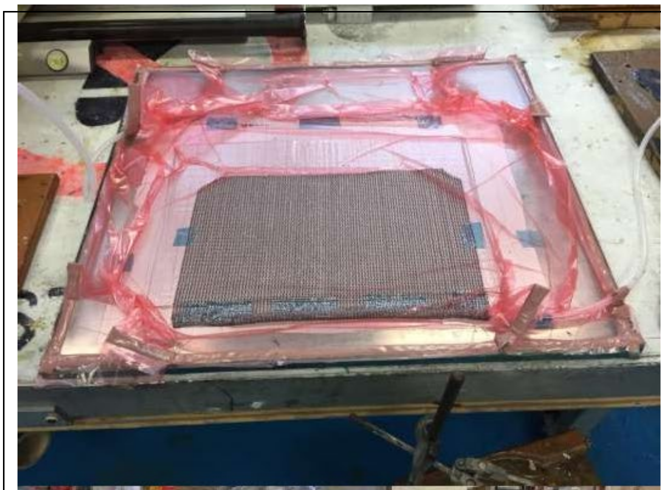
The Plymouth Student Scientist
University of Plymouth

Appendices

Illustrated Laminate Manufacture

The following shows steps taken to manufacture the specimens. The composite plates were manufactured using the RIFT method described Summerscales and Cullen (2021).

<table>
<tr>
<td></td>
<td>1. The glass plate was cleaned and sealed.
2. The fabric lay-up was positioned on the glass.
    a. Add mould if required
3. Peel ply and infusion mesh are cut to size and placed over the fabric.
4. Inlet and outlet tubes are cut to size and positioned.
5. Blue release tape is used to secure everything in place.</td>
</tr>
<tr>
<td></td>
<td>6. Vacuum bag is cut to size.
7. Bagging tape is applied to bag.
8. Protective film of bagging tap is removed, and the bag is stuck on the glass plate.
9. The tape is then press on to create a seal.
10. The outlet pipe is attached to the pump and the inlet to a pressure gauge.
11. The pump is activated, and the level of vacuum assessed using the gauge.</td>
</tr>
</table>

	12. The bagging tape is checked for leaks, closing any that are found. 13. The outlet tube is crimped and the leak rate is measured in mbar/min. 14. If the leak rate and achieved vacuum are suitable the inlet tube is crimped and the outlet is uncrimped. 15. Now the resin is weighted. 16. The recommend amount of hardener is added.
 	17. Now the resin and hardener are mixed. 18. The inlet tube is inserted into the resin pot. 19. The inlet tube is uncrimped and the resin flows. 20. Now the flow is monitored, and the inlet tube is crimped again once the resin reaches the outlet. 21. The set up is left under vacuum until gelled.

	22. The pipes are crimped and then the laminate is post cured whilst still in the bag.
	23. Once finished the laminate is demoulded.
	24. Then it is mounted for waterjet cutting. 25. Due to the nature of waterjet cutting the continuous line leave one uncut edge. 26. Then the remaining edges are cut using a band saw. a. Then drilled if required

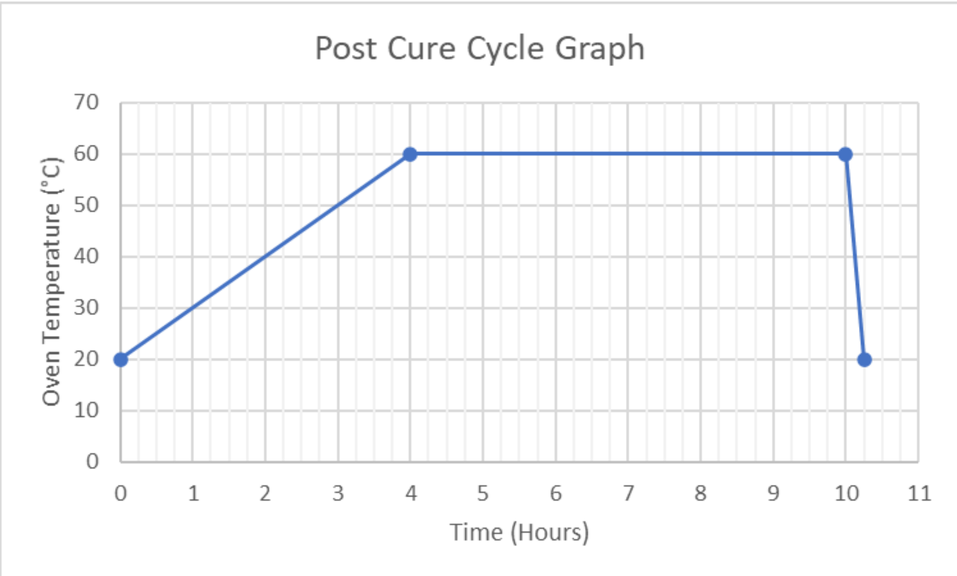
	27. Glass fibre tabs are then bonded and clamped.

Manufacturing Conditions

The following table shows the conditions on the day of manufacture.

	Plate A	Plate B
Date	09/03/2022	21/03/2022
Time	12:28	15:31
Temperate (°C)	18	21
Relative Humidity (%)	45	42
Pressure (mbar Abs.)	999	1011
Pressure reached (mbar Abs.	4.5	5.0
Leak rate (mbar/min)	0.10	0.35

Oven Programme for post cure:



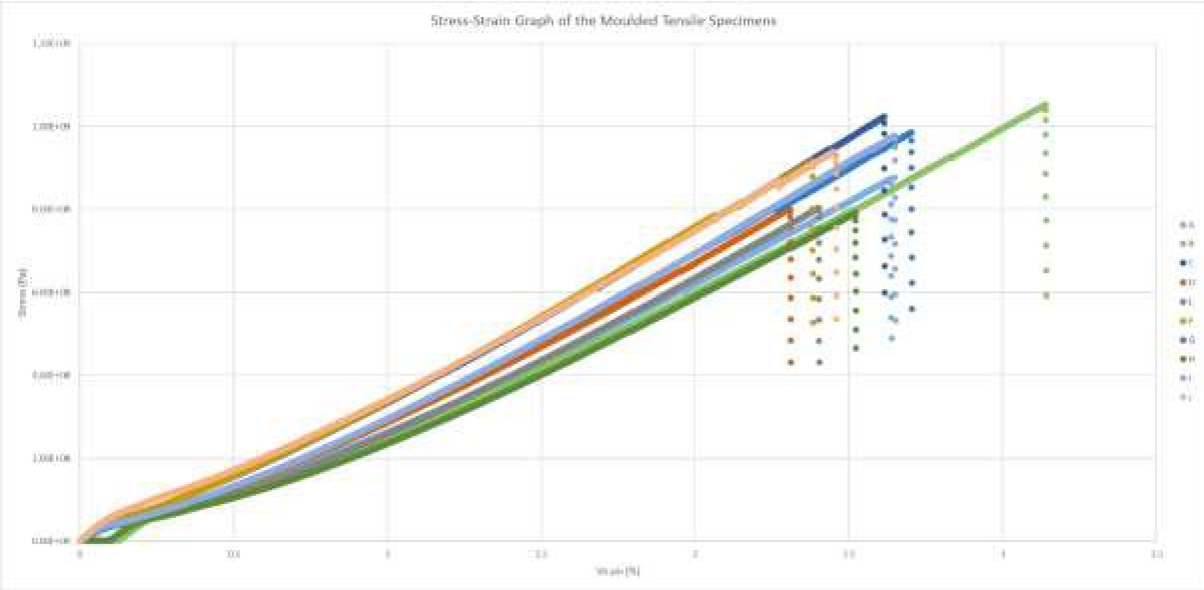
Property	Unit	Value
Programme Number	Pr	1
Number of steps	n	3
Periodic repeat (1=yes , 0=no)	r	0
Initial temperature (°C)	p0	20
Time step 1	t1	4
Second temperature (°C)	p1	60
Time step 2	t2	6
Third temperature (°C)	p2	60
Time step 3	t3	0.15
Final Temperature (°C)	p3	20

