A Comparison of Autoclave and Press-Formed Composites

Major Project M6X00417

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Date:

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Abstract

This report focuses on the comparison of two different carbon fibre manufacturing methods. Specimens are made using both processes, and they undergo mechanical testing to learn how the different materials produced compare mechanically.

The data is collected and analysed, and the failure modes are investigated. A brief manufacturing time and cost comparison is also carried out.

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1.0 Introduction

Development of new manufacturing processes in a changing engineering environment is crucial. Carbon fibre composites have found a place in the automotive, motorsport, and other high performance industries such as aviation, with the emphasis shifting ever further towards weight reduction, improved structural performance and improved overall efficiency.

The autoclave manufacturing process is well established for composite production, but in some situations, the lengthy process is causing bottlenecks in the overall manufacturing flow. Using an alternative composite manufacturing process, such as press forming, has the potential to dramatically reduce component production times.

However, due to the different ways in which these processes apply force to the composite layup, as well as differences in the timings of the applications of temperature and pressure, there are unknowns about how components produced using both manufacturing methods compare mechanically.

This project aims to increase understanding of the differences and similarities between the autoclave and press forming processes, by producing test specimens using both processes, and then undertake mechanical testing. In addition, a production time and cost investigation will be undertaken of both processes, to further compliment the mechanical comparison. These tasks will increase understanding of the press forming process in relation to the autoclave process, and perhaps encourage increased usage of the press forming process.

2.0 Carbon Fibre Composites

2.1 Background

Carbon fibre reinforced polymer (CFRP) is a composite material comprising of a polymer resin and carbon fibres. The polymer resin acts as a matrix, and the carbon fibres act as reinforcement, providing the strength and structure of the material, and are suspended in the matrix.

Carbon fibre development began in the 1950's, during experiments in finding the triple point (thermal equilibrium of solid, liquid, and gas) of graphite. Pure graphite filaments were inadvertently created, and after experimentation, were determined to have ten time the tensile strength of steel. In the early 1970's, pre-impregnated material was under development in the aviation industry in the United Kingdom, and the 1980's saw carbon fibre in use in motorsport for the first time.

Over the years, the improvements in carbon fibre composites in these high-performance industries has opened new areas in which the material can be used, such as the wider automotive industry and others.

(Frost, 2017)

2.2 Construction

Components manufactured from carbon fibre use a pre-determined number of layers of CFRP fabric, increasing the number of these layers increases the thickness of the final component. Fibre orientation is crucial in the design of the layup. Carbon fibre can only provide strength along its length, and it is common to see the same fabric oriented differently throughout the layup to help increase the performance of the part.

There are many different types of CFRP fabric, and which type to use should be determined by the function of the component.

2.2.1 Unidirectional fabric

This fabric features fibres which all run at 0°, providing excellent tensile strength along one axis, but very poor performance elsewhere. Only a few fibres running at 90° hold the fabric together. This type of fabric is useful for building strong, alternating layers in the centre of the layup, where aesthetics are not a concern.

Figure 1 - unidirectional weave example (Boeriu, 2014)

2.2.2 Twill weave 2/2

This fabric features fibres which run at 0° and 90°, in a weave which passes over two, then under two warps (collections of unidirectional fibres). This provides good tensile strength in both axis, and the 2/2 weave allows the fabric to be easily manipulated during the layup process, but also means fabric is more susceptible to distortion and should be handled with care.

Figure 2 - twill weave 2/2 example (Boeriu, 2014)

This type of fabric is commonly found in the automotive industry, where aesthetics can be an important consideration, this is another reason why the fabric should be handled with care during layup.

2.2.3 Plain weave 1/1

This fabric is similar to a twill weave 2/2 fabric. Its fibres also run at 0° and 90° orientation, but the weave passes over one, then under one warp, as opposed to over two, under two. This weave forms a distinctive checkerboard pattern.

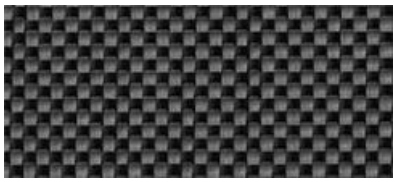

Figure 3- plain weave 1/1 example (Boeriu, 2014)

The tighter weave reduces the risk of distortion during layup, but this also means the fabric is more difficult to manipulate, and can increase layup time.

2.2.3 Other types of construction

In addition to these, there are other types of carbon fibre construction, for use in specific circumstances. For example, carbon fibre tape can be used to provide additional reinforcement in small or challenging areas of a layup. Since the tape is provided on a roll, it is often quicker and more efficient to use this, rather than cutting fabric from a large spool.

In addition to this, rovings (bunches of carbon fibres) can be wound around repairs for extra reinforcement, and sleeves of woven carbon fibre fabric can be stretched to perfectly fit around mandrels or tubes.

(Easy Composites, n.d.)

2.2.4 “Dry” and “Wet” layup

Some carbon fibre fabrics contain only fibres. During the layup process, as the plies (layers) are stacked, a two-part resin, which must be mixed, is applied, usually with a brush. This resin forms the matrix in which the carbon fibres are suspended.

The alternative is to use a fabric with the resin already impregnated into the weave, this is shortened to “pre-preg”. To prevent the fabric from curing, it must be stored at a certain reduced temperature. Using this type of fabric can decrease the layup time (since there is no need to apply resin manually between plies) but the fabric can become tacky and difficult to handle once the resin starts to cure.

3.0 Carbon Fibre Reinforced Polymer manufacturing processes

3.1 CFRP Autoclave manufacture

Once the layup for a CFRP part is complete, it must be cured. In the autoclave manufacturing process, this achieved by pulling a vacuum over the surface of the layup, then loading the layup into the autoclave, which applies heat and pressure over a predetermined period of time.

Figure 4 - UWTSD autoclave

3.1.1 Preparing the layup for vacuum

Once the layup is complete, a release film must be applied to the top surface. This important step ensures that no additional layers touch and bond to the layup, and this creates a more desirable surface finish to the top face of the part.

Next, breather cloth needs to be applied. It should wrap underneath and cover all areas of the layup. The breather cloth allows air to be pulled from all areas around the layup, helping to ensure a good vacuum.

The next step is to seal the layup in a vacuum bag. The bagging film is cut to size (usually around twice the size of the layup), and all edges but one are sealed with tape. After the layup is loaded into the bag, the vacuum valve must be inserted through the bag in such a way that it pulls vacuum though a section of breather material. Once the final edge is sealed, a vacuum can be pulled on the part to check for leaks.

(Easy Composites)

3.1.2 Curing

Once the vacuum is confirmed, the part can be cured. It is sealed in the autoclave. The temperature and pressure are increased inside the autoclave during a period called the “ramp-up” time. Once the desired temperatures and pressures are reached, these are stabilised and the cure takes place, usually over a number of hours.

There is a “ramp-down” time after the cure is complete, to allow the autoclave to return to atmospheric pressure and the internal temperature to drop.

3.2 CFRP Press forming manufacture

An alternative manufacturing process to the autoclave for carbon fibre parts is the press forming process. The principle is the same, using heat and pressure to cure the pre-preg carbon fibre, but instead of using what is essentially a large pressure cooker, this process uses a hydraulic press.

Figure 5 - UWTSD Press

To ensure the correct dimensions of the final part, male and female press tools must be machined, usually from aluminium. Before the press can be used, these tools must be brought up to the curing temperature of the carbon fibre being cured.

There is no difference required in the process of laying up plies over a mould. When the time comes to cure, there is no need to apply release film, breather cloth or vacuum bags to the layup. After the layup is removed from the mould, and a release agent is applied to each side of the press tool, it is inserted directly into the press tool and the tool is closed. Depending on the process, the press can pause before closing, leaving an approx. 4mm gap, this is called dwelling. This raises the temperature of the layup and allows the resin to flow freely before pressure is applied. Once the dwell time is over, the press closes and applies pressure to the layup.

After the part has cured and the pressure is released, the part is removed from the press tool by hand, or with assistance such as pushing compressed air between the part and the press tool. Since the tool is already up to temperature, another part can be inserted into the tool and the process can begin again almost immediately.

3.3 Comparing autoclave and press forming processes

This author has seen in practice the ability to produce composite components using the press forming process in minutes, rather than the hours required in autoclave manufacture. However, this same process produced many defective or unsuitable parts (blemished, distorted surface plies, poor mechanical performance) which had to be rectified through the process of experimentation and trial and error (varying dwell times, cure times, pressures etc.).

The autoclave and press each apply pressure in different ways. Since the autoclave increases the pressure surrounding the part, pressure is applied uniformly from all directions. In contrast, the press applies pressure from above only, even when parts feature concave or convex, or steep-walled geometry (see figures 6 and 7 below).

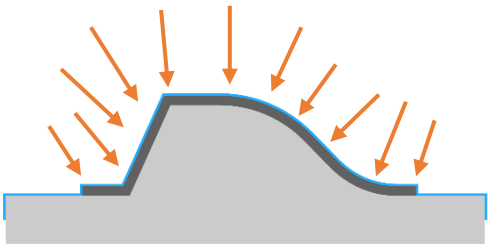

Figure 7 - how pressure is applied in an autoclave

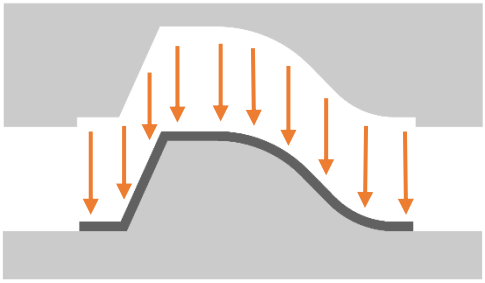

Figure 6 - how pressure is applied in a press

This difference in how the load is applied could have an impact on the appearance and the mechanical performance of the part. In addition to this there are differences in how the part is brought up to temperature and pressure. In the autoclave, pressure and temperature is ramped up slowly, over 20 minutes or longer. In contrast, the press applies heat and pressure immediately. By producing identical specimens using both processes, the effect that these variables have on the mechanical performance of the material can be better understood.

The extra time and energy used for ramping up and down the autoclave increases manufacturing costs and decreases effieciency. The press requires expensive high quality tooling to produce parts which match the parts produced using the autoclave. The autoclave is larger meaning more parts can be produced at once, but the process uses for more consumables than the press forming process, increasing manufacturing costs further. If these aspects are investigated in addition to the mechanical comparision, a fairer judgement can be made as to which manufacturing method to use in a perticular application.

4.0 Mechanical testing

4.1 Why undertake mechanical testing?

If an understanding of the mechanical properties of parts produced using these two processes is to be attained, test specimens from both must undergo mechanical testing. As Hodgkinson, 2000 describes, there are many questions which require answers regarding mechanical testing:

- What tests should be carried out to give the required data?
- What does the data actually mean?
- How reliable is the data produced?
- Is data obtained from small test specimens meaningful when large structures are being designed?
- What effect will the operating environment have?

(Hodgkinson, 2000)

Unlike crystalline materials, CFRP is a composite material, and its mechanical properties are dependent on the variables of the composition of the reinforcement (fibres) and matrix (resin). These variables include:

- Properties of the fibre
- Surface character of the fibre
- Properties of the matrix material
- Properties of any other phase
- Spatial distribution and alignment of the second phase (including fabric weave)
- Nature of the interfaces

(Turner, 2000)

In literature, the matrix of the composite is often described as the first phase, and the reinforcement is described as the second phase. There can be more phases, depending on the choice of ply orientation, or if totally different materials are used as part of the layup.

4.2 Tensile testing

The first mechanical characteristic selected to be tested is tension. As Godwin, 2000 explains, it is not only the ultimate tensile strength which can be determined when performing a tensile test on a material. For instance, composites have various failure modes. They can split, splinter or delaminate (where plies are pulled apart). By looking closely at these failures, an understanding can be gained as to how and where the initial damage occurs. There is also the nature of the failure; did it occur suddenly, or was a failure obviously about to occur through observing audible or visual clues?

(Godwin, 2000)

Figure 8 - an example of a composite test specimen undergoing tensile testing

When testing composites in this way, the load applied in tension is measured in newtons (N), and the extension of the specimen is measured in mm.

4.3 Three-point bending testing

Although flexure tests such as three-point bending can often yield similar results from other testing methods (such as tension), it can be useful in other ways. Firstly, as may be obvious, three-point bending introduces compression loading in addition to tension loading as experienced in tensile testing. This may create a slightly more realistic scenario, it is quite likely that composite components could be loaded in more than one direction, experiencing tension and compression simultaneously.

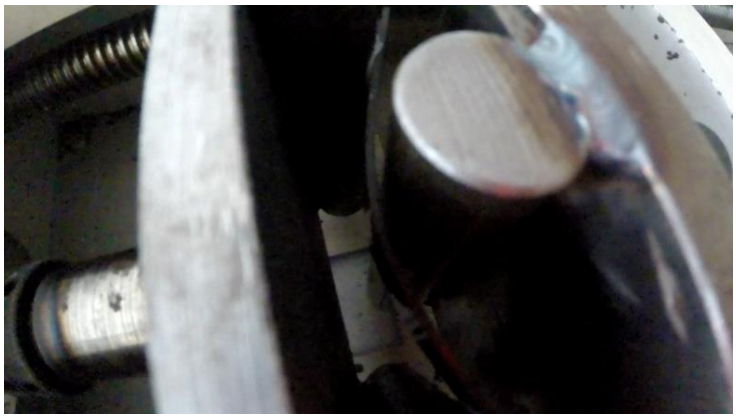

Figure 9 - a close-up view of a composite test specimen undergoing flexural texting using three-point bending

As Hodgkinson, 2000 states, flexure type tests are applicable to process, quality control and material selection experiments, where comparative values (rather than absolute values) are required.

"Data obtained from some flexure test methods have to be treated with caution, if not scepticism, because it is possible to achieve results which are a function of the method used, not reflecting in any way the properties of the material it was intended to measure."

(Hodgkinson, Flexture, 2000)

This suits the autoclave/press comparison reasonably well, since the objective of this project is not to achieve high absolute values from either tensile or three-point bending experiments, but rather to gain an understanding about the differences and similarities these two processes produce.

5.0 Standards

It is critical to comply with standards as closely as possible when performing mechanical testing on engineering materials. In terms of the standards which must be followed throughout this project, parameters such as the ones listed below require attention and should be carefully considered:

- Requirements of the press
- Correct autoclave process
- Test plate dimensions
- Test specimen dimensions
- Requirements of mechanical testing equipment
- Correct tabbing for test specimens (if required)
- Correct mechanical testing processes

There are many reasons why standards should be followed during the manufacturing and testing phase of this project. First, thinking locally, if the experiments are carried out in accordance to certain standards, the information gathered is more useful to others in the university. Following standards make the results gathered more relatable, and they make it easier for others to use the results gathered in future research or experimentation.

As standardised services and products are considered more dependable, the same can be said for results obtained from a standardised testing procedure, and thinking more broadly, adhering to standards closely ensures all manufacturing and testing processes are carried out safely.

(European Telecommunications Standards Institute, n.d.)

5.1 BS ISO 1268

British Standard (BS) International Standards Organisation (ISO) 1268 Fibre – reinforced plastics – Methods of producing test plates is the standard which needs to be followed to correctly manufacture the test plates from which the specimens will be cut.

Figure 10 - BS ISO 1268

It covers many topics, including the requirements of the press. For instance, its ability to apply a certain force, uniformly across the whole of the press surface, and its ability to maintain this pressure for the duration of the operation. It also details the exact methodology which should be followed when laying up pre-preg and preparing the layup for the autoclave, including all the steps

mentioned previously in section 3.1.1. This standard also covers the dimensions the produced test plate must be, this includes the length and width (the same dimension, in this particular case) as well as the overall thickness of the test plates, including acceptable tolerances.

5.2 BS 2782

British Standard (BS) 2782: part 3: method 320 E EN 61 is the standard which needs to be followed to produce the tensile test specimens. It details when it is appropriate to use this standard, the thickness, width and overall length of the tensile test specimens, as well as the tab length (the length of the material which is sandwiched between the test specimen and the grips of the tensile test equipment) and the recommended tab material.

5.3 ISO 14125

International Standards Organisation (ISO) 14125 recommends the appropriate flexural specimen dimensions for various material types. Depending on material selection, parameters such as length, span, width and thickness should change, to ensure the results from testing are applicable.

More information on standards listed here is available in the appendix.

6.0 Test plate manufacture

6.1 CFRP test plate specifications

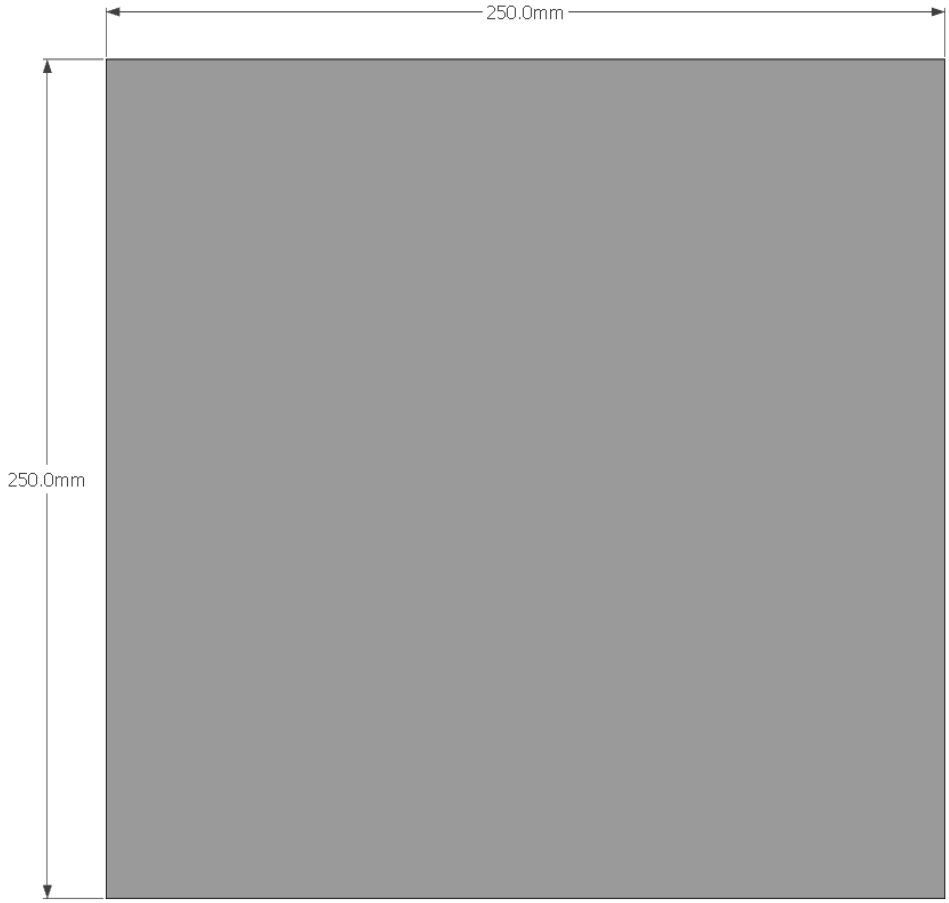

Figure 11 - test plate overall dimensions

The material selected for use in this project was a 2mm, 2/2 twill, pre-impregnated (previously discussed in sections 2.2.2 and 2.2.4) carbon fibre fabric. Through previous experience, it was determined that eight plies of this material would be required to achieve the final thickness of 2mm, as determined by the press tool currently in use by the university, and in accordance to *BS 2782,* where the test plate thickness can be anywhere between 1mm and 10mm. Test plate hieght and width was 250mm, again defined by the available press tool, and in arrordance *BS 2782,* where the minimum overall length of the test specimin is 200mm.