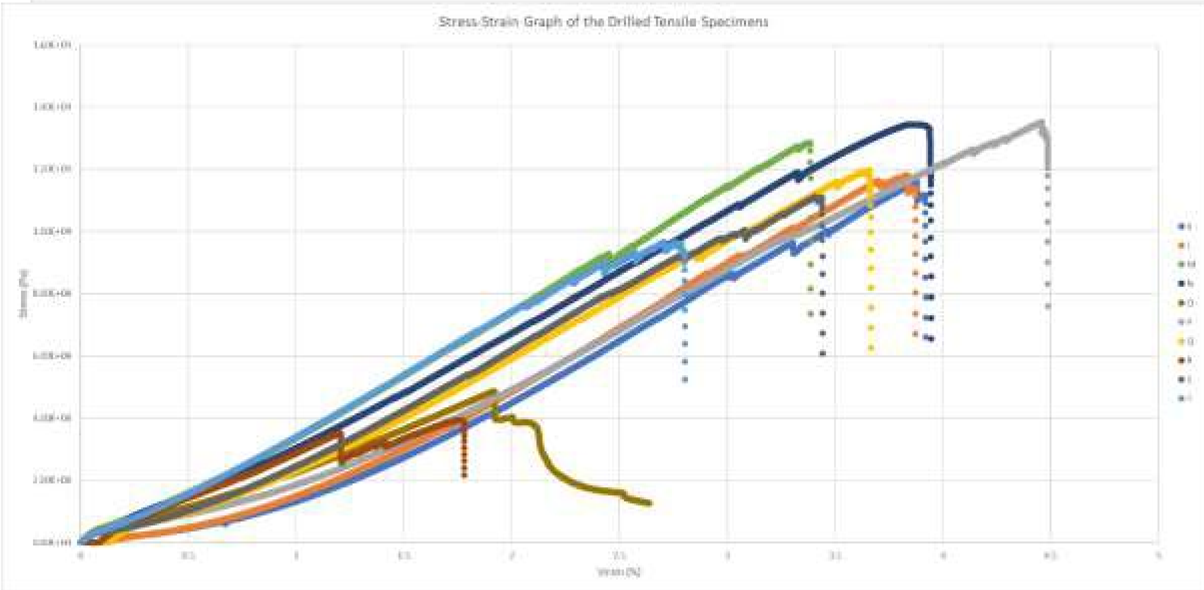
Property Prediction Calculations

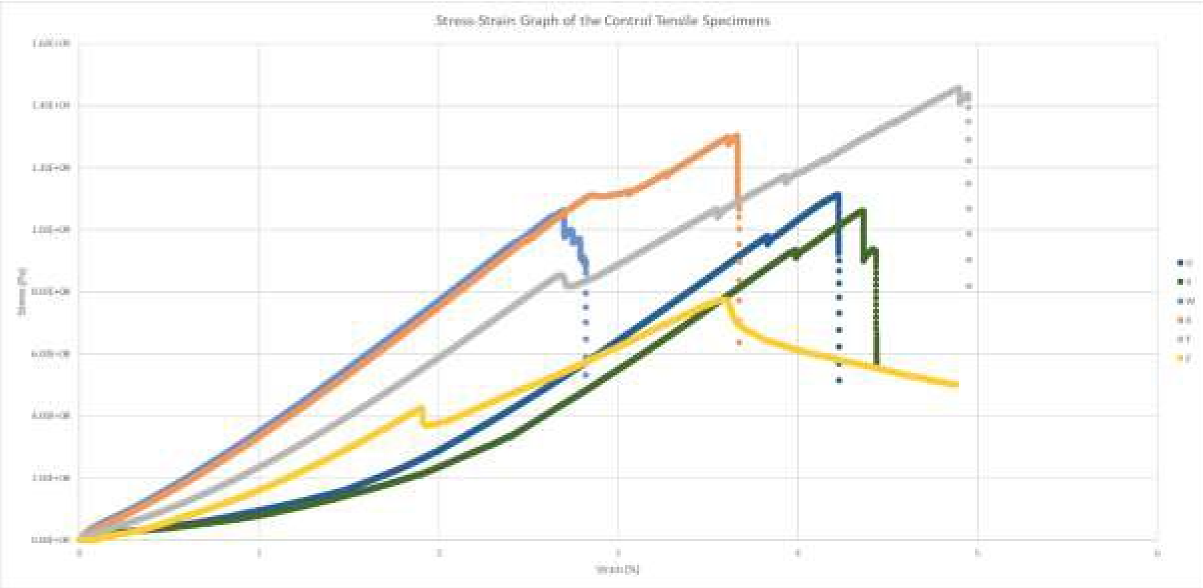
	Property	Symbol	Units	Width Method	Burn Off Method	Density Method	Equation	Comment
Fibre Volume Fraction	Fabric Areal Weight	Af	gsm	595.148	595.148	595.148	n/a	From average of 5 $100cm^3$ samples
	Fabric Areal Weight	Af	kg/m^2	0.5951	0.5951	0.5951	/1000	
	Number of Plies	n	n/a	3	3	3	n/a	From layup
	Density of Fibre	pf	g/cm^3	1.77	1.77	1.77	n/a	From (Fu et al., 2000)
	Density of Fibre	pf	kg/m^3	1770	1770	1770	10^6/10^3	
	Specimen Thickness	t	mm	1.997	2.00	2.00	n/a	From average sample thickness
	Specimen Thickness	t	mm	0.002	0.002	0.002	/1000	
	Cured Ply Thickness	T	mm	0.666	0.666	0.666	t/n	
	Fibre Volume Fraction	Vf	n/a	0.516	0.579	0.648	(n*Af)/(pf*t)	
	Matrix Volume Fraction	Vm	n/a	0.484	0.421	0.352	1-Vf	
Matrix Properties	Tensile Strength Matrix	σm	MPa	71	71	71	n/a	From IN2 Datasheet 67.0-75.0 MN/m^2
	Tensile Strength Matrix	σm	Pa	7.10E+07	7.10E+07	7.10E+07	*10^6	
	Youngs modulus Matrix	Em	MPa	2800	2800	2800	n/a	From IN2 Datasheet 2500-3100
	Youngs modulus Matrix	Em	Pa	2.80E+09	2.80E+09	2.80E+09	*10^6	
	Fibre strain to Failure Matrix	ε_{Fm}	%	8	8	8	n/a	From IN2 Datasheet 7-9 %
	Fibre strain to Failure Matrix	ε_{Fm}	n/a	0.08	0.08	0.08	/100	
Fibre Properties	Tensile Strength Fibre	σf	GPa	4.9	4.9	4.9	n/a	From (Mesquita et al., 2021)
	Tensile Strength Fibre	σf	Pa	4.90E+09	4.90E+09	4.90E+09	*10^9	
	Youngs modulus Fibre	Ef	GPa	230	230	230	n/a	From (Mesquita et al., 2021)
	Youngs modulus Fibre	Ef	Pa	2.30E+11	2.30E+11	2.30E+11	*10^9	
	Fibre strain to Failure Fibre	ε_{fF}	%	2.1	2.1	2.1	n/a	From (Mesquita et al., 2021)
	Fibre strain to Failure Fibre	ε_{fF}	n/a	0.021	0.021	0.021	/100	
Rule of Mixtures Tensile Modulus Prediction	Fibre length Distribution Factor	ηl	n/a	1	1	1	n/a	All unidirectional so set to unity
	Fibre Orientation Distribution Factor	ηO	n/a	1	1	1	n/a	Fabric so set to unity
	Rule of Mixtures Elastic Modulus Prediction	Ec	Pa	1.20E+11	1.34E+11	1.50E+11	n/a	
	Rule of Mixtures Elastic Modulus Prediction	Ec	GPa	119.93	134.28	150.10	/10^9	
Kelly-Tyson Tensile Strength Prediction	Tensile stress in matrix at failure strain of the fibre	σm*	Pa	1.86E+07	1.86E+07	1.86E+07	(εfF/εfm)*σm	Assuming Linear Elastic
	Kelly-Tyson Compoiste Strength Prediction	σc	Pa	2.54E+09	2.84E+09	3.18E+09	σfVf+σm*Vm	
	Kelly-Tyson Compoiste Strength Prediction	σc	GPa	2.54	2.84	3.18	/10^9	
Assumed Failure Strain Strength Prediction	Assumed failure strain strength prediction	σc	Pa	3.00E+08	3.36E+08	3.75E+08	Ec*(0.25/100)	
	Assumed failure strain strength prediction	σc	GPa	0.300	0.336	0.375	/10^9	

Tensile Test Results

Below are the results from the tensile tests in tabular and graphical form.

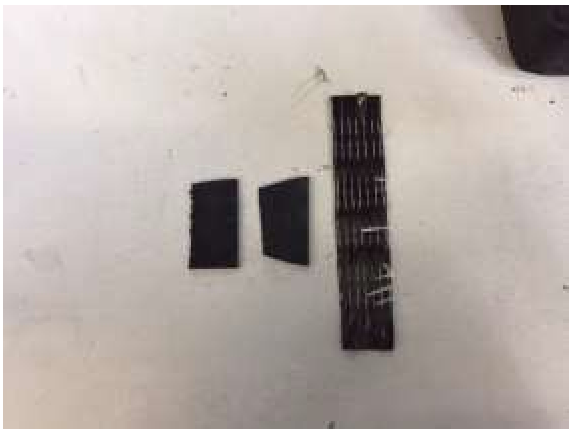


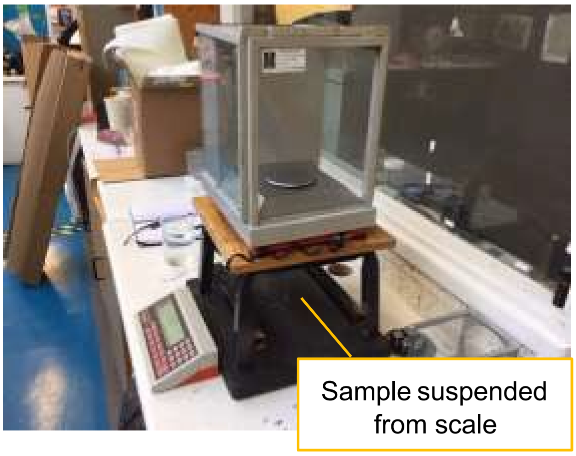




Experimental Derivation of Composite Density

The following shows the method of determining the composite density:





The samples are cut from unused remnants of the plates. Also, a piece of the raw fibre is prepared. The sample was suspended from the scales.

Then the ‘in air’ weight was recorded. Then sample was submerged and apparent ‘in water’ weight is recorded. This was repeated for all samples.

Table of composite density calculations

			A (Control and Drilled)	B (Moulded)
Fluid Density	*px*	g/cm^3	0.9975	0.9975
Mass of plate in air	a	g	1.21031	1.50264
Mass of plate in water	b	g	0.40824	0.53529
Composite Density	*pc*	g/cm^3	1.50521	1.54947

Below are the calculations used to calculate the fibre volume fractions.

Thickness method:

Property	Unit	Symbol	Drilled	Moulded	Control
Plate Thickness	mm	t	1.94	1.93	2.00
	m	t	0.001944	0.00193	0.001997
Fibre Density	g/cm^3	pf	1.77	1.77	1.77
	Kg/m^3	pf	1770	1770	1770
Measured Areal Weight	g/m^2	Af	595.15	595.15	595.15
	Kg/m^2	Af	0.595148	0.595148	0.595148
Number of Layers	n/a	n	3	3	3
Fibre Volume Fraction	n/a	Vf	0.518802	0.522565	0.505204

Burn off method:

Property	Unit	Symbol	Plate A	Plate B	Control Fibres
Crucible Weight	Mcruc	g	26.05346	25.72575	25.36831
Crucible and Plate Initial	Mc+p	g	27.22216	27.18966	26.39931
Crucible and Plate After 10 minutes in Furnace	Mc+p	g	26.85007	26.73967	26.36351
Plate Weight after 10 minutes	Mp	g	0.79661	1.01392	0.9952
Crucible and Plate After 5 hours in Furnace	Mc+p	g	26.26179	26.03748	25.68840
Plate Weight after 310 minutes	Mp	g	0.20833	0.31173	0.32009
Crucible and Plate After 25 minutes in Furnace	Mc+p	g	26.19912	25.95479	25.58473
Plate Weight after 335 minutes	Mp	g	0.14566	0.22904	0.21642
Initial Composite Mass	Mc	g	1.16870	1.46391	1.031
Fibre loss correction	Mcorr	g	0.693907	1.09112	
Fibre Weight	Mp	g	0.693907	1.09112	
Composite Density	pc	g/cm^3	1.50521	1.54947	
Fibre Density	pf	g/cm^3	1.77	1.77	
Fibre Volume fraction	Vf	%	50.49199	65.2483	

Density method:

Property	Unit	Symbol	A	B
Resin Density	pr	g/cm^3	1.08	1.08
Fibre Density	pf	g/cm^3	1.77	1.77
Composite Density	pc	g/cm^3	1.505211	1.549474
Graph Gradient	m	g/%cm3	0.0069	0.0069
Fibre Volume Fraction	Vf	%	61.6247	68.0397

Finite Element Validation

The Solidworks simulation software was used to conduct tensile test simulation for the drilled and control specimens.

Modelling of the moulded plates required a separate software Ansys Composite PrepPost, which had the capability of modelling the fibre orientation. This was attempted but insufficient time was available to conduct meaningful studies as manufacturing took longer than anticipated due to lack of composite specific technician and the difficult of representing the true fibre orientation in Ansys Composite PrepPost shown in Figure 35. Additionally, the moulded specimens were modelled as flat plates as modelling the surface topology of the raised section presented additional challenges.

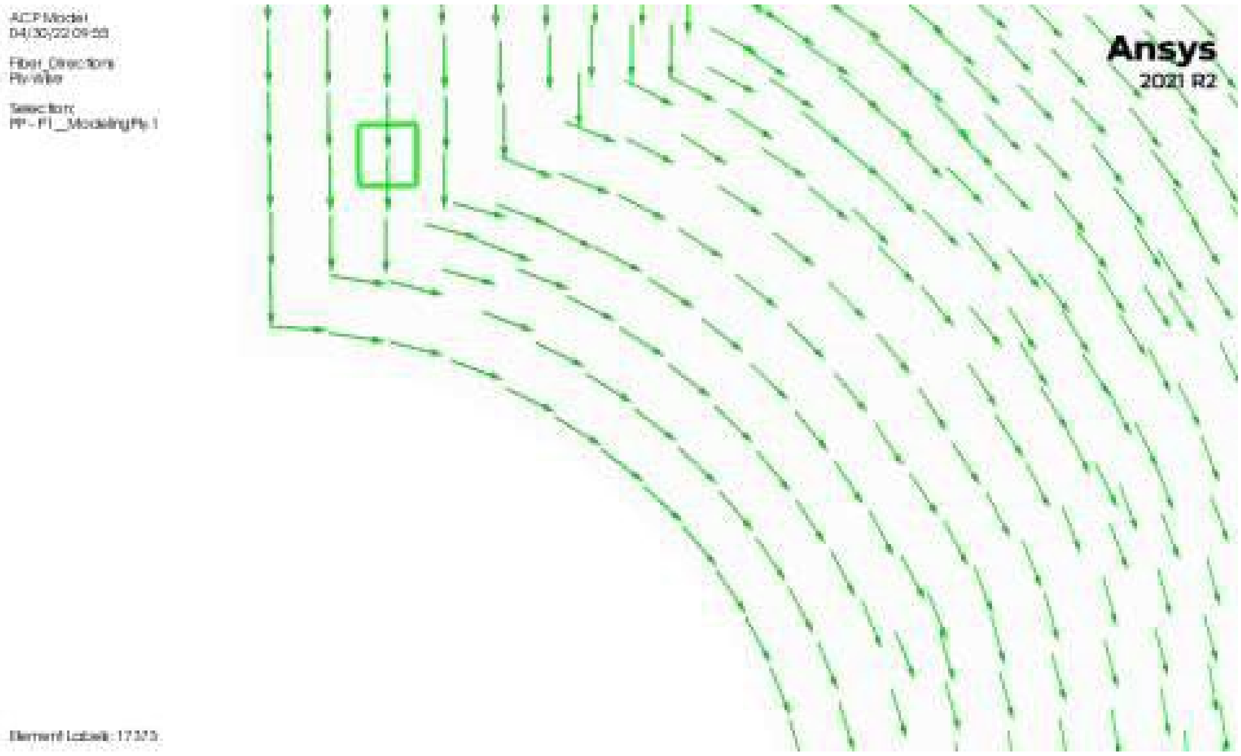


Figure 35: 10.5 attempted model of fibre orientation around hole.

Digital Image Correlation

The shape, motion and deformation of solid objects can be measured from video using DIC (LePage, 2022). Specimens were prepared by removing burrs and applying the speckle pattern using spray paint as advised by Dantec Dynamics (2022) which can be seen in Figure 16. Only the specimens with holes were analysed on the flat side of the specimens as they were more likely to fail around the hole which was the area of interest, whereas the control samples could fail anywhere in the gauge length and therefore not give any meaningful data. Video footage of the tensile tests was taken and then divided into frames. These images were then processed using GOM Correlate software where the hole diameter was used as the scale reference. Figure 36 Shows more detail of the surface settings.