6.1.2 CFRP test plate dimensions

Thickness:	2mm
Width:	250mm
Height:	250mm

6.1.3 Layup selection

Since the material in use in the project is a 2/2 twill fabric, it includes fibres running at 0° and 90° orientation. For the sake of being thorough, and since 8 plies will mean a symmetrical layup, it was decided that plies should be configured in both the 0° and 90° configuration.

Top -	0	Reference plane – bottom Designation = [0/90/90/0]:s Full description = [0/90/90/0/0/90/90/0]
	+90	
	+90	
	0	
	0	
	+90	
	+90	
Bottom -	0	

Figure 12 - layup selection and notation

6.2 CFRP test plate manufacture

What follows shows in detail the manufacturing process of the test plates using both the autoclave and the press.

6.2.1 Kit cutting

To begin, the pre-preg fabric was removed from the cold storage area and the total amount of fabric needed to produce the four test plates (two for manufacture in the autoclave, two in the press) was calculated. Since each 250mm x 250mm plate required 8 plies to reach 2mm thickness, 1m² of fabric was required for each test plate, meaning a total material usage of 4m².

Figure 13 - Individual plies being cut from the roll of pre-preg fabric

A simple template was made to help ensure dimensional consistency for all plies. As each ply was cut, a small mark was made to indicate the 0° orientation. A total of 32 250mm x 250mm plies were cut.

6.2.2 Layup

Using the bottom ply as a reference, the layups were constructed, paying close attention to the indicators to maintain the correct ply orientation. As each ply is applied, it is carefully but firmly pressed, compacting the whole layup. Great care is taken to ensure there was no trapped air between the plies, and that each ply is flat, not creased and undistorted, in an effort to keep the layup's structure as uniform as possible.

Contaminants between the plies can cause weakness or failures during the life of a composite material, and this was another area where attention was paid, ensuring there were no foreign particles between the plies as the layup was constructed.

6.2.3 Using the press

It was determined that both processes should produce specimens using the same curing parameters, to test the fundamental differences in the processes. Therefore, the force exerted on the layup in the pressurised autoclave must be translated to a linear load which can be applied in the press.

Pressure experienced in autoclave *= 3 bar*

= 300kPa

To translate this into a linear force, it makes sense to convert this figure to N/m^2:

Pressure experienced in autoclave *= 300,000 N/m^2*

Area of test plate *= 0.25 x 0.25*

=0.0625m^2

However, there is an overhang which increases the surface area on top of the press tool:

Area of press tool *=0.0729m^2*

This can now be used to find the force needed to match the autoclave pressure:

Force required by press *=300,000 x 0.0729*

=21,870 N

This can now to converted to metric tons and used to allow the press to apply the correct load to match the pressure in the autoclave:

Load required by press *=<u>2.2 metric tons</u>*

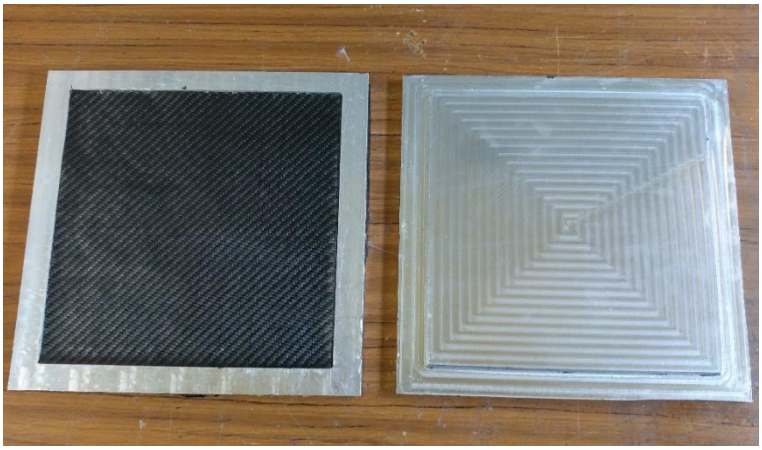

Figure 14 - pre-preg layup inserted into the press tool, ready for curing

The press tool was cleaned and a release agent was applied. This is a crucial step. The surface finish of the press test plates is entirely dependent on the cleanliness of the tool. If there are any contaminants between the layup and the tool, after curing they will damage or become embedded in the surface of the test plate.

The quality of the tool itself also affects the test plates surface finish. It is important to ensure there are no dents or other defects in the surface of the tool, and if surface finish is critical, the tool can be polished. If no release agent is applied, the test plate would be very difficult to recover without damage, especially in a tool of this design (no convex geometry or overhanging edges).

Once the tool is prepared, the layup is inserted into the female half, and the tool is placed into the press. The tool is then brought up to curing temperature, 120°C, which takes around 15 minutes. At this point the press is closed and the 2.2 metric ton load is applied to the layup.

The cure time is 40 minutes, after this period the press can be opened, after a few minutes of cooling, the test plate can be removed, and the process repeated for the second plate.

Figure 15 - the press in operation

6.2.4 Using the autoclave

Preparing the layup for autoclave curing was a more time – consuming procedure. Firstly, the layup was placed onto a flat tool. At the recommendation from the technician, a peel ply was laid down first. This is to help prevent resin loss from thinner parts. The release film was then laid down on top of the peel ply, and both layers are tightly wrapped around and taped to the underside of the tool.

Figure 16 - underside of the autoclave tool, showing peel ply and release film secured

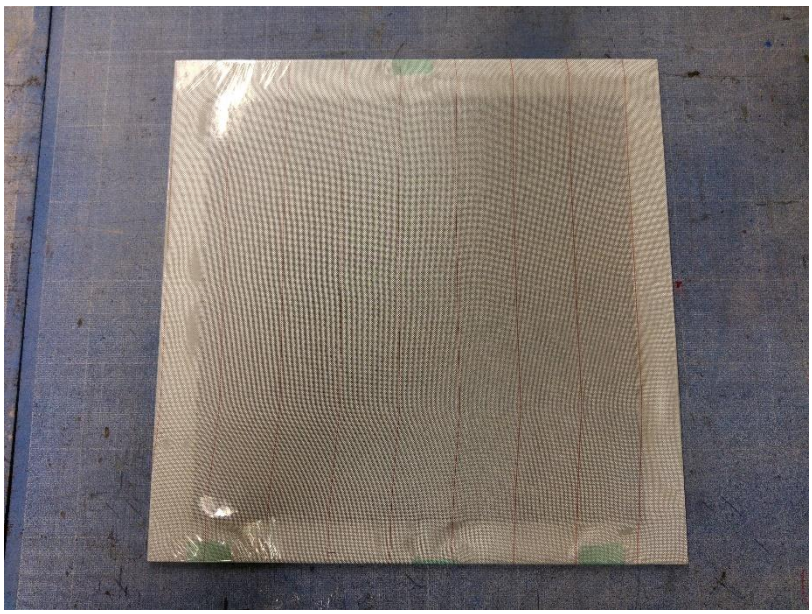

Figure 17 - the layup can be seen through the peel ply and the release film

Next, to achieve a suitable vacuum on the layup, breather cloth was wrapped around the tool, making sure to cover all areas. This was loosely taped, mainly to help keep it in position during the next phase.

Once the breather cloth was in place, the vacuum bag could be prepared. Though not necessary in this particular case due to the flatness of the part being manufactured, it is wise to use a larger bag to ensure a good vacuum. One side of the bag was tape - sealed, and both layups with the peel ply, release film and breather cloth surrounding the tool were positioned in the bag together. One half of the vacuum valves were then placed inside the bag, making sure they were positioned on top of the layups, touching the breather cloth. This was important to ensure the air can be evacuated from all parts of the bag.

Figure 18 - shows both sides of the vacuum bag sealed, and the vacuum valves in position on the breather cloth

Once this was done, the other side of the vacuum bag was sealed, and the other half of the vacuum valves were attached by cutting though the bag. A vacuum was then pulled to ensure a good seal (using the vacuum hoses inside the autoclave), then the layups were locked into the autoclave ready for curing.

The autoclave has a ramp up time of 5°C per minute, meaning it took 24 minutes to reach curing temperature. During this time, the pressure was increased to 3 bar (300kPa) and once these parameters were reached, the autoclave maintained them for 40 minutes as the layup cured. Once this time had elapsed, the autoclave ramped down at approximately the same rate (around 20 minutes). Once the pressure had equalised, the vacuum bag could be disconnected and the two test plates removed.

7.0 Test specimen production

Now that specification test plates had been manufactured using both the autoclave and the press, the test specimens for use in the mechanical testing equipment needed to be produced. Although it may not have been a quicker option logistically, it was decided that the best method to produce the specimens would be abrasive water jet cutting.

As Hashish et al, 2011 points out, abrasive water jet (AWJ) cutting can have significant advantages when compared to more traditional tool – to – workpiece machining techniques. Using AWJ essentially removes the thermal damage to the workpiece caused by friction, as well as greatly reducing the cutting forces involved. Tool wear is greatly reduced (only the water jet system consumables, such as garnet, orifices and nozzles, and other ancillary items such as external hoses etc.).

(Hashish, 2013)

Figure 20 - one of two test plates produced in the autoclave, Note surface distortion from vacuum tube placement

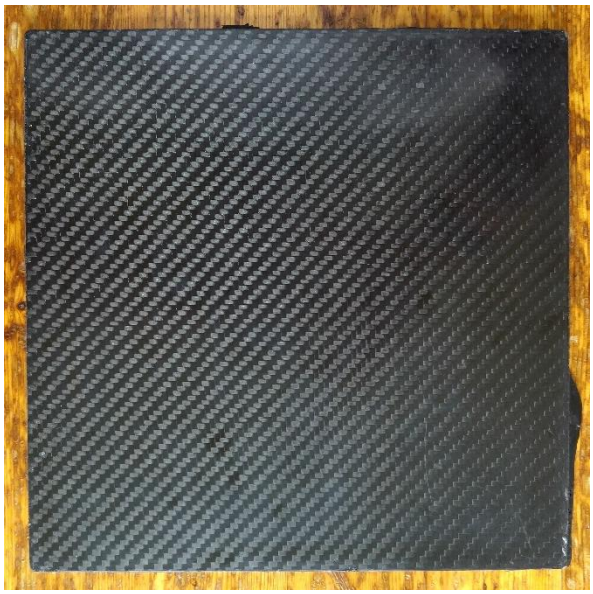

Figure 19 - one of two test plates produced in the press, note the "flash" resin which was forced out during the curing process

After noticing that both autoclave plates suffered surface distorsion in similar locations caused by the vacuum valve, a decision was taken to not use this region in specimen production, since the distorted top ply could cause some anomolous results during testing.

The consequences of this resulted in having to also exclude this region on the press test plates, since only one .DXF file would be used for the production of specimens from all four plates. This did present the opportunity to use this spare material in additional surface finish and cavitation investigations, but in the end this was not carried out.

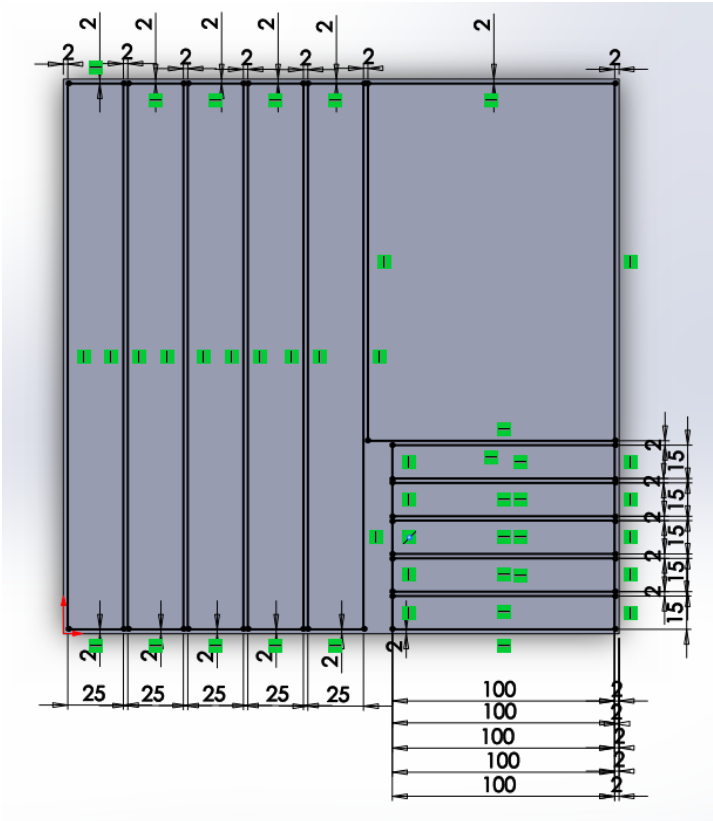

Figure 21 - planning how best to use the space available, note the empty region where the surface defects on the autoclave pates were located

The final test specimen count from each of the four test plates would be five 246mm x 25mm tensile testing specimens (in accordance to *BS 2782*), five 100mm x 15mm flexure testing specimens (in accordance to *ISO 14125*) for use in 3-point bending, and the empty region to account for the surface defects.

Figure 22 shows how little material is wasted in the good regions, thanks to using only 2mm spacing between specimens and around the perimeter of the test plate.

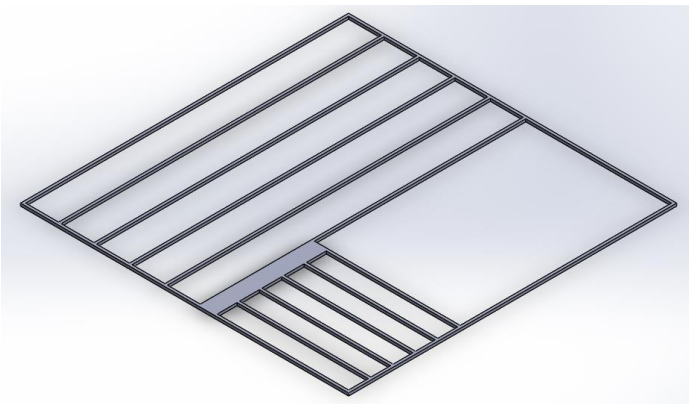

Figure 22 - the approximate remaining material after the abrasive water jet cutting process is complete

Once the final configuration was decided on, and the flash at the edges of the press plates was removed, the cutting plan was sent to the abrasive water jet and the test specimens were produced.

Unfortunately, during the cutting process, three flexural testing specimens (one from each of the two press test plates, and one from one of the autoclave test plates) were unrecoverable from the bed of the abrasive water jet.

The whole abrasive water jet cutting process took just under 60 minutes to complete processing for all four test plates, producing test specimens within tolerance. The jet created a surface finish which required not further processing.

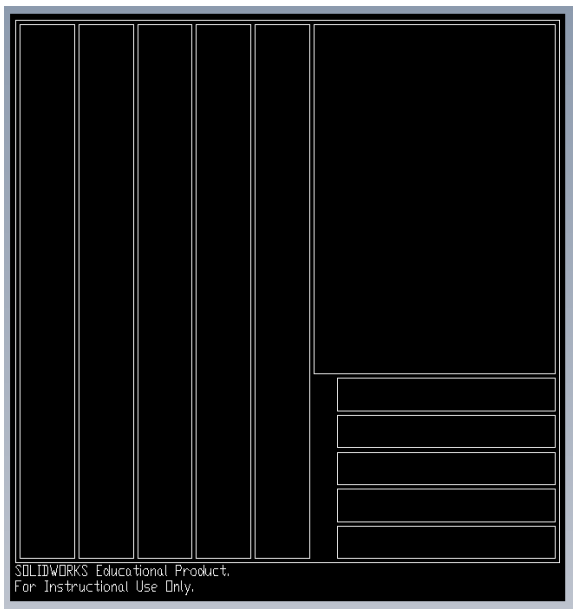

Figure 23 - the .DXF file used by the AWJ

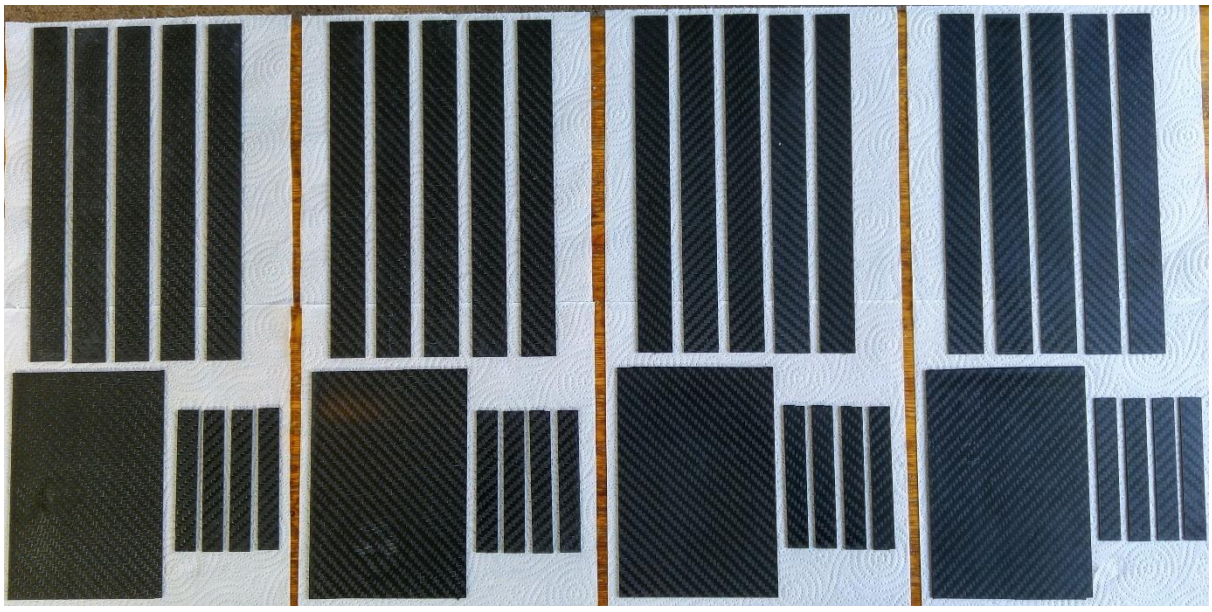

Figure 24 - the complete set of tensile and flexural specimens prior to testing, note the surface defects, highlighted

8.0 Autoclave and press specimen testing

8.1 Flexural testing

The specimens were positioned in a 3-point bending situation, bridging a span of 80mm. The load was applied at a rate of 5mm per minute, and all specimens were successfully loaded until failure occurred.