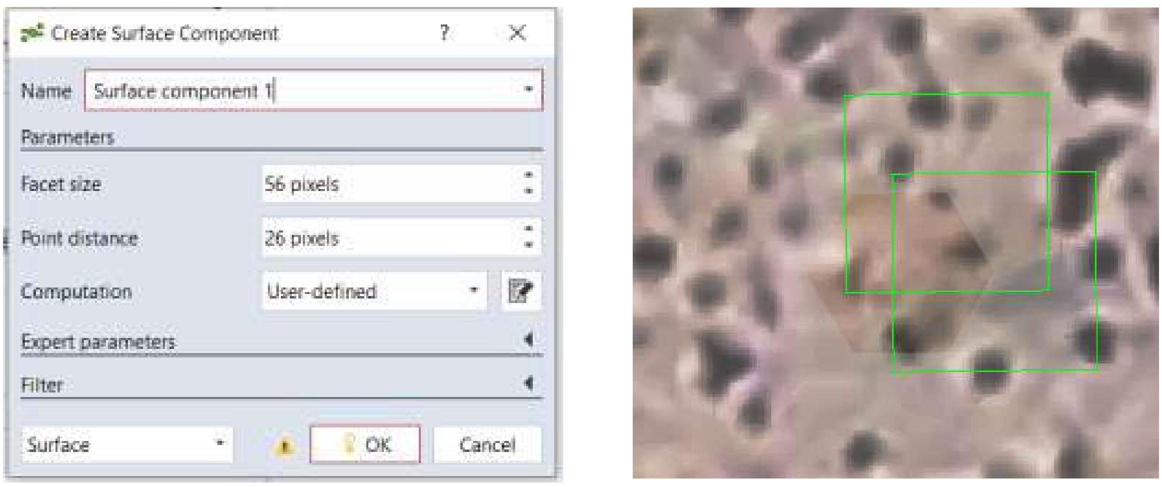
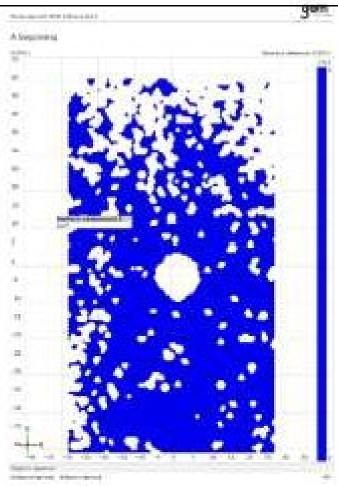
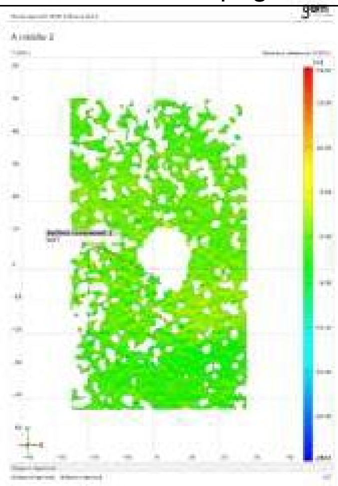
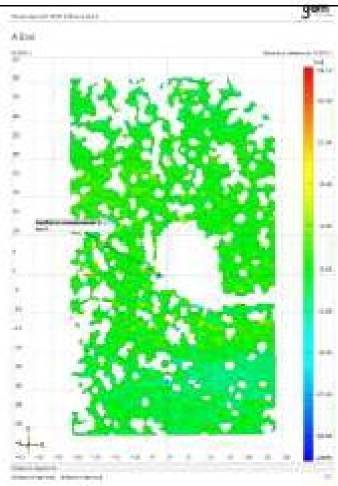
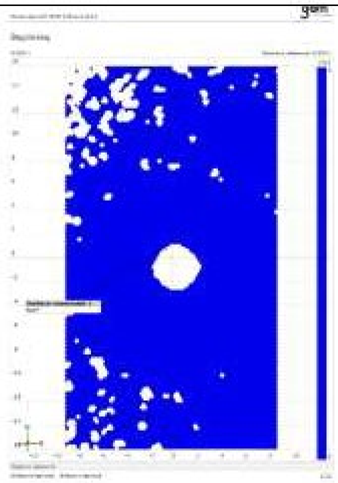
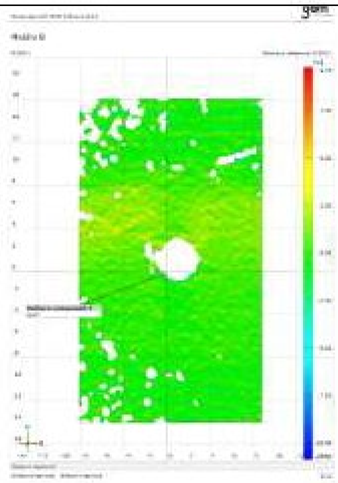
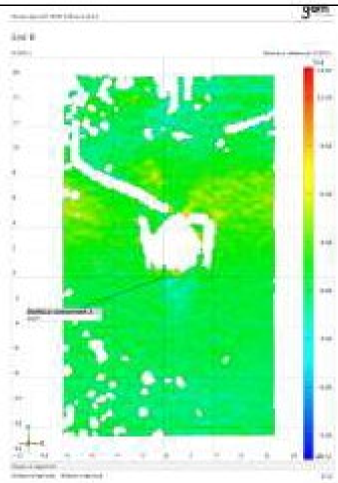
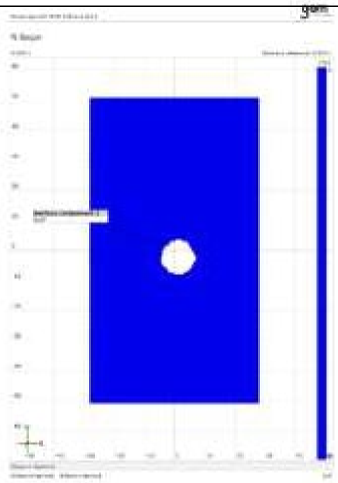
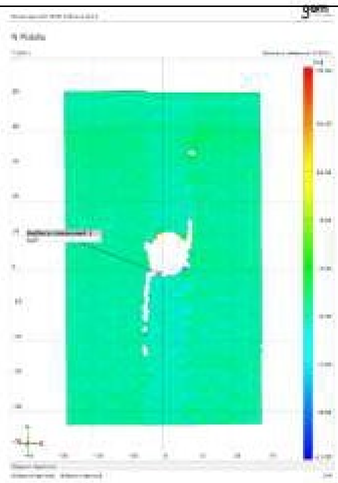
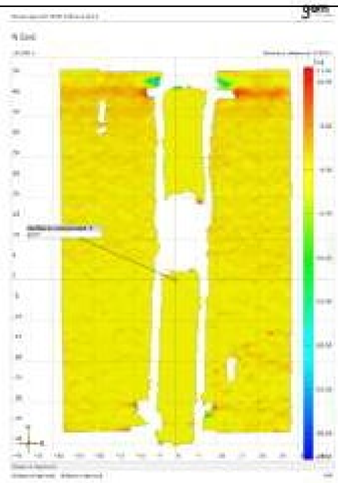
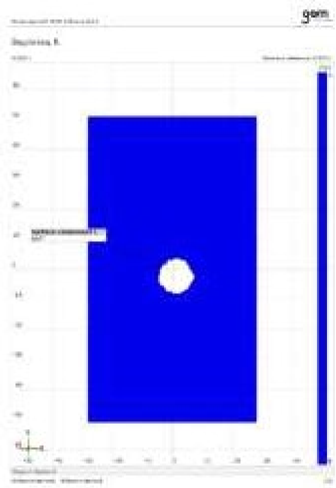
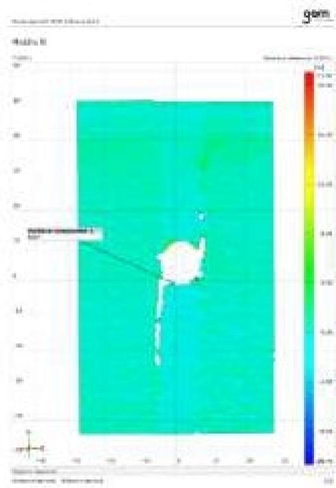
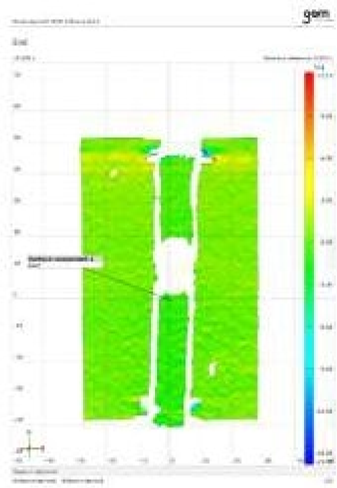
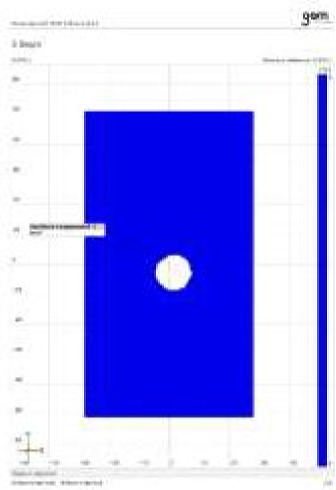
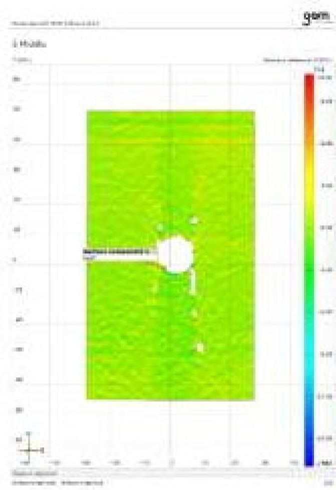
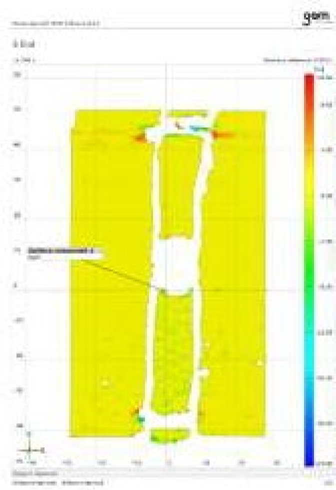


Figure 36: 10.6 GOM surface settling, with detailed visualisation of a facet.

DIC Results

The following table shows the results from the DIC analysis. Sample O was not analysed because the camera resolution in the trial test was insufficient.

	Start of Test	Start of Crack Propagation	End of Test
A			
B			
N			

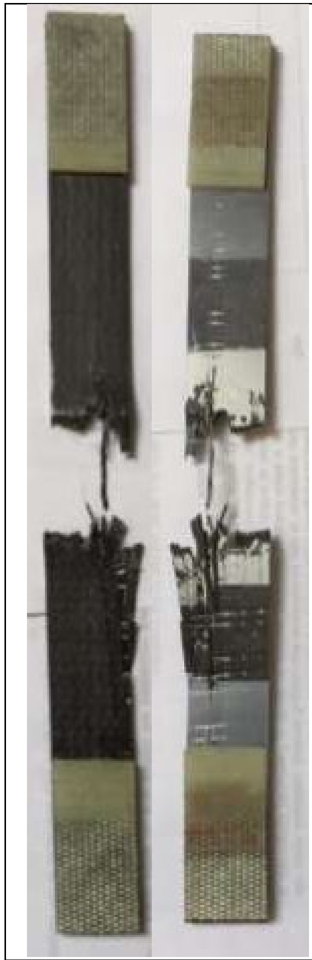
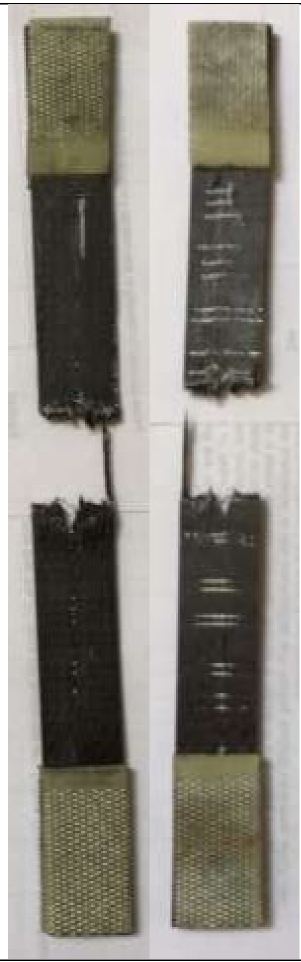
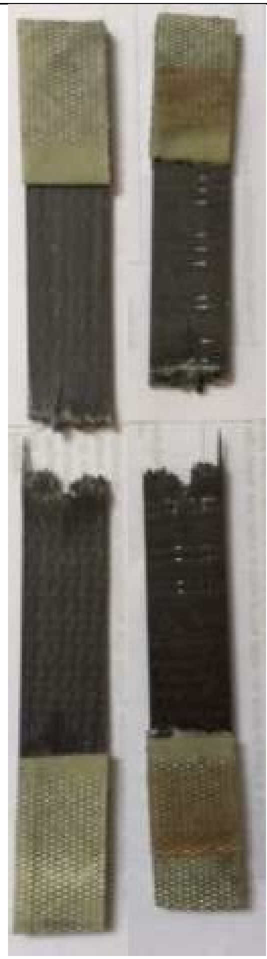
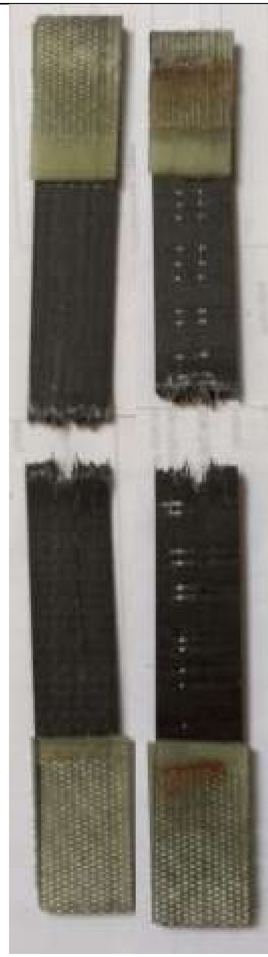
R			
S			

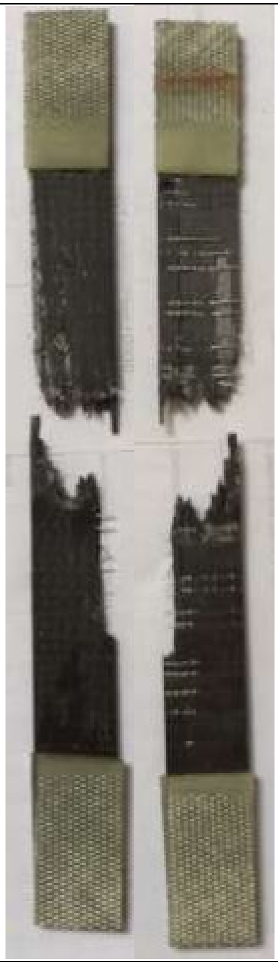
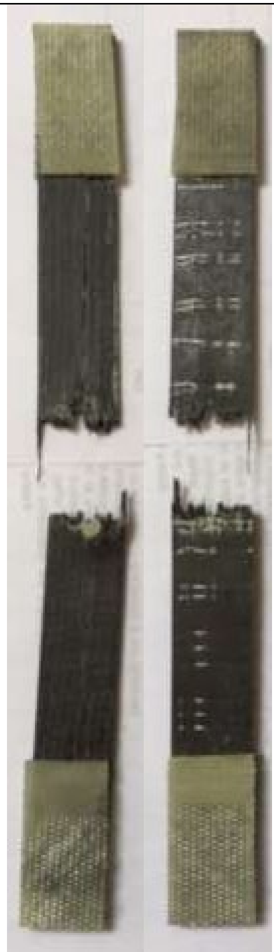
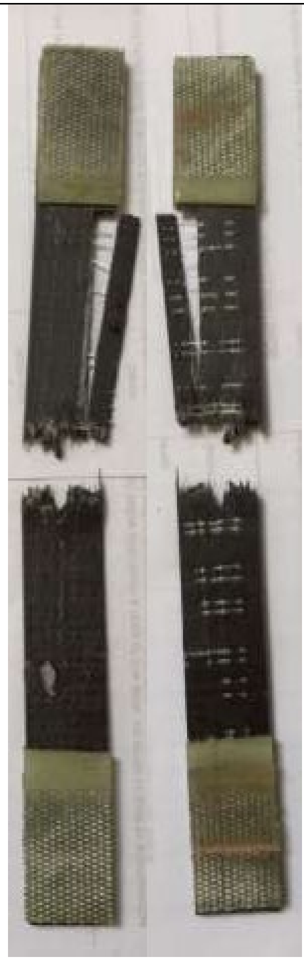
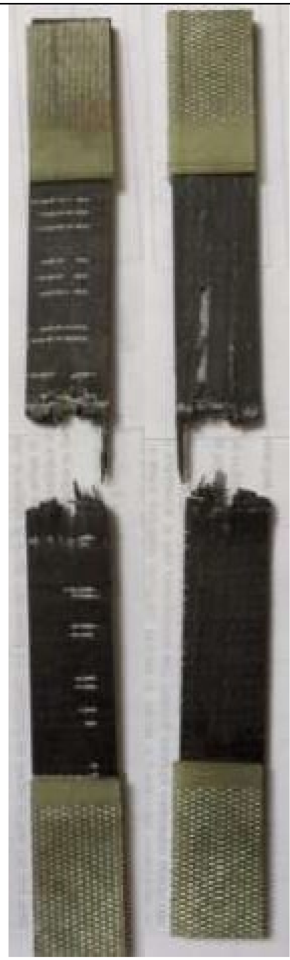
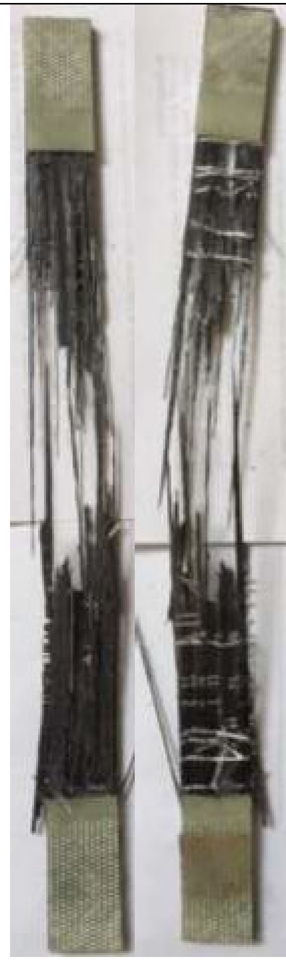
Specimen Dimensions