Figure 25 - one of the flexural specimens moments before failure, in a 3-point bending loading condition

Data was output in excel and graphs were produced automatically, though both axis on the graph were negative, since this method of data collection involves running tensile testing equipment in reverse, producing negative results.

8.2 Tensile testing

Before the tensile samples could be tested, tabs had to be bonded at both ends of each specimen. These tabs are in place to reduce localised stresses caused by the significant clamping forces of the grips. According to *BS 2782,* These tabs should be made from a material "similar to that under test" and of a thickness no less than 3mm.

Figure 26 - one of the tensile specimens during testing, note the emery cloth tabs between the self – tightening grips and the specimen

The spare composite was not enough to tab all the test specimens, and even if it was, it would not be thick enough to meet the standard, so it was decided to compromise and bond emery cloth to both sides of each specimen with an epoxy.

Attention was paid to the fibre orientation and ensuring the specimens were as close to vertical as possible, to minimise shear

stresses in the specimen. The load was applied at 2mm per minute, and after testing one specimen from each test plate, all four had tab bond failures prior to specimen failure.

After this, all tabs were removed and the remaining specimens were re-tabbed using a superglue. After this change, no more bond failures occurred, and all remaining specimens were successfully loaded until failure.

9.0 Analysis

9.1 Initial observations

Most specimen failures occurred after reaching similar loads and displacements. This suggests that attempts to minimise contaminants and defects in the manufacturing stage successfully produced a material with reasonably consistent properties throughout.

The failures occurring on both the autoclave and press specimens were similar. Meaning, the failures are occurring in similar areas on both, and the failure modes themselves were similar. In addition, the way in which the failures developed were similar. There were no sudden failures, they were always preceded by audible clicks and pops (individual fibres failing) and regarding tensile testing, sometimes even small surface propagations were visible at the edge of the specimen.

9.2 Raw data - flexural

Displacement (mm)	Autoclave 1-1 Load (N)	Autoclave 1-2 Load (N)	Autoclave 1-3 Load (N)	Autoclave 1-4 Load (N)
9	246	300	260.666	230
9.1	250	303.333	264.666	230.666
9.2	254.666	216.666	264.666	232.666
9.3	258.666	202.666	249.333	233.333
9.4	260.666	199.333	252	233.333
9.5	264.666	199.333	254	234.666
9.6	266.666	200.666	254	223.333
9.7	270.666	202	256	220
9.8	275.333	202.666	259.333	219.333
9.9	279.333	202.666	261.333	220
10	284	203.333	264	220.666
10.1	288.666	204.666	266.666	222
10.2	293.333	204.666	268	223.333
10.3	297.333	206	261.333	225.333
10.4	284	206	261.333	227.333
10.5	285.333	206.666	262	228.666
10.6	289.333	204.666	252.666	210.666
10.7	274	201.333	227.333	14
10.8	272.666	14.666	111.333	14.666
10.9	255.333	15.333	10	14.666
11	256	15.333	10	0
11.1	255.333	15.333	0	
11.2	250.666	0		
11.3	232.666			
11.4	218			
11.5	217.333			
11.6	212.666			
11.7	210.666			
11.8	207.333			
11.9	200.666			

Figure 27 - an example of the raw data collected during flexural testing

Figure 27 shows an example of the raw data collected during flexural testing. Specifically, the data is from specimens of one of the autoclave plates (designated Autoclave test plate 1), and the loads experienced by each of the four flexural specimens (Autoclave 1-1 through to Autoclave 1-4) are shown in each column, along with their corresponding displacement. Loads through the specimen were recorded at 0.1mm displacement intervals, providing a detailed insight into the increasing loads. The data begins immediately from 0.1mm displacement, and when the load reaches zero, the specimen has already failed and the test has concluded.

The raw data from the flexural tests for all specimens from Autoclave 1, Autoclave 2, Press 1 and Press 2 are available in the appendix.

9.3 Analysis – flexural

9.3.1 Autoclave test plate 1 - flexural

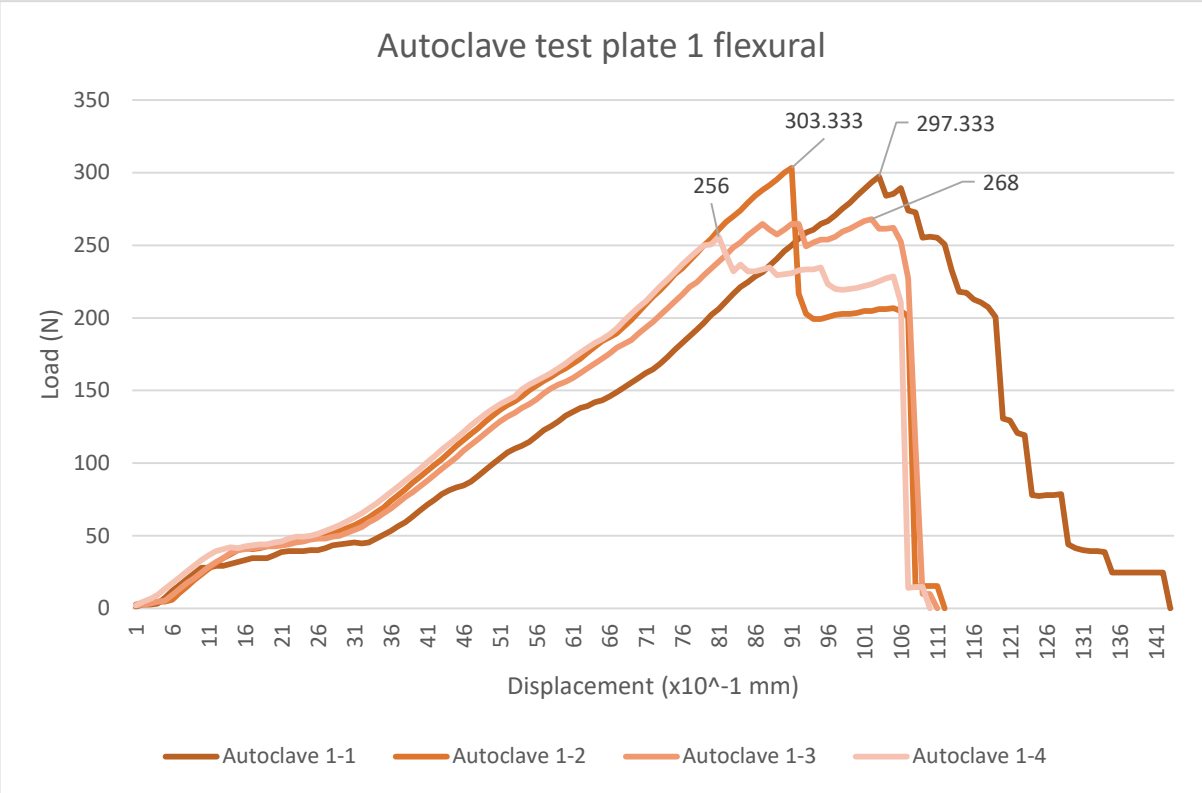

Figure 28 - Autoclave test plate 1 flexural graph

Specimen	Load at failure (N)	Displacement at failure (mm)
Autoclave 1-1	297.333	10.3
Autoclave 1-2	303.333	9.1
Autoclave 1-3	268	10.2
Autoclave 1-4	256	8.1

Autoclave 1 average load at failure *= 281.1665 N*

Autoclave 1 average displacement at failure *=9.425mm*

Load at failure variation = 47N *Displacement at failure variation = 2.2mm*

9.3.2 Autoclave test plate 2 - flexural

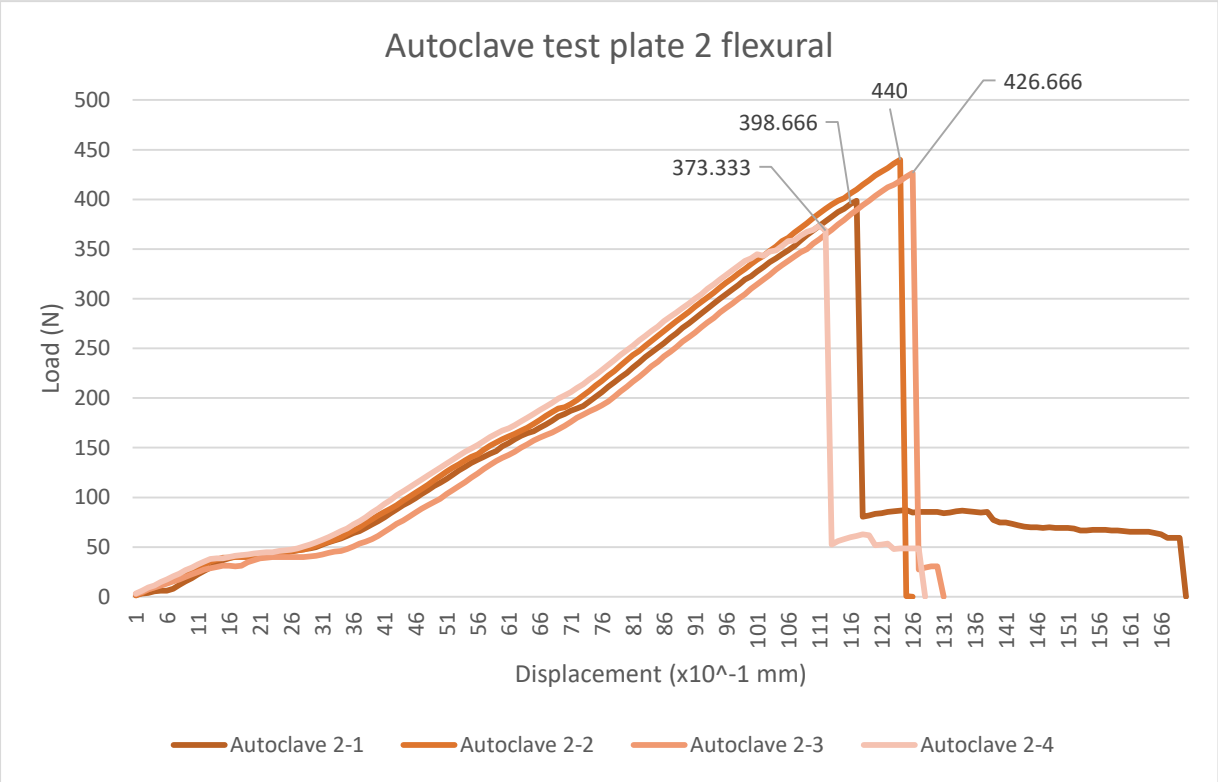

Figure 29 - Autoclave test plate 2 flexural graph

Specimen	Load at failure (N)	Displacement at failure (mm)
Autoclave 2-1	398.666	11.7
Autoclave 2-2	440	12.4
Autoclave 2-3	426.666	12.6
Autoclave 2-4	373.333	11.1

Autoclave 2 average load at failure = 409.49975 N

Autoclave 2 average displacement at failure =11.95 mm

Load at failure variation = 66.667 N

Displacement at failure variation = 1.5 mm

9.3.3 Press test plate 1 - flexural

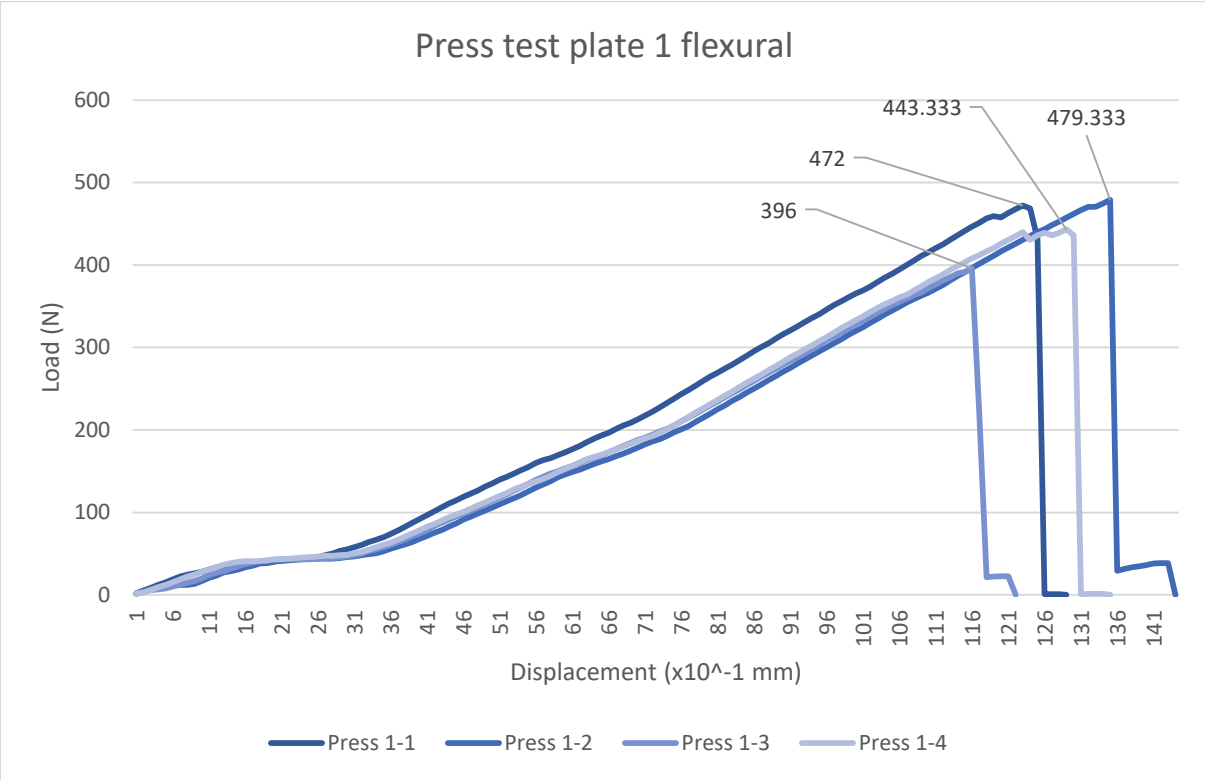

Figure 30 - Press test plate 1 flexural graph

Specimen	Load at failure (N)	Displacement at failure (mm)
Press 1-1	472	12.3
Press 1-2	479.333	13.5
Press 1-3	396	11.3
Press 1-4	443.333	12.9

Press 1 average load at failure *= 444.99975 N*

Press 1 average displacement at failure *= 12.5 mm*

Load at failure variation = 83.333 N *Displacement at failure variation = 2.2 mm*

9.3.4 Press test plate 2 - flexural

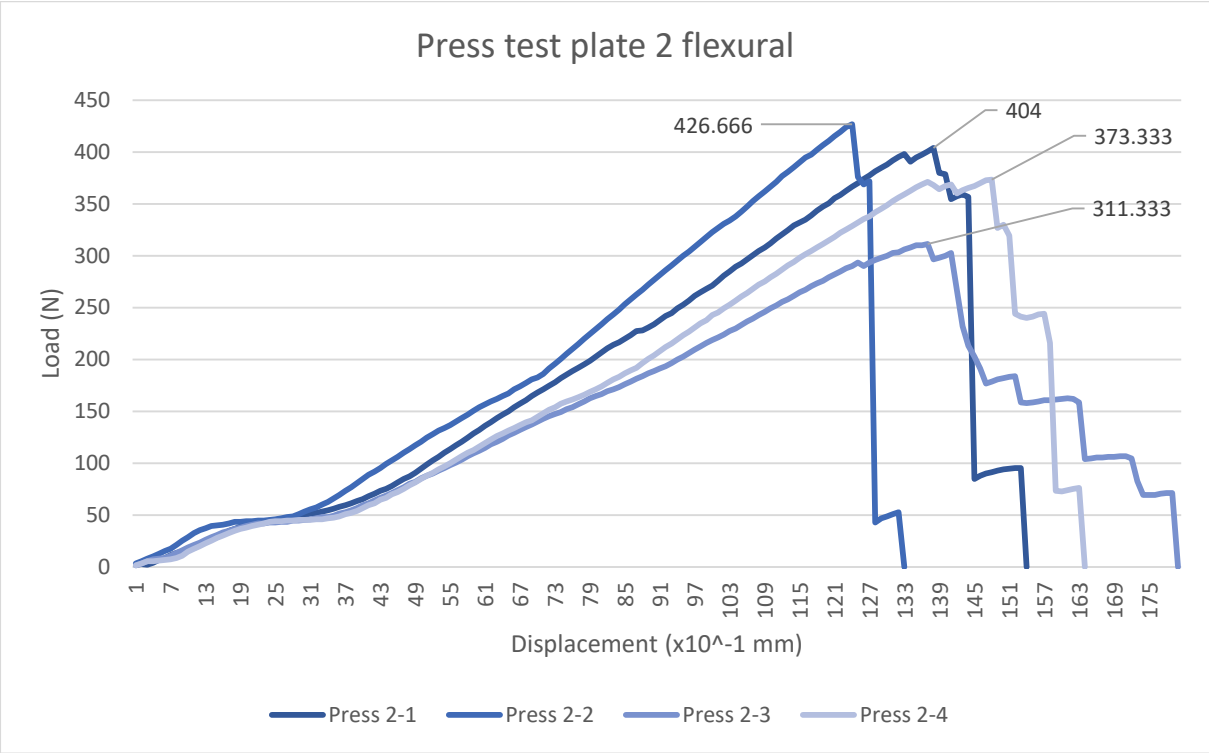

Figure 31 - Press test plate 2 flexural graph

Specimen	Load at failure (N)	Displacement at failure (mm)
Press 2-1	404	13.8
Press 2-2	426.666	12.4
Press 2-3	311.333	13.7
Press 2-4	373.333	14.8