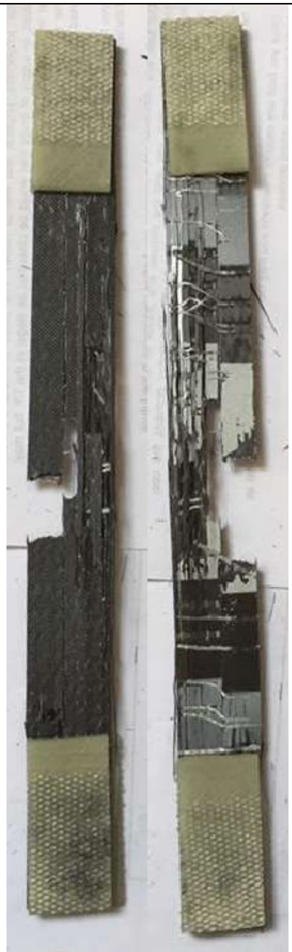
Plate 1 Moulded Holes								
Test	**Width R1 (mm)**	**Width R2 (mm)**	**Width R3 (mm)**	**Width Average (mm)**	**Thickness R1 (mm)**	**Thickness R2 (mm)**	**Thickness R3 (mm)**	**Thickness Average (mm)**
a	24.80	24.73	24.69	24.74	1.88	1.99	1.96	1.94
b	24.70	24.69	24.70	24.70	2.01	2.01	1.91	1.98
c	24.62	24.66	24.71	24.66	1.91	1.96	1.94	1.94
d	24.78	24.66	24.78	24.74	1.91	1.98	2.01	1.97
e	24.62	24.78	24.67	24.69	1.92	1.91	1.97	1.93
f	25.01	24.78	24.74	24.84	1.87	1.86	1.85	1.86
g	24.66	24.71	24.69	24.69	1.87	1.91	1.91	1.90
h	24.56	24.74	24.63	24.64	1.93	1.90	1.95	1.93
i	24.64	24.66	24.69	24.66	1.95	1.96	1.91	1.94
j	24.57	24.61	24.67	24.62	1.91	1.90	1.96	1.92
			Mean	24.70			**Mean**	1.93
			StDevP	0.06			**StDevP**	0.03
Plate 2 Drilled Holes								
Test	**Width R1 (mm)**	**Width R2 (mm)**	**Width R3 (mm)**	**Width Average (mm)**	**Thickness R1 (mm)**	**Thickness R2 (mm)**	**Thickness R3 (mm)**	**Thickness Average (mm)**
k	24.70	24.68	24.67	24.68	1.88	1.96	1.99	1.94
l	24.68	24.68	24.65	24.67	1.96	1.98	1.97	1.97
m	24.68	24.71	24.71	24.70	1.91	2.02	2.04	1.99
n	24.72	24.63	24.65	24.67	1.82	1.89	1.98	1.90
o	24.68	24.77	24.67	24.71	1.84	1.88	1.76	1.83
p	24.72	24.69	24.72	24.71	1.95	1.95	1.91	1.94
q	24.68	24.69	24.72	24.70	1.93	1.94	1.99	1.95
r	24.72	24.63	24.65	24.67	1.82	1.89	1.98	1.90
s	24.79	24.80	24.77	24.79	2.01	2.02	2.03	2.02
t	24.68	24.68	24.64	24.67	2.02	1.98	2.03	2.01
			Mean	24.70			**Mean**	1.94
			StDevP	0.03			**StDevP**	0.06
Plate 2 Control Plates								
Test	**Width R1 (mm)**	**Width R2 (mm)**	**Width R3 (mm)**	**Width Average (mm)**	**Thickness R1 (mm)**	**Thickness R2 (mm)**	**Thickness R3 (mm)**	**Thickness Average (mm)**
u	24.70	24.71	24.80	24.74	2.01	2.01	1.98	2.00
v	24.70	24.71	24.69	24.70	2.06	1.95	1.97	1.99
w	24.70	24.68	24.69	24.69	2.07	1.99	2.03	2.03
x	24.73	24.75	24.75	24.74	1.98	1.97	1.99	1.98
y	24.69	24.71	24.70	24.70	2.02	2.05	2.06	2.04
z	24.65	24.63	24.68	24.65	1.95	1.95	1.90	1.93
			Mean	24.70			**Mean**	2.00
			StDevP	0.03			**StDevP**	0.04

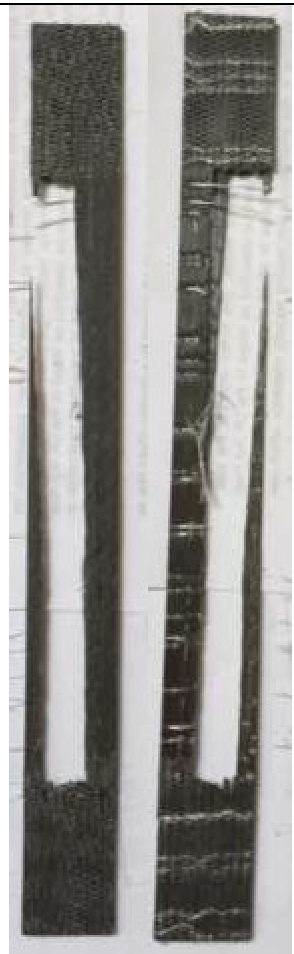
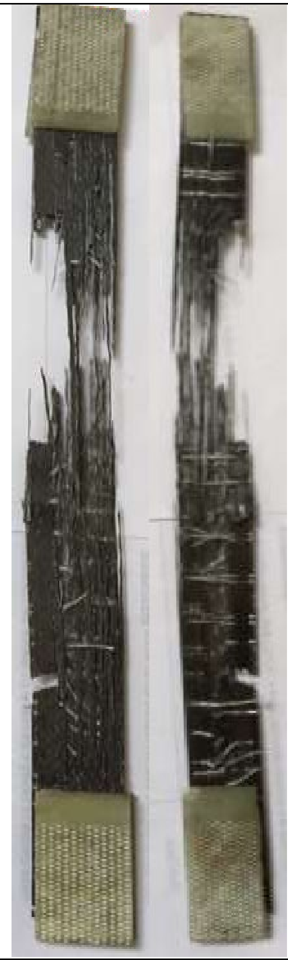
Fractured Specimens

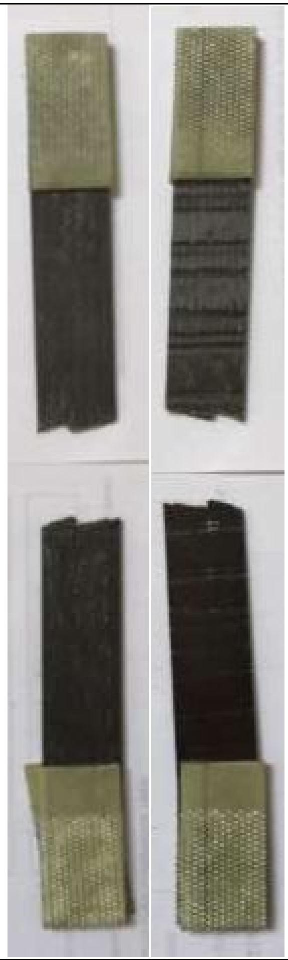
The following table shows each of the specimens after the tensile test. Each specimen has a top face, shown first, and mould facing side shown second.

					
A	B	C	D	E	F

					
G	H	I	J	K	L

					
M	N	O	P	Q	R

					
S	T	U	V	W	X

					
Y	Z				

Specimen Details
The relative tow and stitch distances were determined using only the mould tool face and therefore the first ply.

Type	Specimen Number	Largest Remnant Length (mm)	Distance of Stitch from Hole (mm) Above/Below		Tow Relative to Hole	Detail of failure
Moulded	A	30	4	6	Between single tow	Break across midpoint, with l remnant spanning to one side
	B	25	3	10	Between single tow	Break across midpoint, with large remnant (25mm) spanning midpoint to one side
	C	30	1	9	In-between tows	Break across midpoint with thin remnant
	D	15	4	6	In-between tows	Break across midpoint with thin remnant
	E	0	3	8	Between single tow	Break across midpoint
	F	20	6	4	In-between tows	Break across midpoint with thin remnant, Missing section (6X45mm)

	G	24	7	5	In-between tows	Break across midpoint with thin remnant
	H	10	3	5	In-between tows	Break across midpoint with thin remnant
	I	7	3	8	Between single tow	Break across midpoint with thin remnant
	J	20	9	4	In-between tows	Break across midpoint with thin remnant
Drilled	K	145	2	10	In middle of tow	Large scale fibre pull out
	L	150	3	10	In middle of tow	Large scale fibre pull out
	M	145	2	6	In middle of tow	Large scale fibre pull out
	N	130	2	6	In middle of tow	Large scale fibre pull out, missing section
	O	n/a	7	5	In middle of 2 tows	Crack down side of hole which continues to other side hole and down
	P	140	10	2	In middle of 2 tows	Large scale fibre pull out

	Q	1450	Stitch in middle of hole		In middle of tow	Large scale fibre pull out
	R	n/a	5	3	In middle of tow	Crack down side of hole which continues to other side hole and down
	S	150	5	2	In middle of tow	Large scale fibre pull out
	T	n/a	6	2	In middle of 2 tows	Large scale fibre pull out
Control	U	14	n/a		n/a	Specimen slipped and failure is not valid
	V	14	n/a		n/a	Large section broke out, specimen is still attached
	W	15	n/a		n/a	Fibre pull out along whole gauge length
	X	15	n/a		n/a	Fibre pull out along whole gauge length
	Y	15	n/a		n/a	Fibre pull out along whole gauge length
	Z	n/a	n/a		n/a	Break not due to tension, Specimen slipped and failure is not valid

Waterjet Route

The following drawings show the dimensions of the waterjet profile, they account for the 0.7mm curf of the waterjet cutter. These files were converted to DXF files when cut.