Press 2 average load at failure *= 378.833 N*

Press 2 average displacement at failure *= 13.675 mm*

Load at failure variation = 115.333 N *Displacement at failure variation = 2.4 mm*

9.3.5 Combined analysis - flexural

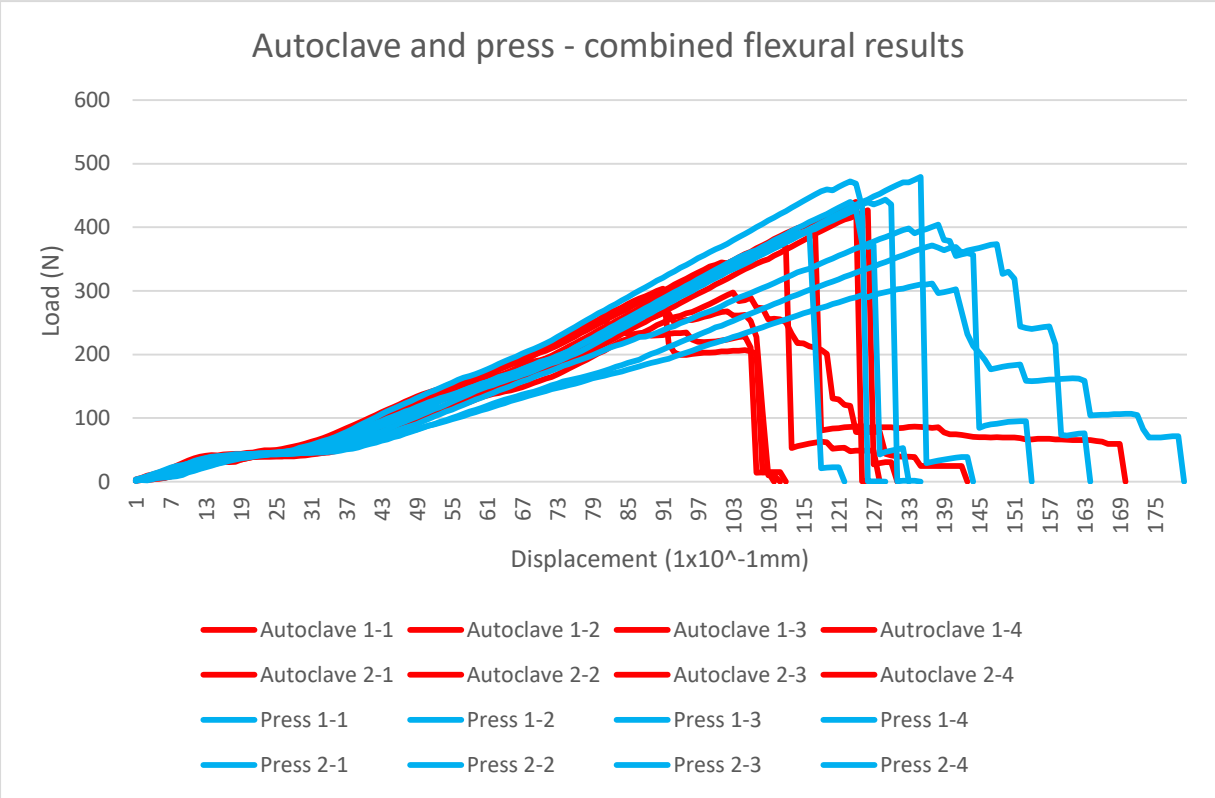

Figure 32 - autoclave and press - combined flexural results

Autoclave 1 average load at failure	*= 281.1665 N*
Autoclave 2 average load at failure	*= 409.49975 N*
Therefore, average autoclave flexural specimen load at failure	*= 345.3 N*
Press 1 average load at failure	*= 444.99975 N*
Press 2 average load at failure	*= 378.833 N*
Therefore, average press flexural specimen load at failure	*= 411.9 N*

Autoclave 1 average displacement at failure	*=9.425mm*
Autoclave 2 average displacement at failure	*=11.95 mm*
Therefore, average autoclave flexural specimen displacement at failure	*= 10.69 mm*
Press 1 average displacement at failure	*= 12.5 mm*
Press 2 average displacement at failure	*= 13.675 mm*
Therefore, average press flexural specimen displacement at failure	*= 13.09 mm*

As can be seen from these results, the specimens produced from the test plates manufactured using the press clearly outperformed the autoclave specimens in a 3 – point flexural test, both in terms of higher loads before failure, and greater displacement before failure.

Regarding load at failure, the press specimen average of 411.9 N is 19.2% higher than the autoclave specimen average of 345.3 N.

Regarding displacement at failure, the press specimens average of 13.09 mm is 22.5% higher than the autoclave specimen average of 10.69 mm.

As Hodgkinson, 2000 states, it is possible to calculate the flexural modulus (E_f) using the dimensions of the specimen, and the results from a 3 – point flexural test. To use the results from press specimen 2-2 as an example:

$$E_f = \frac{S^3 m}{4bh^3}$$

Where: *S = support span*

m = slope of the load/deflection curve

b = specimen width

h = specimen thickness

$$E_f = \frac{(80x10^{-3})\left(\frac{143333}{4000}\right)}{4x(15x10^{-3})(2x10^{-3})^3}$$

Therefore $E_f = 5972208333\ Pa$*, or 5.9 GPa*

(Hodgkinson, Flexture, 2000)

The combined results graph in section 9.3 is available in greater detail in the appendix.

9.4 Raw data – tensile

Time (seconds)	Load (KN)	Elongation (mm)	Displacement (mm)
343.648	39.3	11.071	11.42
344.648	39.39	11.105	11.453
345.647	39.475	11.138	11.487
346.646	39.56	11.171	11.52
347.644	39.65	11.205	11.553
348.644	39.735	11.238	11.587
349.642	39.82	11.272	11.621
350.641	39.905	11.305	11.653
351.64	39.995	11.338	11.687
352.639	40.08	11.372	11.721
353.638	40.165	11.405	11.753
354.637	40.255	11.438	11.787
355.636	40.335	11.472	11.821
356.636	40.42	11.505	11.853
357.635	40.505	11.538	11.887
358.634	40.585	11.572	11.921
359.633	40.665	11.605	11.953
360.631	40.745	11.638	11.987
361.63	40.82	11.672	12.021
362.63	40.89	11.706	12.054
363.629	40.95	11.738	12.087
364.628	-0.18	11.797	12.146
365.627	-0.175	11.827	12.176
366.626	-0.175	11.858	12.207
367.625	-0.17	11.89	12.238
368.624	-0.17	11.921	12.269

Figure 33 - an example of the raw data collected during tensile testing

Figure 33 shows an example of the raw data collected during tensile testing. Specifically, this data is from a specimen (autoclave 1-1) from one of the plates produced in the autoclave (the plate designated autoclave 1).

The data shown above has a time-step approximately every second, but the raw data obtained from the tensile testing equipment features a time-step of approximately 10 per second. For this application, there is no need for such detailed data recording, and although the majority of data is excluded, what remains is more than sufficient.

The automatically-generated graphs for each tensile test is available in the appendix.

9.5 Analysis – tensile

9.5.1 Autoclave test plate 1 – tensile

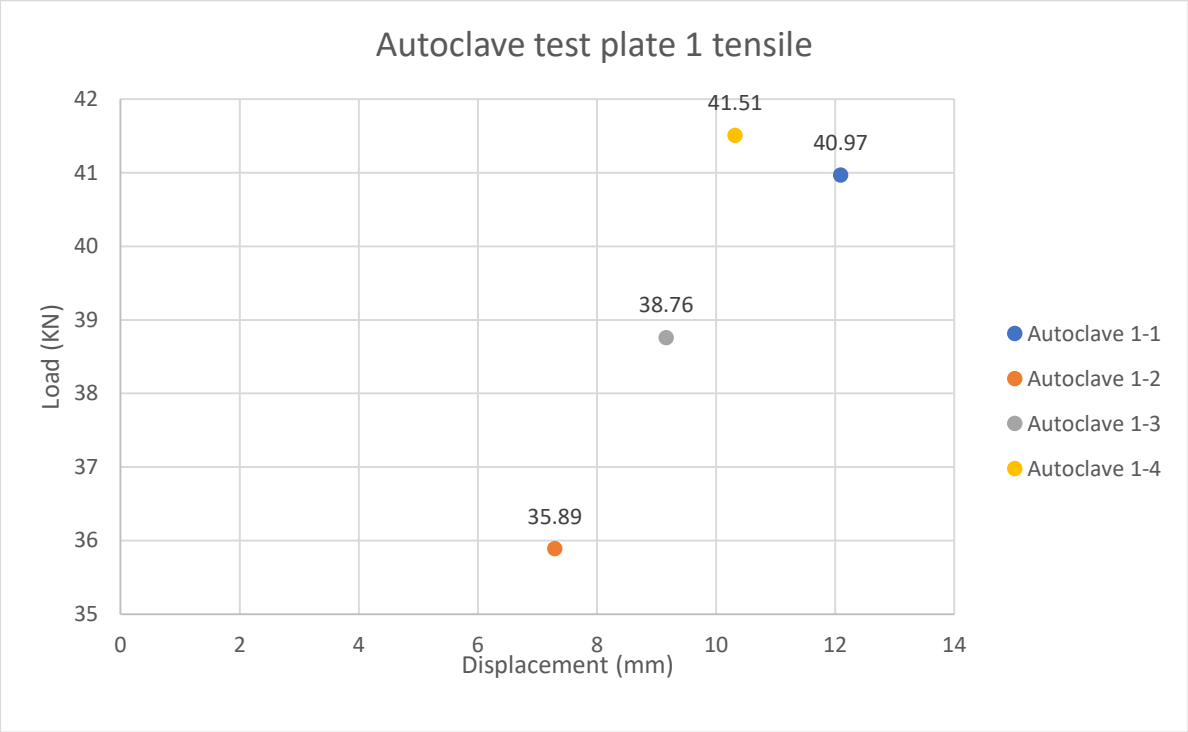

Figure 34 - Autoclave test plate 1 tensile chart

Specimen	Load at failure (KN)	Displacement at failure (mm)
Autoclave 1-1	40.97	12.09
Autoclave 1-2	35.89	7.29
Autoclave 1-3	38.75	9.16
Autoclave 1-4	41.51	10.32

Autoclave 1 average load at failure = 39.28 KN

Autoclave 1 average displacement at failure = 9.715 mm

Load at failure variation = 5.62 KN

Displacement at failure variation = 4.8mm

9.5.2 Autoclave test plate 2 – tensile

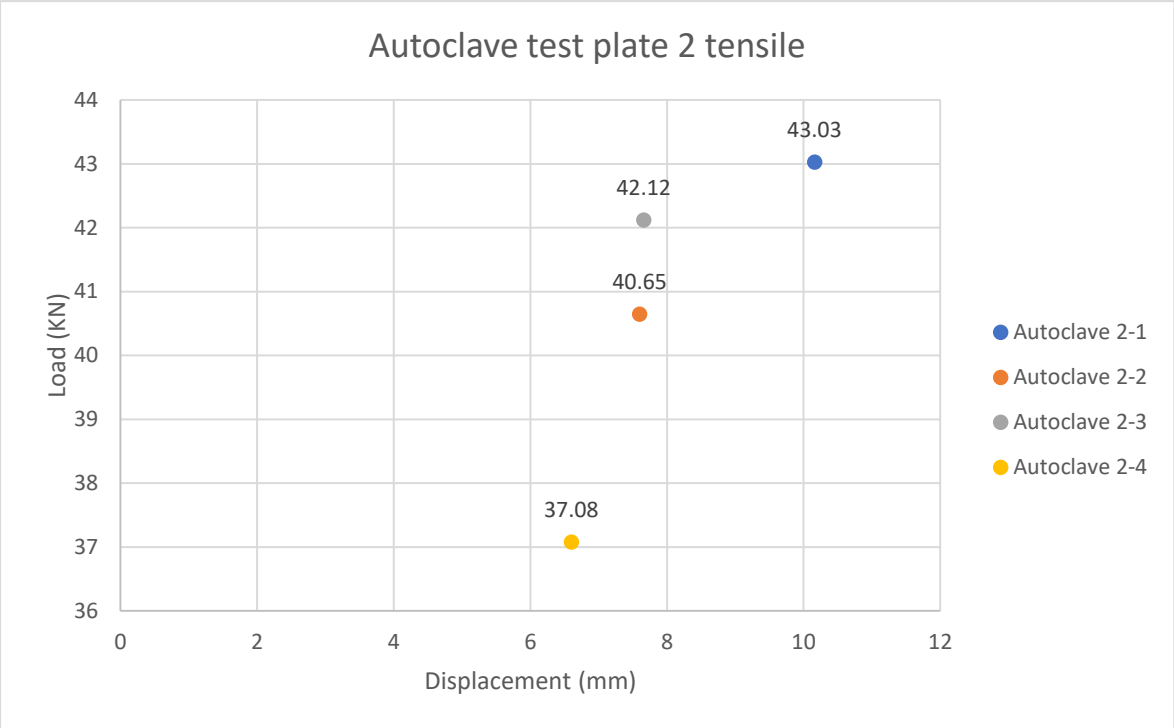

Figure 35 - Autoclave test plate 2 tensile chart

Specimen	Load at failure (KN)	Displacement at failure (mm)
Autoclave 2-1	43.03	10.16
Autoclave 2-2	40.65	7.6
Autoclave 2-3	42.12	7.66
Autoclave 2-4	37.08	6.6

Autoclave 2 average load at failure = 40.715 KN

Autoclave 2 average displacement at failure = 8.005 mm

Load at failure variation = 5.95 KN

Displacement at failure variation = 3.56 mm

9.5.3 Press test plate 1 – tensile

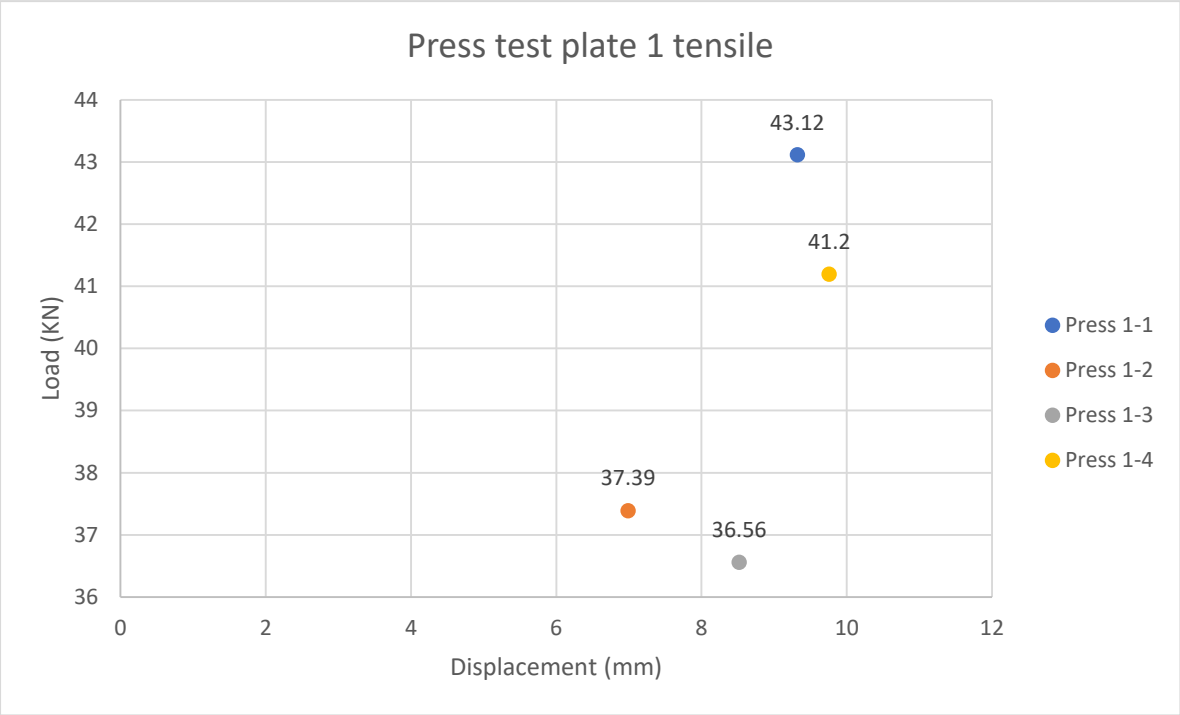

Figure 36 - Press test plate 1 tensile chart

Specimen	Load at failure (KN)	Displacement at failure (mm)
Press 1-1	43.12	9.32
Press 1-2	37.39	6.99
Press 1-3	36.56	8.52
Press 1-4	41.2	9.76

Press 1 average load at failure *= 39.5675 KN*

Press 1 average displacement at failure *= 8.648 mm*

Load at failure variation = 6.56 KN *Displacement at failure variation = 2.77 mm*

9.5.4 Press test plate 2 – tensile

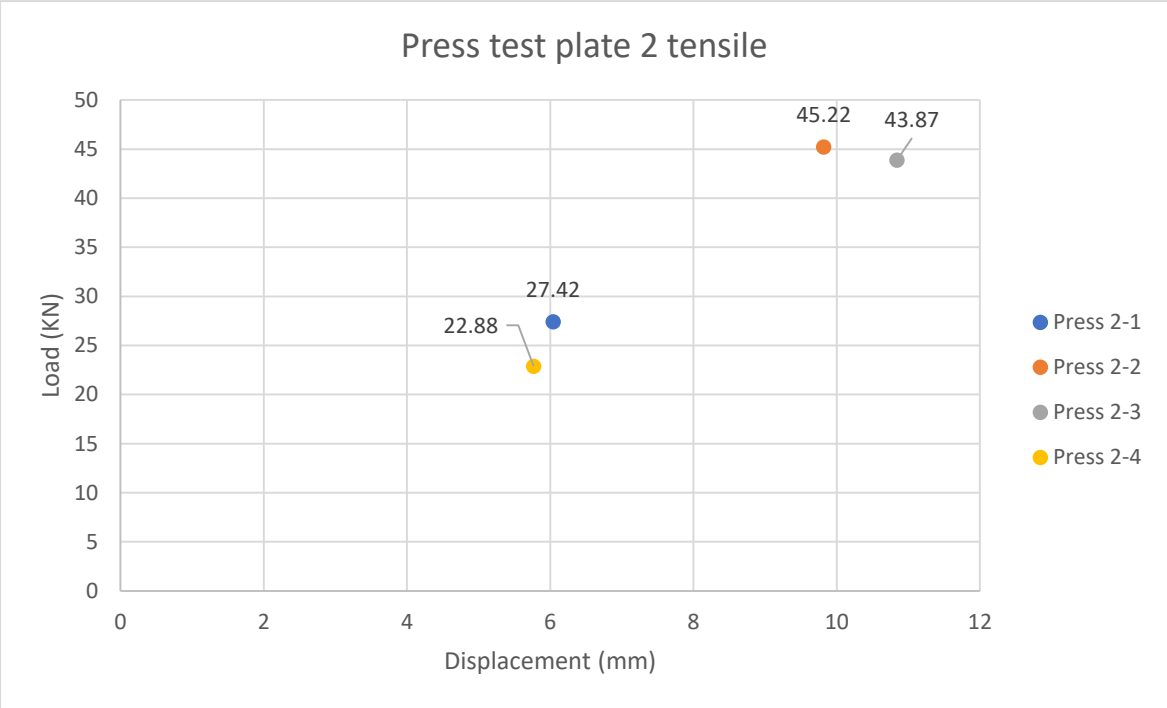

Figure 37 - Press test plate 2 tensile chart

Specimen	Load at failure (KN)	Displacement at failure (mm)
Press 2-1	27.42	6.04
Press 2-2	45.22	9.82
Press 2-3	43.87	10.84
Press 2-4	22.88	5.77

Press 2 average load at failure *= 34.8475 KN*

Press 2 average displacement at failure *= 8.118 mm*

Load at failure variation = 22.34 KN *Displacement at failure variation = 5.07 mm*

9.5.5 Combined analysis – tensile

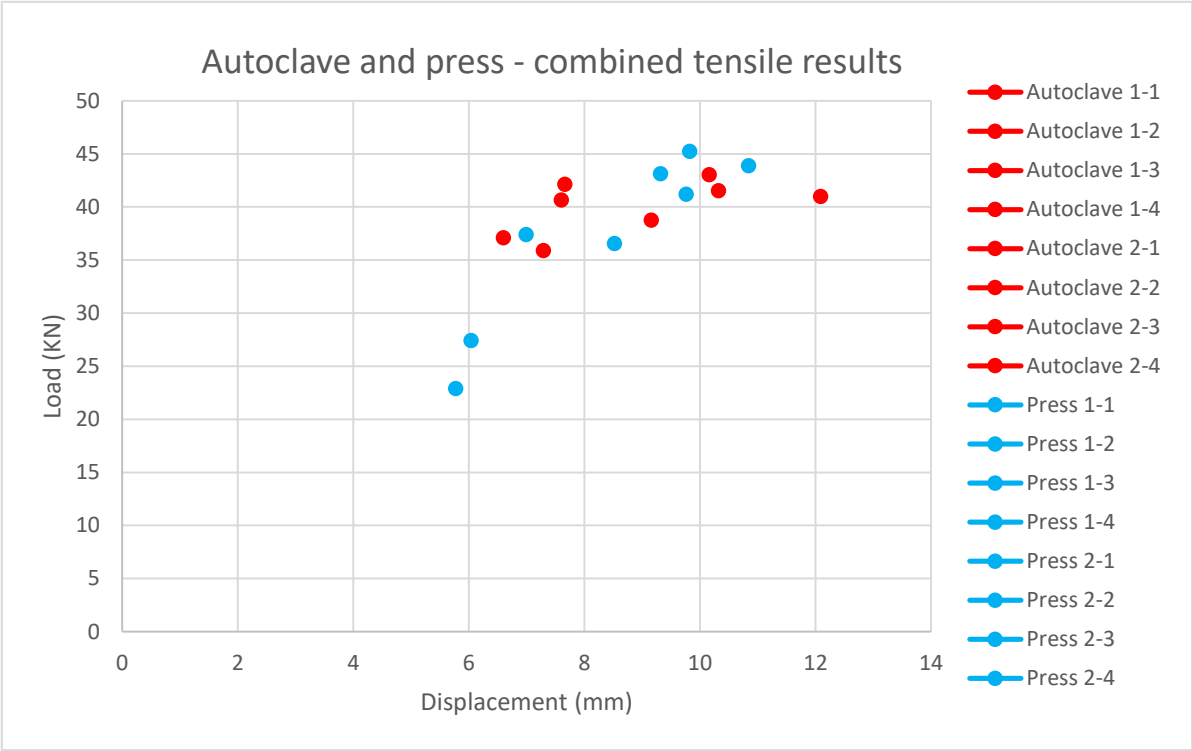

Figure 38 - Autoclave and Press - combined tensile results

Autoclave 1 average load at failure	*= 39.28 KN*
Autoclave 2 average load at failure	*= 40.715 KN*
Therefore, average autoclave tensile specimen load at failure	*= 39.9975 KN*
Press 1 average load at failure	*= 39.5675 KN*
Press 2 average load at failure	*= 34.8475 KN*
Therefore, average press tensile specimen load at failure	*= 37.2075 KN*

Autoclave 1 average displacement at failure	*= 9.715 mm*
Autoclave 2 average displacement at failure	*= 8.005 mm*
Therefore, average autoclave tensile specimen displacement at failure	*= 8.86 mm*
Press 1 average displacement at failure	*= 8.648 mm*
Press 2 average displacement at failure	*= 8.118 mm*
Therefore, average press tensile specimen displacement at failure	*= 8.383 mm*

Overall, the autoclave and press specimens produced very similar tensile results. If the results for press 2-1 and press 2-4 are excluded, since they appear to be anomalous, the average load at the point of failure for press specimens is 41.226 KN (as opposed to 37.2075 KN if these results are included). This would mean a mere 3% variance in results between the two processes regarding maximum load before failure.

If the same two results are excluded when considering the maximum displacement, the press specimen average rises to 9.208 mm (as opposed to 8.86 mm if these results are included). This would mean a variance of 4% between the autoclave specimens and the press specimens.

By dividing load at the point of failure by the cross-sectional area of the test specimen, the ultimate tensile strength (UTS) of the material can be calculated.

The cross-sectional area is calculated as:

$A = (2 \times 10^{-3}) \times (25 \times 10^{-3})$

$A = 5 \times 10^{-5}\ m^2$

Now, the average loads at failure can be divided by this area to calculate the UTS:

Autoclave specimen ultimate tensile strength $= 39998 / 5 \times 10^{-5}$

$= 799.96 \times 10^6 N/m^2$

$= \underline{799.96\ MPa}$

Press specimen ultimate tensile strength $= 41226 / 5 \times 10^{-5}$

$= 824.52 \times 10^6 N/m^2$

$= \underline{824.52\ MPa}$

The Young's modulus (E) for both materials can also be calculated. This will determine the stiffness characteristics of a material.

E = stress / strain

Young's modulus for autoclave specimen $= (39.9 \times 10^{6} / 5 \times 10^{-5}) / (8.86 \times 10^{-3} / 246 \times 10^{-3})$

$= \underline{22.156\ GPa}$

Young's modulus for press specimen $= (41.2 \times 10^{6} / 5 \times 10^{-5}) / (9.2 \times 10^{-3} / 246 \times 10^{-3})$

$= \underline{22.033\ GPa}$

9.6 Failure modes

9.6.1 Resin loss

During the manufacturing process of the autoclave test plates, a small amount of resin loss occurred in both plates. This can be seen with macro photography taken before the plates were processed.

This reduction is resin content could reduce the bond between plies, and increase the likelihood of failure due to delamination.

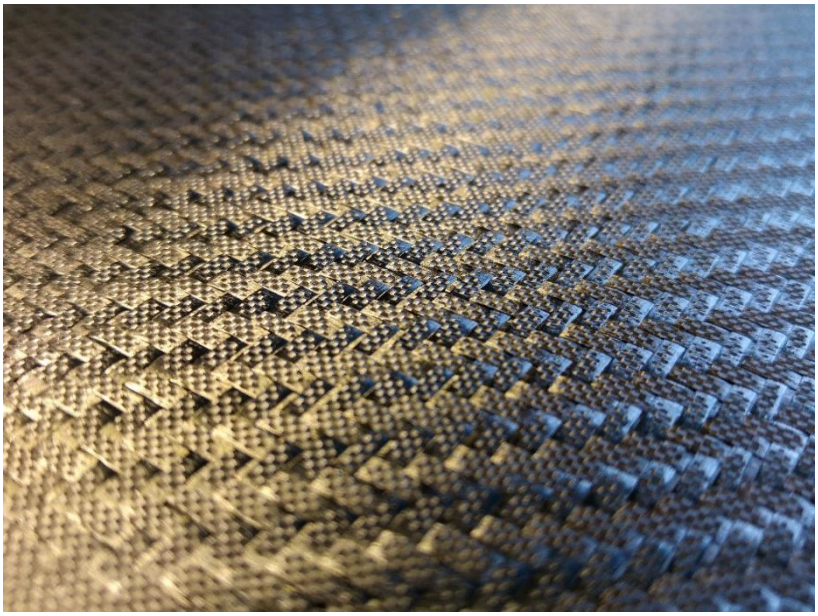

Figure 39 - a view of the top of one of the autoclave test plates, note the debossed pattern of the peel ply

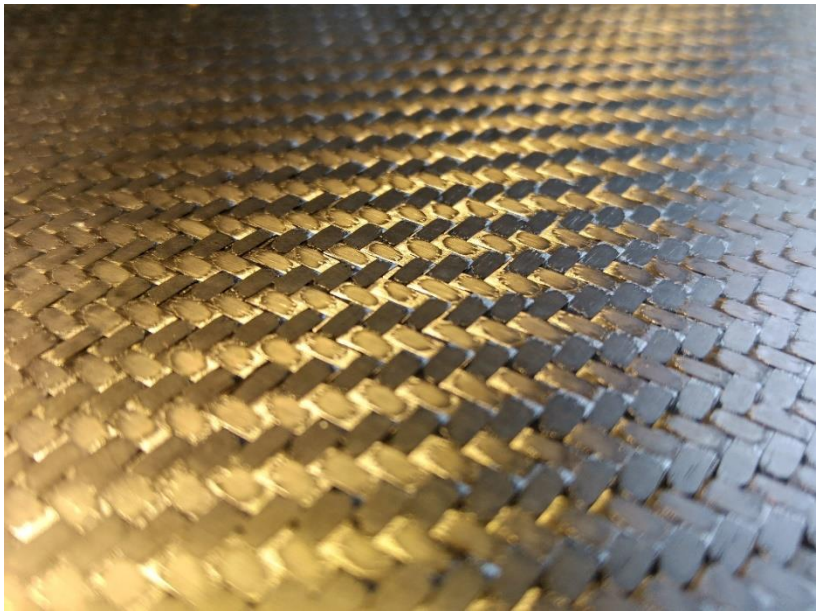

Figure 40 - a view of the bottom of one of the autoclave test plates, the small surface cavitation between the weave

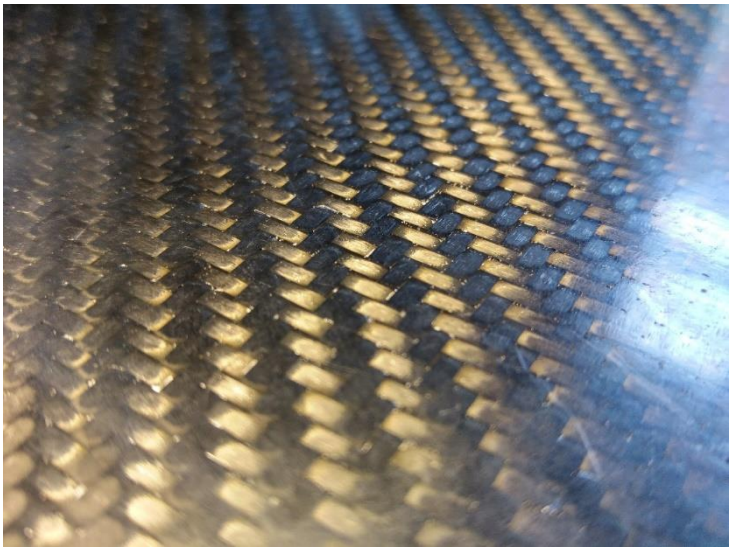

Figure 41 - to compare, the reasonably smooth and uniform surface finish of one of the test plates produced using the press

9.6.2 Flexure failure modes

As Hodgkinson, 2000 notes, there are multiple failure modes which can occur when carrying out a 3-point flexural test. In the case of this project, several of these failure modes were seen.

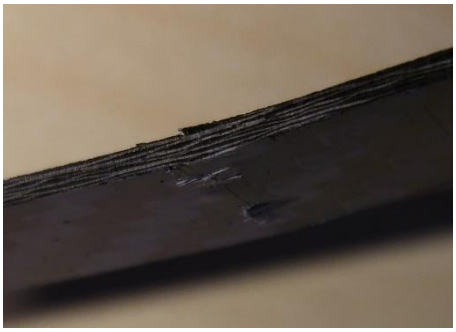

Figure 42 - example of tensile fracture of fibres during flexural test

Pictured in figures 42 and 43 is flexural specimen press 2-4. It failed in the 3 – point flexual test due to a combination of tensile fracture of fibres at the back of the specimen, and compression fractures at the front, in addition to some possible interlaminar shear, though this is not prolific.

Figure 43 - evidence of compression fracture of the outer surface is visible, along with possible interlaminar shear

Although the failures themselves often occurred in different ways (most yeilded almost all strength immediately, though some went through a more gradual failure of the material), almost all the specimens appeared like this after inspection.

A small number of specimins did break in two at failure, and it is more difficult to undertand the failure in these situations.

The slight resin loss may have contributed to the autoclave specimens not performing comparably with the press specimens. It is obvious that composite materials are heavily reliant on the matrix to suspend the reinforment properly during flexural loading conditions.

(Hodgkinson, Flexture, 2000)

9.6.3 Tensile failure modes

The main challenge regarding tensile failure modes is the effort to achieve failure at the centre of the specimen, away from the high stress concentrations of the self-tightening grips at either end of the specimen.

The most common tensile failure during this project was a double-break, one failure occuring nearer the grips, and another more centrally located.

There were very few delamination failures, which is understandable, since the reinforcement running in the direction of the load is more critical in this loading condition when compared to flexural testing.

This may be why the under-resined autoclave specimens were able to match the performance of the press specimens in this situation.

Figure 44 - a detailed view of fibre pull-out failure during tensile testing

10.0 Production time and costs investigation

As a small addition to comparing the mechanical properties of specimens produced using the two processes, it is also worth considering how the autoclave and press compare from a more practical standpoint, beginning with investigating if either process is more time effective.

10.1 Production time

Firstly, the activities which are shared between the two processes should be determined:

- Kit cutting and laying up the plies – 15-20 minutes
- Cure time after curing temperature is reached – 40 minutes

A layup destined for the autoclave requires additional preparation before the curing process can begin. It must be fitted with release film and breather cloth, sealed in the vacuum and checked for leaks. This adds a minimum of 15 minutes (depending on how long the vacuum bag is leak-checked).

The press tool requires around 15 minutes to achieve 120°C, then the curing can begin. The autoclave, on the other hand, takes 24 minutes (5°C per minute) to reach 120°C and the required 3 bar pressure, and requires the same time to ramp down after the curing is complete.

Since the press tool can remain up to temperature at all times, once a part is removed from the tool, only more release agent is required (can be sprayed onto the required surfaces) and a new layup can be inserted into the tool for the curing process to begin again within minutes, if no dwell time is designated.

During an 8 hour work day, a press has the potential to produce 10 test plates, with 15 minutes remaining at the days end for cleanup and shutdown.

Despite the layup preperation taking longer for autoclave parts, this can usually be covered during the curing process of another layup. If the autoclave had the capacity for only one layup, there is only the opportunity to produce 3 plates per day. However this is increased thanks to the autoclave's larger capacity.

10.2 Comsumables and their costs

The only consumables used in the press forming process are the tool cleaner and release agent, yet these are also required in the autoclave process. These two products together are priced at £15 (ex VAT).

(Easy Composites, n.d.)

The consumables required for the autoclave process include vacuum bagging film (between £12 and £15 per meter ex VAT), peel ply (between £10 and £14 per meter ex VAT), release film (between £1 and £15 per meter, ex VAT), breather cloth (£7.50 per meter ex VAT), and other items such as vacuum bagging gum sealant tape (£5 per roll ex VAT).

(Easy Composites, n.d.)

11.0 Conclusion

The goal of this project was to gain a better understanding of how the autoclave process and the press forming process compare. Producing identical test plates using the same curing parameters would allow insight into if the different methods of applying heat and pressure to composite layups would affect the material's mechanical properties.

Firstly, research into various carbon fibre fabrics was carried out, as well as research into producing composite parts using both the autoclave and press methods. The importance of mechanical testing was discussed, and certain required standards were highlighted. The entire specimen manufacturing process was described, and the chosen testing procedures were outlined.

The tensile and flexural testing ran essentially trouble-free, despite the small issue with the tab failures. It is satisfying to see the results so closely matching one another, it might have been expected that there should have been more variances in the result, considering the two very different manufacturing methods.

Various material properties were calculated using the data collected from the tensile and flexural tests, and again the two specimen types yielded very similar ultimate tensile strength, Young's modulus, and flexural modulus results. The failure modes of both tests were investigated, and finally the production time and consumables costs for both manufacturing processes were considered.

This project can be considered a success because the autoclave process and the press forming process were compared fairly and adhering to recognised standards. The data gathered may be useful to others who are looking to expand on this area in the future.

12.0 Further work

There are two main areas which deserve some further study. Firstly, now that the two processes have been shown to produce comparable results using the same parameters, coupled with the information that it is possible to massively decrease production times using the press forming process to mere minutes, efforts should be made to experiment with higher pressures and different temperatures to see if there are ways to reduce the manufacturing time but still achieve comparable mechanical performance to that of the autoclave process.

In addition to this, more research into the cost of each process should be carried out. The cost of the consumables for each process was briefly discussed, but more detailed financial data should be acquired. Specifically, the energy costs for each process. This type of research is crucial, and would help to achieve a broader understanding, and build on the topics covered in this project to produce a true comparison of the two processes.