Plate A:

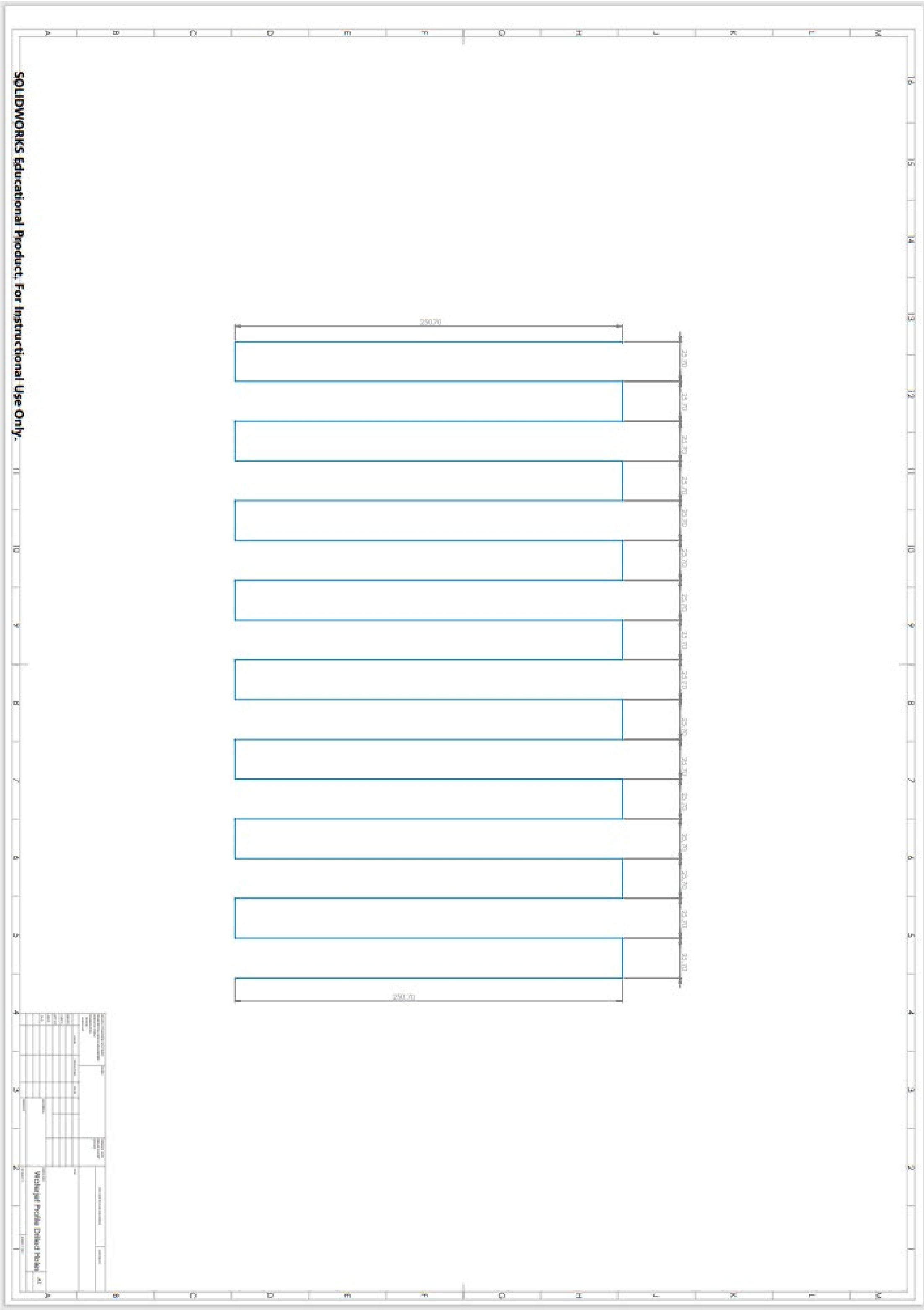
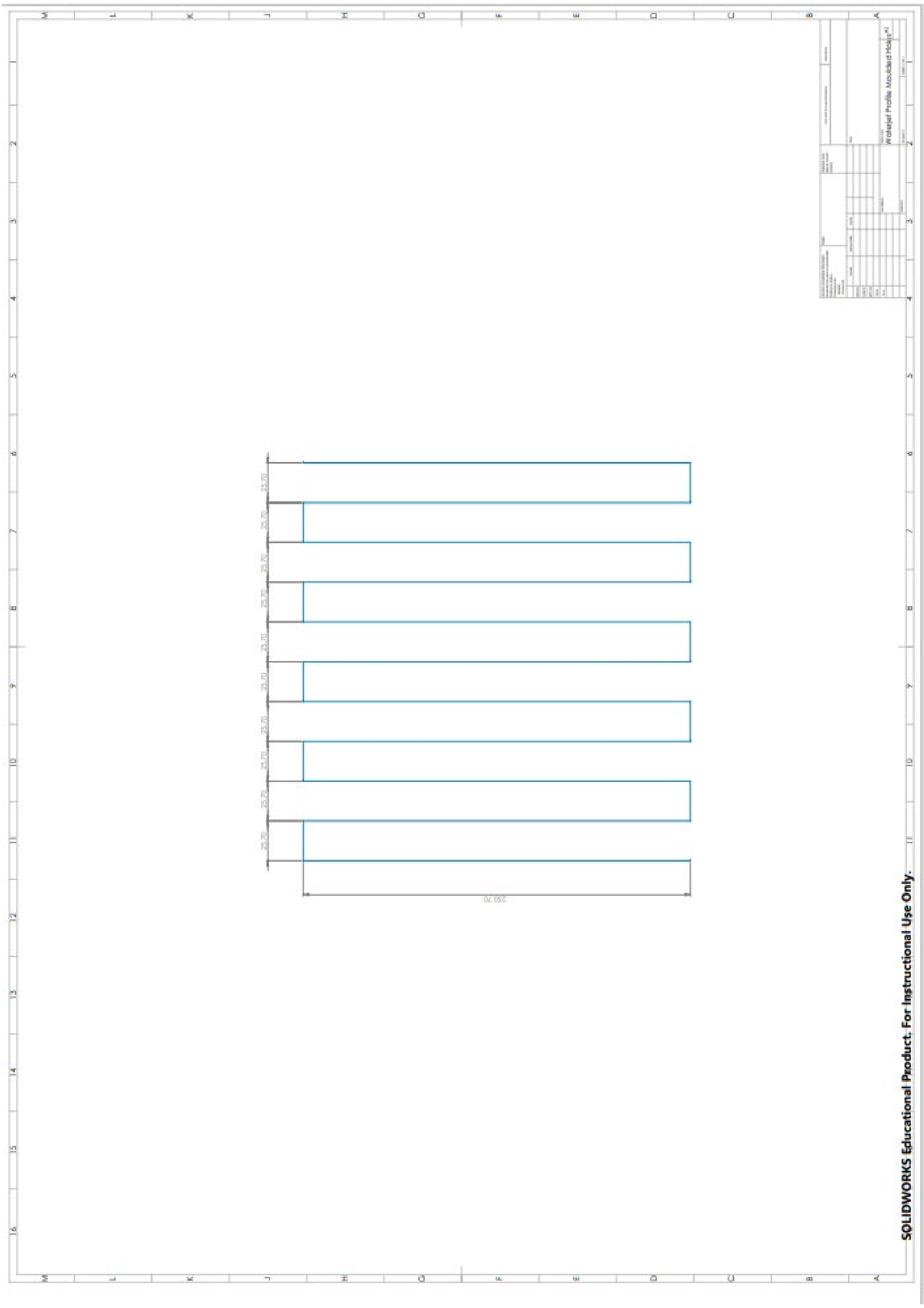
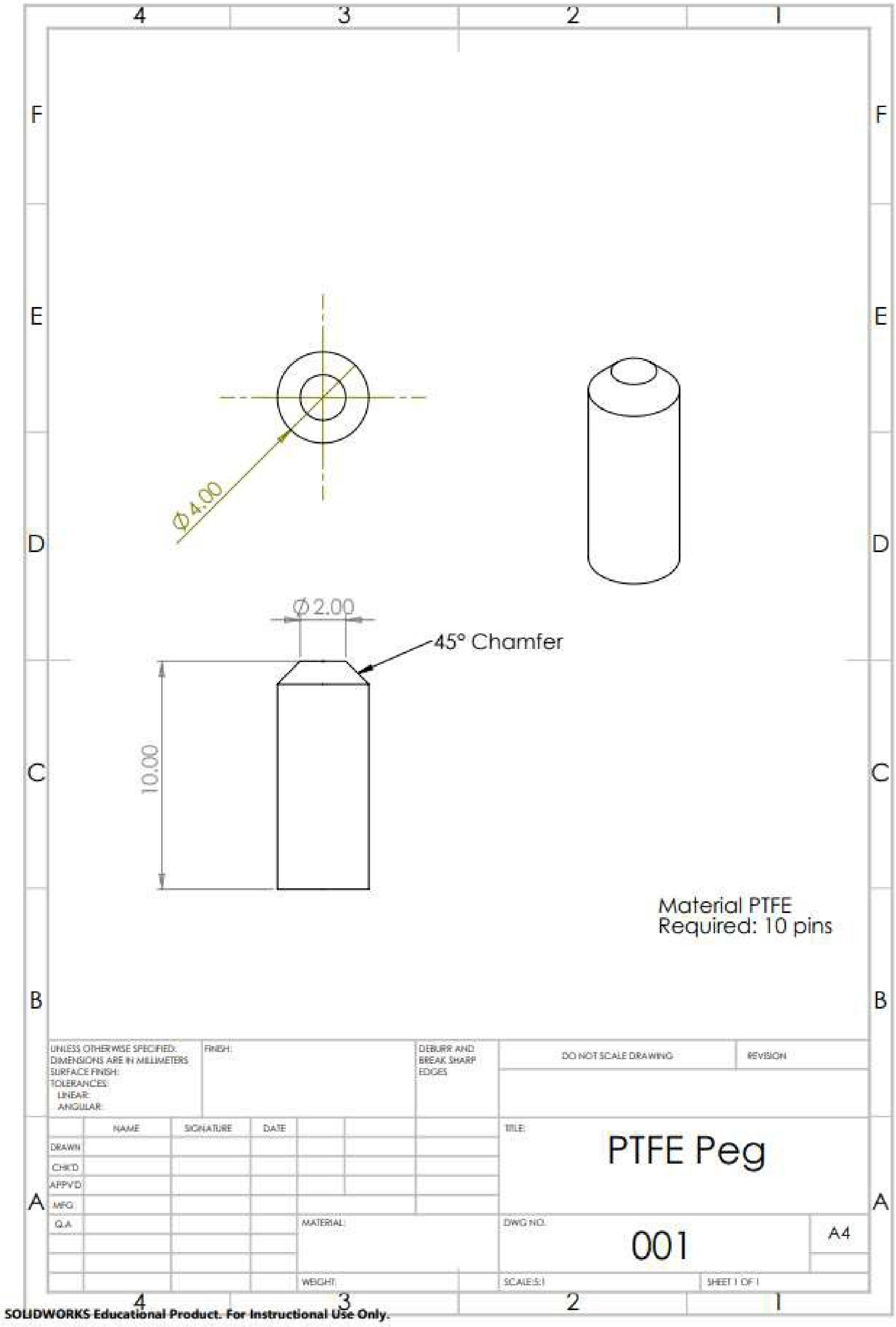