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15.0 Appendix

Appendix 1: details on standards BS 2782 and ISO 12145 (Hodgkinson, Mechanical testing of advanced fibre composites, 2000)

Table 4.1. Comparison of selected details of standard tensile test methods.[a]

Standard	ASTM D3039	BS 2782: part 3: method 320 E, EN 61	CRAG methods 300 & 301	CRAG method 302	ISO 527
Applicability	Balanced symmetric composites reinforced with continuous or discontinuous high modulus fibre.	Composites incorporating mat, cloth, woven rovings including prepregs.	Unidirectional fibre-reinforced plastics 0° (Method 300) 90° (Method 301)	Multidirectional tape or woven fibre-reinforced materials. Must be axially orthotropic.	Fibre reinforced polymers 'Not normally suitable for multidirectional materials'.
Thickness (t)	1.0 (0° UD) ±4% 2.0 (90° UD) " 2.5 (Other)[b] "	1.0 to 10.0 ± 0.5 Machined if necessary	1.0 ± 0.04 (Method 300) 2.0 ± 0.04 (Method 301)	1 to 4	1 ± 0.2 (0°) 2 ± 0.2 (90°)
Width (W)	15 (0° UD) ±1% 25 (90° UD and other)	25 ± 0.5 for strength 12.5 ± 0.5 modulus only	10 to 20, uniform	9t min. 10t typical absolute min 20	15 ± 0.5 (0°) 25 ± 0.5 (90°)
Overall length (L)	250 ± 4% (0° UD and other) 175 (90° UD) Gauge length 10 to 50	200 (min) Gauge (free) length 110 min	100 to 150 + $2L_T$	Greater of (100 + $2L_T$) or $[w(1 + 1/\tan\theta) + 2L_T]^2$ If $\theta < 15°$ $L = (w/\tan\theta + 2L_T)$ where θ = fibre angle	150 ± 1 + $2L_T$[c] Gauge length 50
Tab length (L_T)	56 (0° UD) 25 (90° UD)	45 (min)	50 (min)	50 (min)	50
Tab thickness	1.5	Not less than 3 mm	0.5 to 2.0	0.5 to 2.0	0.5 to 2.0
Tab material recommended	0°/90° GFRP, commonly applied at +/–45° Emery cloth (Other)	Similar to that under test	GRP for hot/moist conditions Light alloy 'satisfactory' for ambient conditions		+/–45° GFRP

Table 7.4. Recommended specimen dimensions for different material types for three-point flexure in ISO-14125.

Material	Length (mm)	Span (mm)	Width (mm)	Thickness (mm)
Class I	80	64	10	4
Class II	80	64	15	4
Class III	60	40	15	2
Class IV	100	80	15	2

Appendix 2: Finished test plates from both processes

Appendix 3: tensile test specimen

Appendix 4: Raw data – flexural

mm	A 1-1	A 1-2	A 1-3	A 1-4
0.1	1.333	2.666	2	2
0.2	2.666	4	2.666	4.666
0.3	2.666	4.666	3.333	6.666
0.4	3.333	4.666	4.666	9.333
0.5	7.333	4.666	5.333	13.333
0.6	12	6	9.333	17.333
0.7	16	10.666	13.333	21.333
0.8	20	14.666	17.333	25.333
0.9	24	19.333	20.666	29.333
1	28	23.333	24.666	33.333
1.1	28	27.333	28.666	36.666
1.2	29.333	31.333	32	39.333
1.3	29.333	34.666	34.666	40.666
1.4	30.666	37.333	38	42
1.5	32	40	40	41.333
1.6	33.333	41.333	40.666	42.666
1.7	34.666	40.666	41.333	43.333
1.8	34.666	41.333	42	44
1.9	34.666	42.666	42.666	44
2	36.666	43.333	42.666	45.333
2.1	38.666	43.333	43.333	46
2.2	39.333	44.666	44	48
2.3	39.333	46	45.333	49.333
2.4	39.333	47.333	46	49.333
2.5	40	48.666	47.333	50
2.6	40	49.333	48	51.333
2.7	41.333	50	48	53.333
2.8	43.333	51.333	49.333	55.333
2.9	44	53.333	50	57.333
3	44.666	55.333	52	60
3.1	45.333	57.333	54	62.666
3.2	44.666	60	56	65.333
3.3	45.333	62.666	59.333	68.666
3.4	48	66	62	72
3.5	50.666	69.333	65.333	76
3.6	53.333	74	68.666	80
3.7	56.666	78	72.666	84
3.8	59.333	82	76.666	88
3.9	63.333	86.666	80	92
4	67.333	90.666	84	96
4.1	71.333	94.666	88	100.666
4.2	74.666	98.666	92	104.666

mm	A 2-1	A 2-2	A 2-3	A 2-4
0.1	2	1.333	2.666	3.333
0.2	3.333	4	4.666	6
0.3	4	7.333	7.333	9.333
0.4	5.333	9.333	9.333	11.333
0.5	6	12	11.333	14.666
0.6	6	14	13.333	17.333
0.7	8	16	15.333	20.666
0.8	12	19.333	17.333	23.333
0.9	15.333	22.666	20	26.666
1	18.666	26	22.666	29.333
1.1	22.666	29.333	24.666	32.666
1.2	26	32.666	27.333	35.333
1.3	29.333	35.333	28.666	38
1.4	33.333	37.333	30	38.666
1.5	36.666	39.333	31.333	38.666
1.6	38.666	39.333	31.333	40
1.7	40.666	40	30.666	41.333
1.8	41.333	40	31.333	42
1.9	40.666	40	34.666	42.666
2	41.333	40.666	36.666	43.333
2.1	42	41.333	38.666	44
2.2	42.666	42	39.333	44.666
2.3	43.333	42.666	40	44.666
2.4	44	43.333	40	46
2.5	44	44.666	40	46.666
2.6	45.333	46	40	47.333
2.7	46.666	46.666	40	48.666
2.8	48	47.333	40	50.666
2.9	48.666	49.333	40.666	52.666
3	50	51.333	41.333	54.666
3.1	52.666	53.333	42.666	57.333
3.2	54.666	55.333	44	60
3.3	56.666	57.333	45.333	62.666
3.4	58.666	60	46	66
3.5	61.333	63.333	48	68.666
3.6	64	66.666	50.666	72.666
3.7	66	70	53.333	76
3.8	69.333	74	55.333	80
3.9	72.666	78	58	84.666
4	76	82	61.333	88.666
4.1	80	85.333	65.333	93.333
4.2	84	88.666	69.333	97.333

4.3	78.666	102.666	96	109.333
4.4	81.333	107.333	100	113.333
4.5	83.333	112	104	117.333
4.6	84.666	116	108.666	121.333
4.7	87.333	120	112.666	126
4.8	91.333	124	116.666	130
4.9	95.333	128.666	120.666	134
5	99.333	132.666	124.666	137.333
5.1	103.333	136.666	128.666	140.666
5.2	107.333	140	132	143.333
5.3	110	142.666	134.666	146
5.4	112	146	138	150.666
5.5	114.666	150	140.666	154
5.6	118.666	153.333	144	156.666
5.7	122.666	156.666	148	159.333
5.8	125.333	159.333	151.333	162
5.9	128.666	162.666	154	165.333
6	132.666	165.333	156	168.666
6.1	135.333	168.666	158.666	172.666
6.2	138	172	162	176
6.3	139.333	176	165.333	179.333
6.4	142	180	168.666	182.666
6.5	143.333	184	172	185.333
6.6	146	186.666	175.333	188.666
6.7	148.666	189.333	179.333	192.666
6.8	152	194	182	198
6.9	155.333	198.666	184.666	202.666
7	158.666	204	189.333	207.333
7.1	162	209.333	193.333	211.333
7.2	164.666	214.666	197.333	216.666
7.3	168.666	219.333	202	222
7.4	173.333	224.666	206.666	226.666
7.5	178	230	211.333	231.333
7.6	182.666	234	216	236.666
7.7	187.333	239.333	221.333	241.333
7.8	192	244.666	224.666	246
7.9	196.666	250	229.333	250
8	202	254.666	234	250.666
8.1	206	260.666	238.666	256
8.2	211.333	266	243.333	243.333
8.3	216.666	270	248.666	232
8.4	221.333	274	252	236.666
8.5	224.666	279.333	256.666	232
8.6	228.666	284	260.666	232
8.7	231.333	288	264.666	233.333
8.8	236	291.333	260.666	234.666

4.3	88	92	73.333	102
4.4	92	96.666	76.666	106
4.5	95.333	100.666	80.666	110
4.6	99.333	104.666	84.666	114
4.7	103.333	108.666	88.666	118
4.8	107.333	112.666	92	122
4.9	111.333	117.333	95.333	126
5	114.666	121.333	98.666	130
5.1	118.666	126	103.333	134
5.2	122.666	130	107.333	138
5.3	127.333	133.333	111.333	142
5.4	130.666	137.333	115.333	146
5.5	134.666	140.666	120	149.333
5.6	138	143.333	124	152.666
5.7	140.666	148	128.666	156.666
5.8	144	152	132.666	160.666
5.9	146.666	155.333	136.666	164
6	151.333	158.666	140	167.333
6.1	154.666	161.333	142.666	169.333
6.2	158.666	164	146	172.666
6.3	162	167.333	150	176.666
6.4	164.666	170	153.333	180
6.5	166.666	174	157.333	184
6.6	170	178	160	188
6.7	173.333	182	162.666	191.333
6.8	177.333	186	165.333	195.333
6.9	181.333	189.333	168.666	199.333
7	184	190.666	172	202.666
7.1	187.333	194	176	206
7.2	189.333	198	180	210
7.3	192	202.666	183.333	214
7.4	196.666	207.333	186.666	218.666
7.5	201.333	212.666	189.333	223.333
7.6	206	217.333	192.666	228
7.7	211.333	222.666	196.666	233.333
7.8	216	227.333	201.333	238
7.9	220.666	232.666	206.666	243.333
8	225.333	238	211.333	248
8.1	230.666	243.333	216.666	252.666
8.2	236	247.333	221.333	258
8.3	241.333	252.666	226.666	262.666
8.4	246	257.333	232	267.333
8.5	250.666	262.666	236.666	272
8.6	255.333	267.333	242	277.333
8.7	260.666	272.666	246.666	282
8.8	265.333	277.333	251.333	286

8.9	240.666	295.333	257.333	229.333
9	246	300	260.666	230
9.1	250	303.333	264.666	230.666
9.2	254.666	216.666	264.666	232.666
9.3	258.666	202.666	249.333	233.333
9.4	260.666	199.333	252	233.333
9.5	264.666	199.333	254	234.666
9.6	266.666	200.666	254	223.333
9.7	270.666	202	256	220
9.8	275.333	202.666	259.333	219.333
9.9	279.333	202.666	261.333	220
10	284	203.333	264	220.666
10.1	288.666	204.666	266.666	222
10.2	293.333	204.666	268	223.333
10.3	297.333	206	261.333	225.333
10.4	284	206	261.333	227.333
10.5	285.333	206.666	262	228.666
10.6	289.333	204.666	252.666	210.666
10.7	274	201.333	227.333	14
10.8	272.666	14.666	111.333	14.666
10.9	255.333	15.333	10	14.666
11	256	15.333	10	0
11.1	255.333	15.333	0	
11.2	250.666	0		
11.3	232.666			
11.4	218			
11.5	217.333			
11.6	212.666			
11.7	210.666			
11.8	207.333			
11.9	200.666			
12	130.666			
12.1	129.333			
12.2	120.666			
12.3	119.333			
12.4	78			
12.5	77.333			
12.6	78			
12.7	78			
12.8	78.666			
12.9	44			
13	41.333			
13.1	40			
13.2	39.333			
13.3	39.333			
13.4	38.666			

8.9	270.666	282	256.666	290.666
9	275.333	286.666	261.333	295.333
9.1	280	292	266	300
9.2	285.333	296.666	271.333	304.666
9.3	290	301.333	276	310
9.4	295.333	306	280.666	314.666
9.5	300	311.333	286	319.333
9.6	304.666	316	290.666	324
9.7	309.333	320.666	295.333	328.666
9.8	314	325.333	300	333.333
9.9	319.333	330	304.666	338
10	322.666	334.666	310	340.666
10.1	327.333	339.333	314.666	344.666
10.2	332	343.333	319.333	343.333
10.3	336.666	348	324	347.333
10.4	340.666	352.666	329.333	348.666
10.5	344.666	358	334	353.333
10.6	348.666	361.333	338	358
10.7	353.333	366.666	342.666	358.666
10.8	358.666	371.333	346.666	363.333
10.9	364	376	350	367.333
11	368.666	381.333	355.333	369.333
11.1	373.333	386	360	373.333
11.2	378	390.666	364.666	368.666
11.3	382.666	394.666	369.333	52.666
11.4	387.333	398.666	374.666	56
11.5	390.666	401.333	379.333	58
11.6	395.333	406	384.666	60
11.7	398.666	410	389.333	61.333
11.8	80.666	414.666	394	62.666
11.9	82	419.333	398.666	62
12	83.333	424	403.333	52
12.1	84	428	408	52.666
12.2	85.333	431.333	412	53.333
12.3	86	436	414.666	48
12.4	86.666	440	418.666	48.666
12.5	87.333	0.666	422.666	48.666
12.6	84.666	0	426.666	48.666
12.7	85.333		27.333	48.666
12.8	85.333		29.333	0
12.9	85.333		30.666	
13	85.333		30.666	
13.1	84		0	
13.2	84.666			
13.3	86			
13.4	86.666			

13.5	24.666
13.6	24.666
13.7	24.666
13.8	24.666
13.9	24.666
14	24.666
14.1	24.666
14.2	24.666
14.3	0

13.5	86
13.6	85.333
13.7	84.666
13.8	85.333
13.9	77.333
14	74.666
14.1	74.666
14.2	73.333
14.3	72
14.4	70.666
14.5	70
14.6	70
14.7	69.333
14.8	70
14.9	69.333
15	69.333
15.1	69.333
15.2	68.666
15.3	66.666
15.4	66.666
15.5	67.333
15.6	67.333
15.7	67.333
15.8	66.666
15.9	66.666
16	66
16.1	65.333
16.2	65.333
16.3	65.333
16.4	65.333
16.5	64
16.6	62.666
16.7	59.333
16.8	59.333
16.9	59.333
17	0

mm	P 1-1	P 1-2	P 1-3	P-1-4
0.1	2	2	1.333	2
0.2	5.333	4.666	4	2.666
0.3	8.666	7.333	6	6
0.4	12	9.333	6.666	9.333
0.5	15.333	10.666	8	12
0.6	18.666	12	10	15.333
0.7	22	12	12	18.666
0.8	24.666	12	14.666	22
0.9	26	13.333	16.666	24.666
1	28	16.666	20	28
1.1	30.666	20.666	24	30.666
1.2	33.333	23.333	26.666	33.333
1.3	35.333	27.333	28.666	36.666
1.4	36	28.666	32	38.666
1.5	37.333	30.666	34.666	40
1.6	38.666	33.333	37.333	40.666
1.7	39.333	35.333	39.333	40.666
1.8	40	38	40.666	41.333
1.9	40.666	38.666	41.333	42
2	41.333	40	42.666	43.333
2.1	41.333	42	43.333	43.333
2.2	42	42.666	43.333	44
2.3	42.666	43.333	43.333	44.666
2.4	43.333	44	43.333	45.333
2.5	44	44	43.333	46
2.6	45.333	44	44	46.666
2.7	48	44	44.666	47.333
2.8	50	44	44.666	47.333
2.9	53.333	44.666	45.333	48
3	55.333	46	46.666	48.666
3.1	58	46.666	48	50.666
3.2	60.666	48	50	52
3.3	64	49.333	53.333	54.666
3.4	66.666	50.666	55.333	58
3.5	70	52.666	58	60.666
3.6	74	56	60.666	63.333
3.7	78	58.666	64	66.666
3.8	82.666	61.333	67.333	70.666
3.9	87.333	64	71.333	74.666
4	92	68	74.666	78.666
4.1	96.666	71.333	78.666	82.666
4.2	101.333	75.333	83.333	86
4.3	106	78.666	87.333	90
4.4	110.666	82.666	91.333	94
4.5	114.666	86.666	95.333	97.333

mm	P 2-1	P 2-2	P 2-3	P 2-4
0.1	2	3.333	1.333	1.333
0.2	2.666	5.333	3.333	3.333
0.3	2	8	5.333	5.333
0.4	4	10	7.333	5.333
0.5	6.666	12.666	8	6
0.6	8.666	15.333	8.666	6.666
0.7	11.333	17.333	10.666	7.333
0.8	13.333	21.333	13.333	8.666
0.9	14.666	25.333	16	10.666
1	16.666	28.666	18.666	14.666
1.1	18	32.666	21.333	17.333
1.2	21.333	35.333	23.333	20
1.3	24	37.333	26	22.666
1.4	26.666	39.333	28.666	25.333
1.5	28.666	40	30.666	28
1.6	31.333	40.666	33.333	30
1.7	34.666	42	34.666	32.666
1.8	36.666	43.333	36.666	34.666
1.9	38.666	43.333	38	36.666
2	40	44	39.333	38
2.1	41.333	44	40.666	39.333
2.2	42.666	44.666	42	40.666
2.3	43.333	44.666	42	42
2.4	44.666	45.333	42.666	43.333
2.5	45.333	46	42.666	44
2.6	46	46.666	43.333	44
2.7	46.666	48	43.333	44.666
2.8	48	48.666	44.666	44.666
2.9	48.666	50.666	44.666	45.333
3	50	53.333	45.333	45.333
3.1	51.333	55.333	46	45.333
3.2	52	57.333	46.666	46
3.3	53.333	60	48	46
3.4	54.666	62.666	48	46.666
3.5	56	66	49.333	47.333
3.6	58	69.333	51.333	48.666
3.7	59.333	73.333	52.666	50.666
3.8	61.333	76.666	54.666	52
3.9	63.333	80.666	56.666	54
4	65.333	84.666	59.333	56.666
4.1	68	88.666	61.333	59.333
4.2	70.666	92	64	61.333
4.3	73.333	95.333	66.666	64.666
4.4	75.333	99.333	68.666	66.666
4.5	78	102.666	71.333	70