Plate B:


SOLIDWORKS Educational Product. For Instructional Use Only.
Waterjet Profile Moulded Holes

Components Manufactured by Technicians for Mould

The PTFE pegs were manufactured in Brunel W6 and design for the project by the author. They were turned on a lathe from a piece of 10mm PTFE bar.



Risk Assessment

The following risk assessment is based on one from Summerscales (2017).

Reference	Activity/Task	Hazards	Persons in Danger	Probability (P)	Severity (S)	Risk Factor (R =P*S)	Controls in Place *or* Action to be Taken	Additional Requirements
	Life [JSu]	meningitis	all	2	3	6	Awareness	
	Smoking [JSu]	now illegal indoors in the UK	all					
	Visitors							
	visitors [JSp]	tripping	all	1	1	1	areas kept tidy .. walkways marked .. general good housekeeping	control and guidance by UoP staff
	visitors [JSp]	overhead hazards	all	1	1	1	overhead beams signed .. protective padding as required	control and guidance by UoP staff
	visitors [JSp]	slipping hazards	all	1	3	3	prevent splashing into walkways .. use signs to warn of danger .. do not run	control and guidance by UoP staff
	visitors [JSp]	fire	all	1	2	2	shout fire .. react to bell .. follow evacuation procedures (leave by nearest exit and proceed to assembly point)	control and guidance by UoP staff (fire marshalls)
	hands-on demonstrations/activities [JSp]	general	all	1	2	2	avoid potentially dangerous activities .. engage visitors in actions with little or no risk .. consider the ability of the visitor to actively participate.	control and guidance by UoP staff .. maintain a staff presence at all times and a high staff/student ratio.
C0	**Thermosetting resins**							
C0A	**Epoxide resin**							
	base resin [JSu]	sensitisation	operator	1	2	2	personal protective equipment (specifically lab coat .. barrier cream .. nitrile gloves .. safety glasses)	is the operator already sensitised?
	curing agents [JSu]	skin absorption	operator	1	2	2	personal protective equipment (specifically lab coat .. barrier cream .. gloves)	

	mixing components [JSu]	volatile organic compounds	operator/those adjacent	2	1	2	local extraction during both decanting and mixing	
C0B	**Unsaturated polyester**							
	base resin/diluent [JSu]	solvent (styrene)	operator	2	1	2	vapour extraction ventilation - personal protective equipment (specifically lab coat .. barrier cream .. gloves)	
	peroxide initiator [JSu]	oxidising substance: burns	operator	2	3	6	dispense with single opening partial vacuum polymer pipettes.	personal protective equipment (specifically safety glasses .. lab coat .. barrier cream .. gloves)
	cobalt accelerators	CMR2 reprotoxic. possible carcinogenic class 1B.	operator	1	1	1	cobalt-free accelerator	
	cobalt sulphate	lung carcinogenic category 1B. reproductive toxicant category 1B. mutagenic category 2.	operator	1	1	1	cobalt-free accelerator	
C1	**Reinforcement fibres**							
	all fibres [JSu]	nuisance dust	operator/those adjacent	1	1	1	dust mask .. local extraction	
	all fibres	sharp cutting tool	operator/those adjacent	1	2	2	use chain mail glove(s) provided.	
	carbon fibres [JSu]	electrical conductor leading to short circuit	electrical equipment	2	1	2	avoid floating fibres .. filtered electrical power supplies	synthetic fibres are not anticipated to be respirable, but can irritate.
C2A	**Reinforcement fabrics**							
	lifting reinforcement [JSu]	back injury	operator	2	2	4	use appropriate lifting strategies (hoists or request assistance from others)	
	cutting [JSu]	sharp tools	operator	2	2	4	chain mail gloves .. shielded roller cutter if practical	
C7	**Resin infusion**							
	See C0A, C0B, C1 and C2 above and C10B below as appropriate							
	lifting mould tools [JSu]	back injury	operator	2	2	4	use appropriate lifting strategies (hoists or request assistance from others)	
	releasing panel from mould tool	see C10A						
C8A	**Vacuum bagging**							
	See C0A, C0B, C1 and C2 above and C10B below as appropriate							
	lifting mould tools [JSu]	back injury	operator	2	2	4	use appropriate lifting strategies (hoists or request assistance from others)	
	releasing panel from mould tool	see C10A						
C10A	**Machining composites**							

	demoulding composites [JSu]	sharp edges	operator	2	2	4	protective gloves .. trim at earliest opportunity	
C10B	**Machining all materials**							
	sawing [BDL]	blade	operator	2	2	4	guard .. tools	training
	sawing [BDL]	loose particles	operator	2	2	4	guard .. eye protection	training
	sawing [BDL]	rotating machinery	operator	2	2	4	guard .. emergency stop	training
	sawing [BDL]	loose work-piece	operator/others	2	1	2	guard .. emergency stop	training
	sawing [BDL]	dust	operator/others	2	1	2	extraction .. dust mask	training .. COSHH
	sawing [BDL]	electricity	operator	1	3	3	regular maintenance .. PAT testing	
	diamond slitting saw	rotating blade	operator	2	2	4	guard .. face mask/eye protection	training, leather gloves, due caution.
	diamond slitting saw	dust	operator	1	1	1	cut wet to trap dust	training
C4	**Health and safety**							
	Hot polyurethane including foam: thermal decomposition products may include carbon dioxide, hydrocarbons, **carbon monoxide, nitrogen oxides, hydrogen cyanide, isocyanates, isocyanic acid, amines and other potentially hazardous decomposition products** [A, B].	thermally extreme conditions including fire	operator/those adjacent	2	3	6	avoid exposing materials to high temperatures.	Exposure to such chemicals may cause irritation of the eyes and respiratory tract with symptoms of running nose, watering eyes, coughing, headaches, dizziness, nausea and breathlessness. Isocyanates and amines can also cause allergic reactions (sensitisation) of the skin and lungs. Workers exposed to thermal degradation chemicals may experience immediate or delayed effects. Obtain medical attention if any symptoms occur.
	Universal test machines ~ quasi-static tension ~ compression ~ flexure [Sam Thorpe]							
	Moving parts	Injuries to the user	Operator and others in close proximity	1	2	2	Training will be provided prior to action. Operation in controlled area. Restricted use with close supervision by staff.	Personal protective equipment (PPE) and safety guards are provided. Only one user can operate the test machine.
	Ejection of material	Damage to eyes	Operator and others in close proximity	2	2	4	Guidance will be provided to students and others on good practice.	Use of personal protective equipment (PPE) or safety guards where applicable.
	Optical microscopes [Sam Thorpe]							
	Moving objectives	trapped fingers	Operator	2	1	2	Training will be provided prior to action.	
	Moving objectives	damaged sample or lens	None	1	1	1	Training will be provided prior to action.	
	Glass slides	cut fingers if glass broken	Operator	2	1	2	Guidance provided to students and others on good practice and information on broken glass disposal.	

Reference List

LePage, W. (2022). *DIC fundamentals*. digitalimagecorrelation.org. [Online]. Available at: https://digitalimagecorrelation.org/#:~:text=Digital%20image%20correlation%20(DIC)%20is,can%20be%20difficult%20to%20achieve. [Accessed 9 April 2022].

Summerscales, J. (2017). *Risk Assessments appropriate to the Composites Manufacturing laboratory (Brunel 007)*. University of Plymouth module MATS347. [Online]. Available at: https://ecm- academics.plymouth.ac.uk/jsummerscales/mats347/risk.htm [Accessed 5 November 2021].

Summerscales, J. and Cullen, R. (2021). *Composite plate manufacture by resin infusion*. University of Plymouth module MATS347 Appendix A. [Online]. Available at: https://dle.plymouth.ac.uk/pluginfile.php/1800770/mod_folder/content/0/Appendix_A_RIFT.doc?forcedownload=1 [Accessed 7 November 2021].