4.6	118.666	91.333	98.666	100.666
4.7	122.666	94.666	102	104.666
4.8	126.666	98.666	106	108.666
4.9	131.333	102	110	112
5	135.333	106	114	116
5.1	140	110	118	120
5.2	143.333	114	122	123.333
5.3	147.333	117.333	126.666	128
5.4	151.333	121.333	130.666	131.333
5.5	155.333	126	135.333	134.666
5.6	160	130	139.333	137.333
5.7	163.333	134	143.333	140.666
5.8	166	138	147.333	144.666
5.9	169.333	142.666	150	148.666
6	172.666	146	153.333	152.666
6.1	176.666	149.333	156.666	156.666
6.2	180.666	152	159.333	160.666
6.3	185.333	155.333	163.333	164.666
6.4	189.333	158.666	166.666	167.333
6.5	193.333	162	169.333	170
6.6	196.666	164.666	172.666	173.333
6.7	201.333	168	176.666	176.666
6.8	205.333	171.333	180.666	180
6.9	208.666	174.666	184	183.333
7	212.666	178.666	188	186.666
7.1	217.333	182.666	190.666	190
7.2	222	186	194	192.666
7.3	227.333	188.666	198	196.666
7.4	232.666	192.666	201.333	200.666
7.5	238	197.333	205.333	205.333
7.6	243.333	200.666	210.666	210.666
7.7	248.666	204.666	215.333	216
7.8	254	210	220	221.333
7.9	259.333	214.666	224.666	226
8	264.666	220	230	231.333
8.1	269.333	225.333	234.666	236.666
8.2	274.666	230	240	242
8.3	279.333	235.333	244.666	246.666
8.4	284.666	240	249.333	252
8.5	290	245.333	254.666	257.333
8.6	295.333	250	259.333	262
8.7	300.666	255.333	264.666	267.333
8.8	305.333	260.666	269.333	272.666
8.9	310.666	265.333	274	277.333
9	316	270.666	279.333	282.666
9.1	320.666	275.333	284	288

4.6	81.333	106	74	72
4.7	84.666	110	76.666	75.333
4.8	87.333	113.333	80	78.666
4.9	90.666	117.333	82	81.333
5	94.666	120.666	85.333	84.666
5.1	98.666	124.666	88	88
5.2	102.666	128	90	90.666
5.3	106	131.333	92.666	94
5.4	110	134	95.333	96.666
5.5	113.333	136.666	98	100
5.6	117.333	140	100.666	103.333
5.7	120.666	143.333	103.333	106.666
5.8	124.666	146.666	106.666	110
5.9	128.666	150.666	109.333	112.666
6	132	154	112	116
6.1	136	156.666	114.666	119.333
6.2	139.333	159.333	118	122.666
6.3	143.333	162	120.666	126
6.4	146.666	164.666	123.333	128.666
6.5	150	167.333	126.666	131.333
6.6	154	171.333	129.333	134
6.7	157.333	174	132	136.666
6.8	160.666	177.333	134.666	139.333
6.9	164.666	180.666	137.333	141.333
7	168	182.666	140	144.666
7.1	171.333	186	142.666	148
7.2	174.666	191.333	145.333	151.333
7.3	178	196	147.333	154
7.4	182	200.666	149.333	157.333
7.5	185.333	205.333	152	159.333
7.6	188.666	210	154	161.333
7.7	192	214.666	156.666	163.333
7.8	195.333	220	159.333	166
7.9	198.666	224.666	162.666	168.666
8	202.666	229.333	164.666	171.333
8.1	206.666	234	166.666	174
8.2	210.666	238.666	169.333	177.333
8.3	214	243.333	171.333	180.666
8.4	216.666	248	173.333	183.333
8.5	220	253.333	176	186.666
8.6	223.333	258	178.666	189.333
8.7	227.333	262.666	181.333	192
8.8	228	267.333	184	196.666
8.9	230.666	272	186.666	200.666
9	234	276.666	188.666	204
9.1	238	281.333	191.333	208

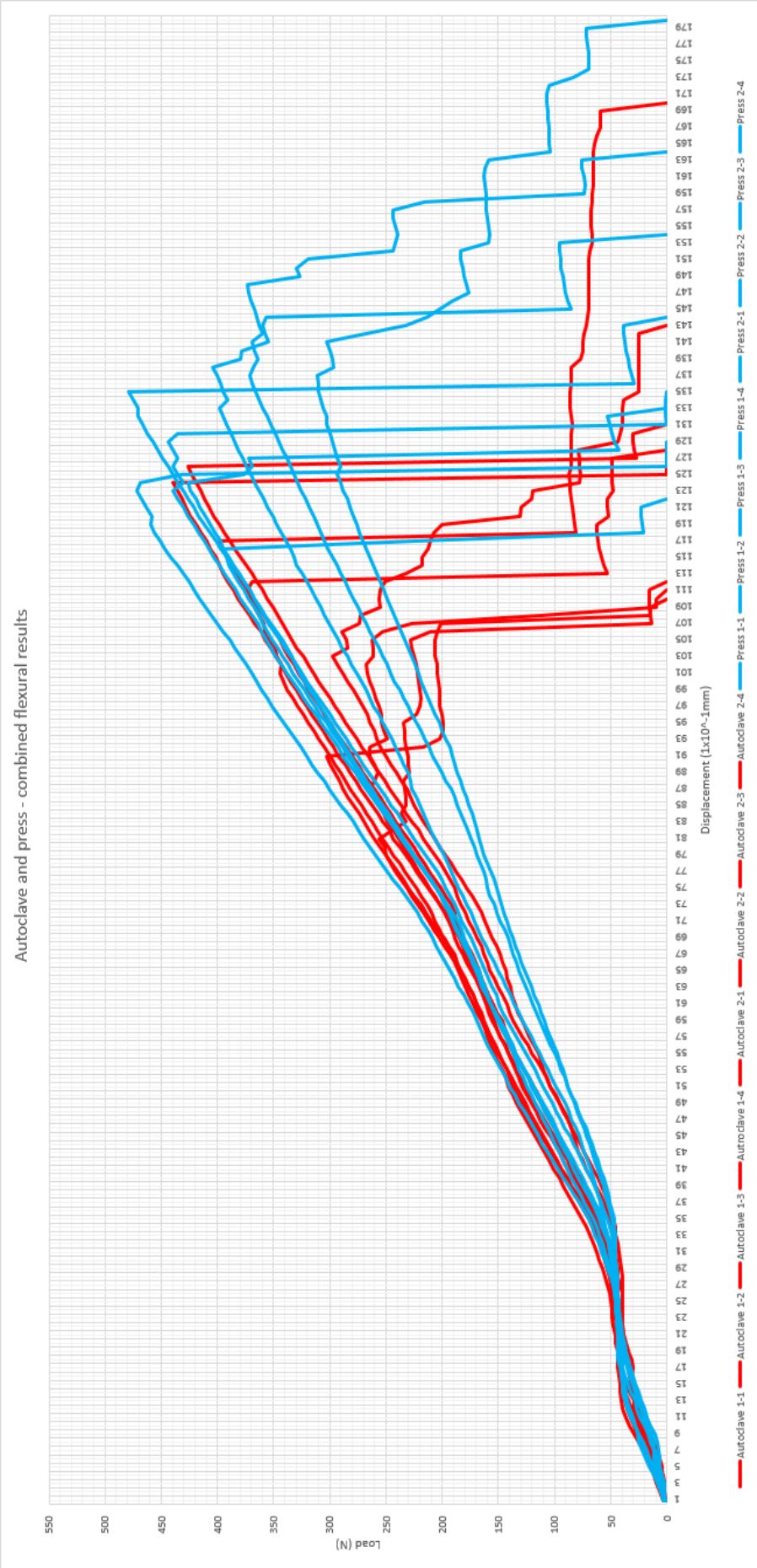
9.2	326	280.666	288.666	292.666
9.3	330.666	285.333	293.333	298
9.4	336	290.666	298.666	302.666
9.5	340.666	295.333	303.333	308
9.6	346	300	308.666	312.666
9.7	351.333	305.333	313.333	318
9.8	356	310	318	323.333
9.9	360.666	315.333	322.666	328
10	365.333	320	328	333.333
10.1	369.333	324.666	332.666	338
10.2	374	330	337.333	343.333
10.3	379.333	334.666	342	348
10.4	384.666	340	346.666	352.666
10.5	389.333	344.666	351.333	356.666
10.6	394.666	349.333	355.333	360.666
10.7	400	354.666	359.333	364
10.8	405.333	358.666	363.333	369.333
10.9	410.666	362.666	366.666	374
11	415.333	366.666	372	379.333
11.1	420.666	371.333	376.666	384
11.2	425.333	376	381.333	388.666
11.3	430.666	381.333	385.333	394
11.4	436	386.666	390	398.666
11.5	441.333	391.333	392	403.333
11.6	446.666	396.666	396	408
11.7	451.333	401.333	221.333	412
11.8	456.666	406.666	21.333	416.666
11.9	459.333	411.333	22	420.666
12	458	416.666	22.666	426
12.1	463.333	421.333	22.666	430.666
12.2	468	426	0	435.333
12.3	472	430.666		440
12.4	468.666	435.333		430.666
12.5	432	440		436
12.6	0.666	443.333		439.333
12.7	0.666	448.666		436
12.8	0.666	452.666		439.333
12.9	0	457.333		443.333
13		462		436
13.1		466.666		0.666
13.2		470.666		1.333
13.3		470.666		1.333
13.4		474.666		1.333
13.5		479.333		0
13.6		29.333		
13.7		31.333		

9.2	242	286	193.333	212
9.3	244.666	290.666	196.666	215.333
9.4	249.333	295.333	200	219.333
9.5	252.666	300	202.666	223.333
9.6	256.666	304	206	226.666
9.7	261.333	308.666	209.333	230.666
9.8	264.666	313.333	212.666	234.666
9.9	268	318	216	238
10	271.333	322.666	218.666	242.666
10.1	276	326.666	221.333	245.333
10.2	280.666	330.666	224	249.333
10.3	284.666	334	227.333	252.666
10.4	289.333	338	230	256.666
10.5	292.666	342.666	233.333	260.666
10.6	296.666	347.333	236.666	264
10.7	300.666	352.666	239.333	268
10.8	304.666	357.333	242.666	272
10.9	308	362	246	275.333
11	312	366.666	249.333	279.333
11.1	316.666	371.333	252	282.666
11.2	320.666	376.666	255.333	286.666
11.3	324.666	380.666	258	290.666
11.4	329.333	385.333	261.333	294
11.5	332	390	264.666	298
11.6	334.666	394.666	267.333	301.333
11.7	338.666	397.333	270.666	304.666
11.8	343.333	402	273.333	308
11.9	347.333	406.666	276	311.333
12	350.666	410.666	279.333	314.666
12.1	355.333	415.333	282	318
12.2	358.666	419.333	284.666	322
12.3	362.666	424	288	325.333
12.4	366.666	426.666	290	328.666
12.5	370	376	293.333	332
12.6	374	368.666	290	335.333
12.7	377.333	372	293.333	338
12.8	381.333	42.666	296	342
12.9	384.666	46.666	298	345.333
13	388	48.666	300	348.666
13.1	392	50.666	302.666	352.666
13.2	395.333	52.666	303.333	356
13.3	398	0	306	359.333
13.4	390.666		308	362.666
13.5	394.666		310	366
13.6	397.333		310	368.666
13.7	400.666		311.333	371.333

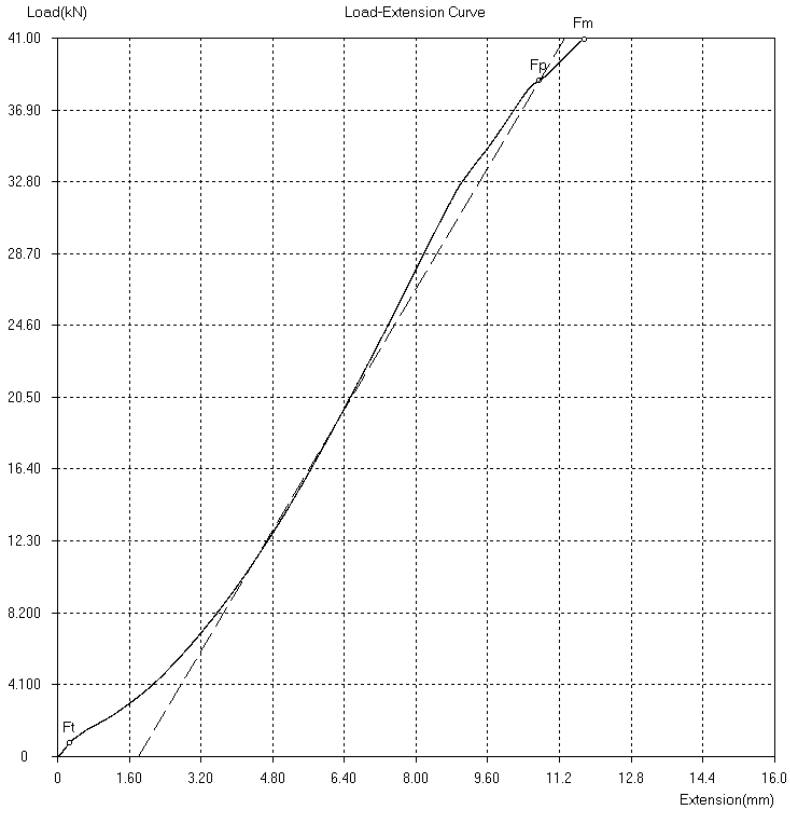
13.8	33.333
13.9	34.666
14	36
14.1	38
14.2	38.666
14.3	38.666
14.4	0

13.8	404	296.666	368
13.9	380	298	364
14	378.666	300	367.333
14.1	354.666	302.666	368.666
14.2	357.333	267.333	360
14.3	359.333	232	363.333
14.4	356.666	213.333	365.333
14.5	84.666	202.666	367.333
14.6	88	191.333	370
14.7	90	176.666	372.666
14.8	91.333	178.666	373.333
14.9	92.666	180.666	326.666
15	94	182	330
15.1	94.666	183.333	319.333
15.2	95.333	184	244
15.3	95.333	158.666	241.333
15.4	0	158	240
15.5		158.666	241.333
15.6		159.333	243.333
15.7		160.666	244
15.8		160.666	216
15.9		161.333	73.333
16		162	72.666
16.1		162.666	74
16.2		162	75.333
16.3		158.666	76
16.4		104	0
16.5		104.666	
16.6		105.333	
16.7		105.333	
16.8		106	
16.9		106	
17		106.666	
17.1		106.666	
17.2		104.666	
17.3		82.666	
17.4		69.333	
17.5		69.333	
17.6		69.333	
17.7		70.666	
17.8		71.333	
17.9		71.333	
18		0	

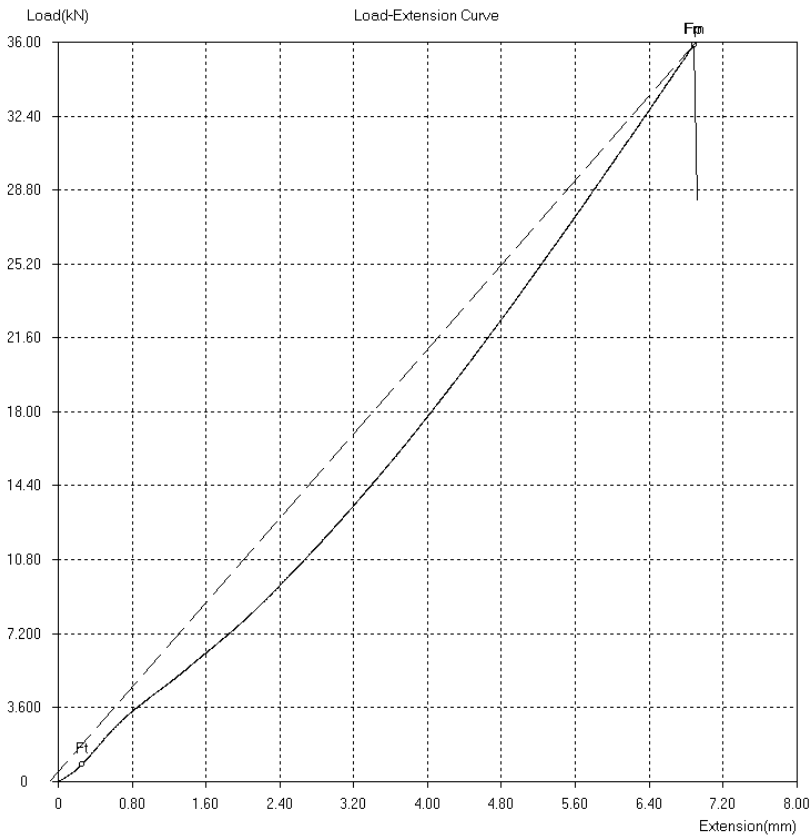
Appendix 5: Autoclave and press – combined flexural results graph



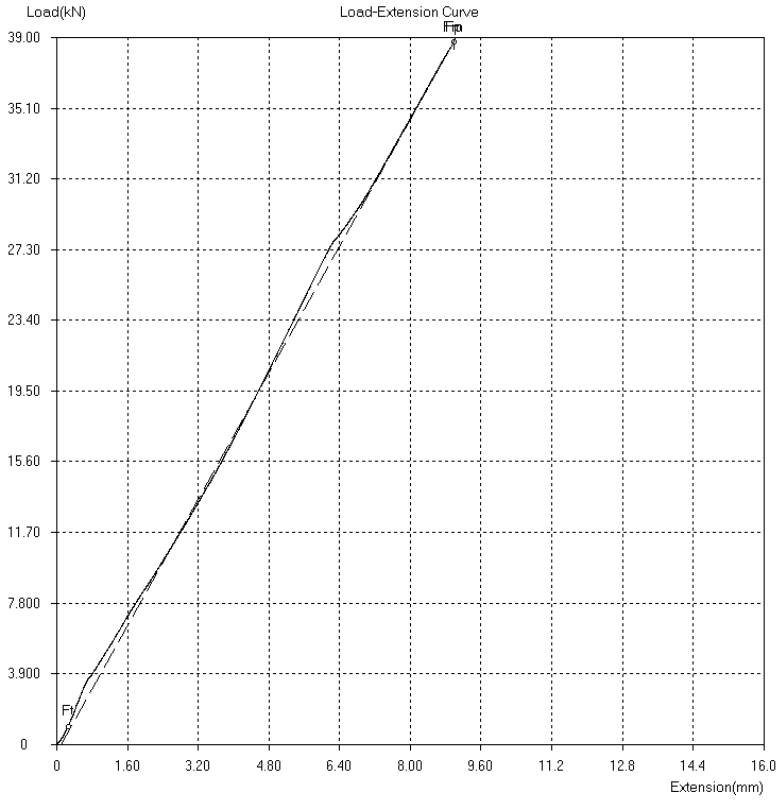
Appendix 6: Automatically-generated graphs from tensile testing



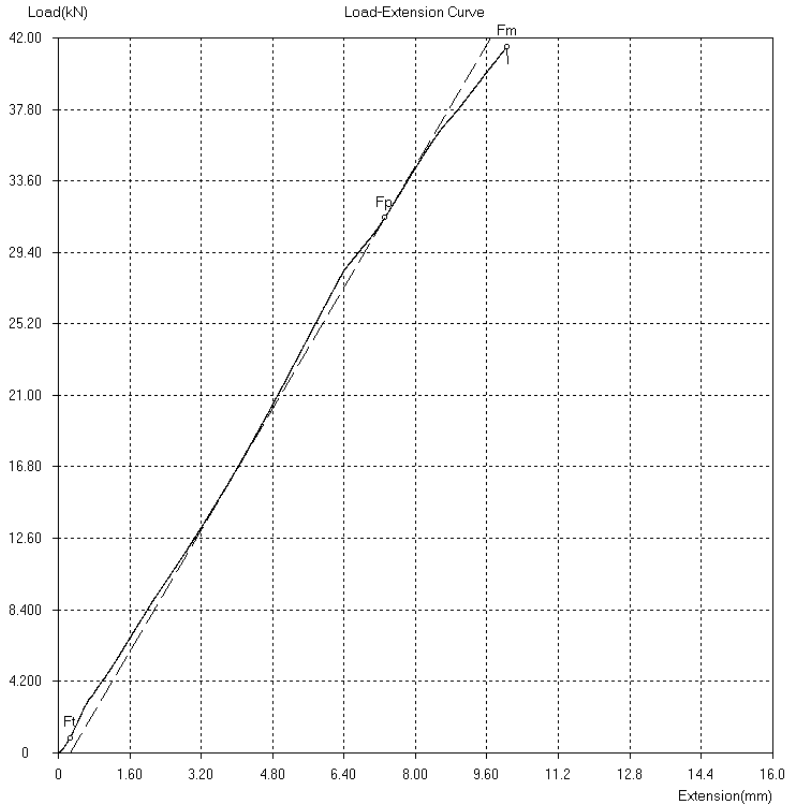
A 1-1



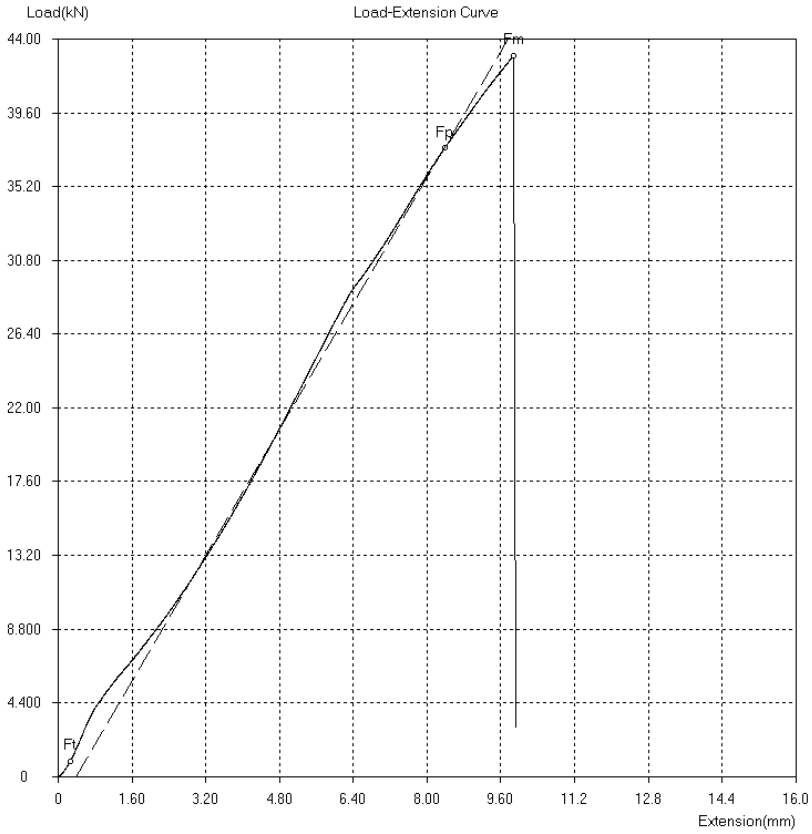
A 1-2


Load(kN)
Load-Extension Curve
Fm
Ft
39.00
35.10
31.20
27.30
23.40
19.50
15.60
11.70
7.800
3.900
0
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

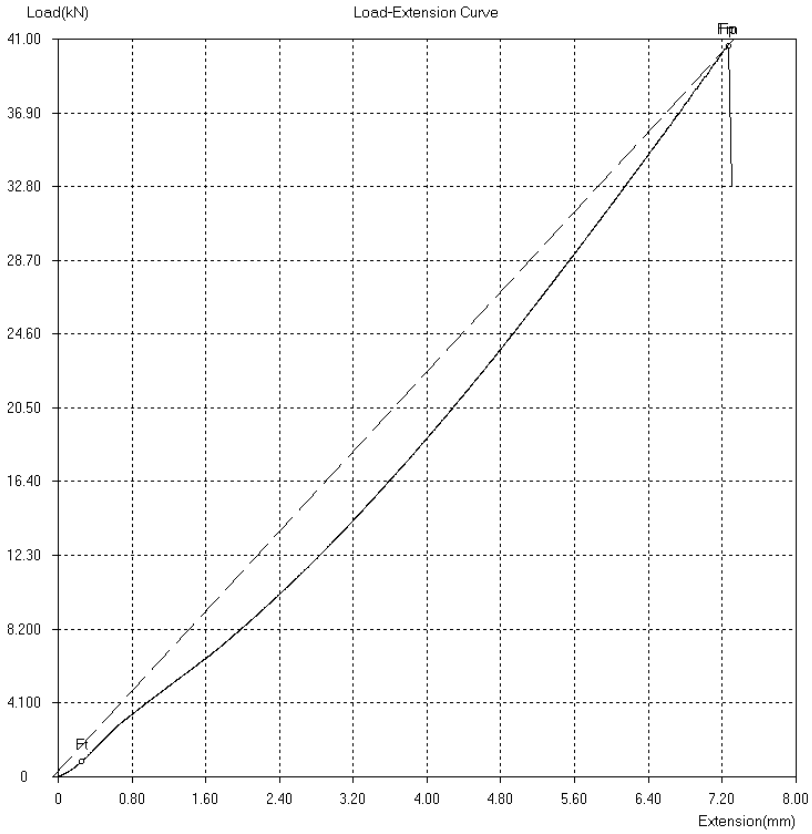
A 1-3


Load(kN)
Load-Extension Curve
Fm
Fp
Ft
42.00
37.80
33.60
29.40
25.20
21.00
16.80
12.60
8.400
4.200
0
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

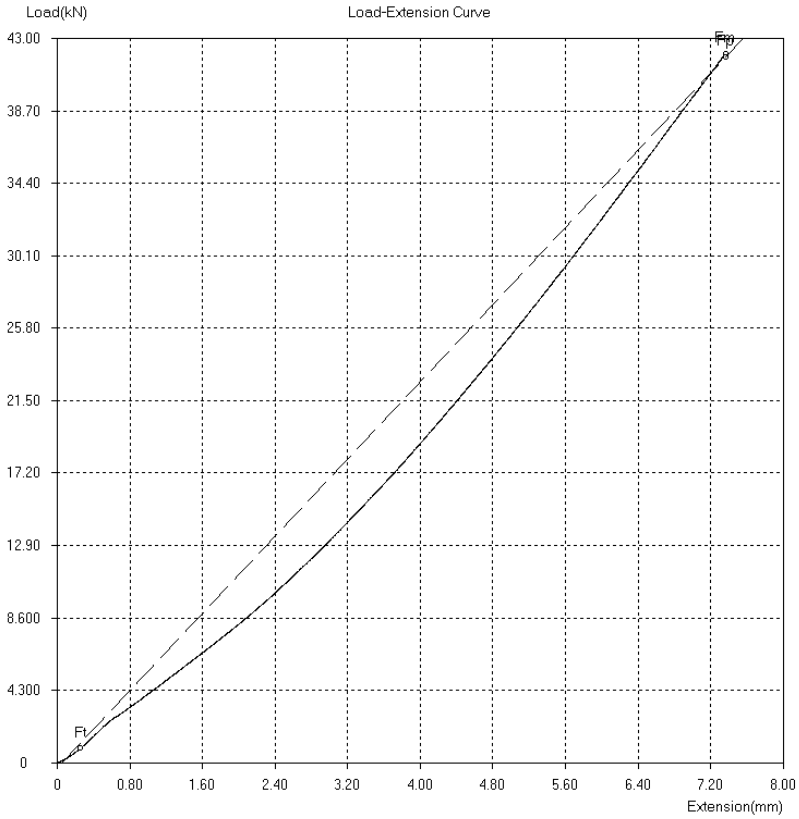
A 1-4


Load(kN)
Load-Extension Curve
44.00
39.60
35.20
30.80
26.40
22.00
17.60
13.20
8.800
4.400
0
Fm
Fp
Ft
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

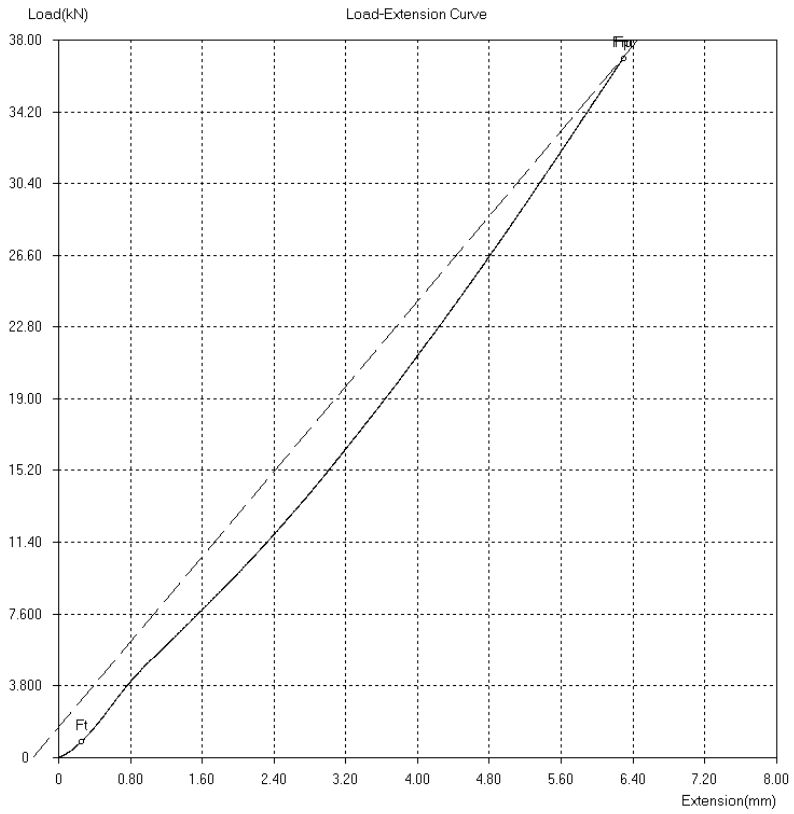
A 2-1


Load(kN)
Load-Extension Curve
41.00
36.90
32.80
28.70
24.60
20.50
16.40
12.30
8.200
4.100
0
Fm
Fp
Ft
0
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
Extension(mm)

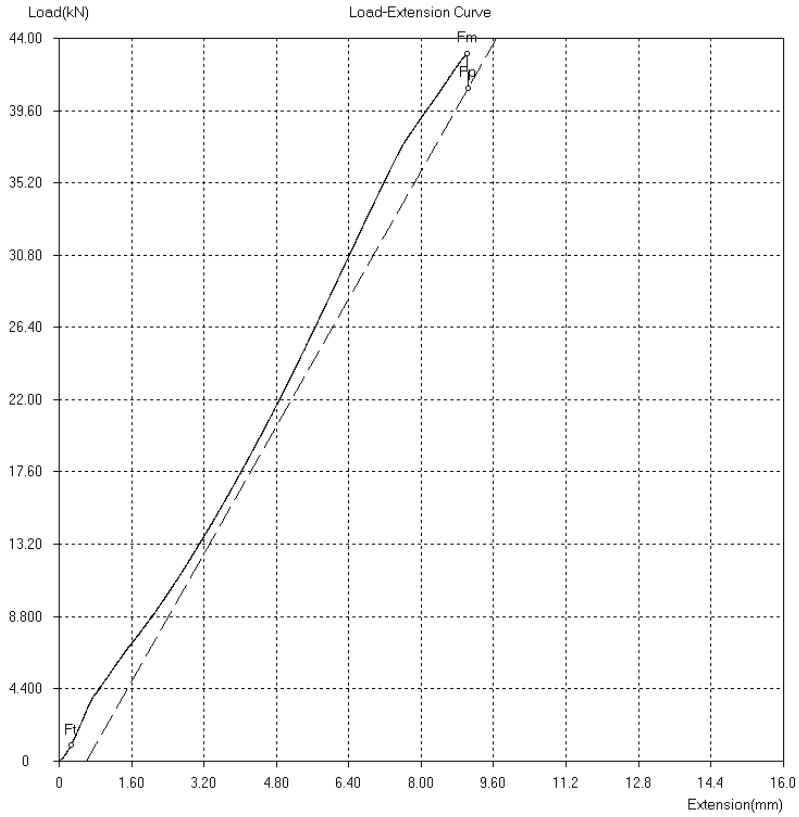
A 2-2


Load(kN)
Load-Extension Curve
43.00
38.70
34.40
30.10
25.80
21.50
17.20
12.90
8.600
4.300
0
Ft
0
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
Extension(mm)

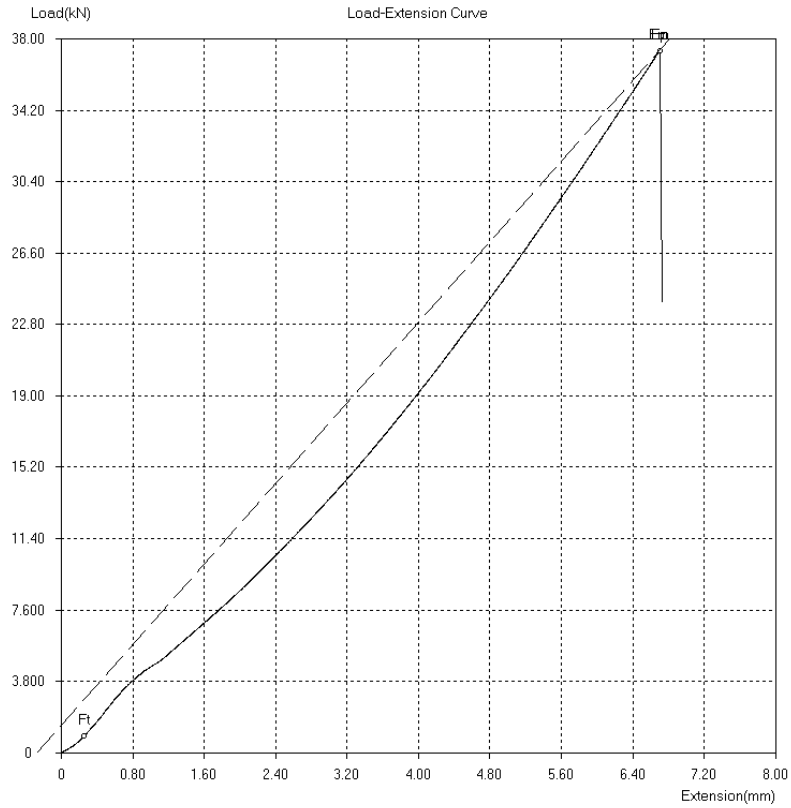
A 2-3


Load(kN)
Load-Extension Curve
38.00
34.20
30.40
26.60
22.80
19.00
15.20
11.40
7.600
3.800
0
Ft
0
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
Extension(mm)

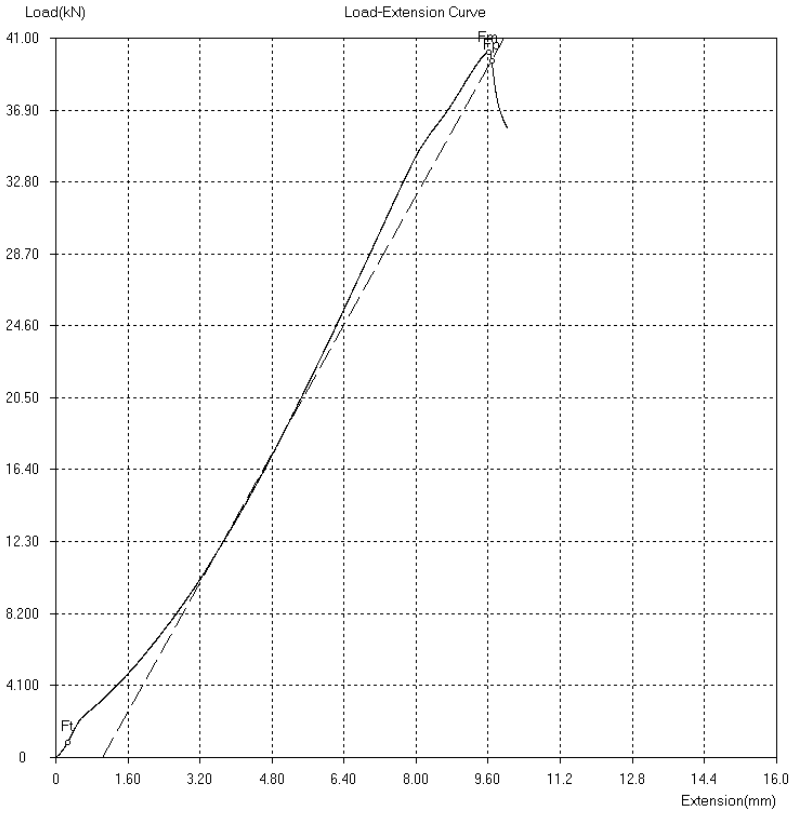
A 2-4


Load(kN)
Load-Extension Curve
Fm
Fp
Ft
44.00
39.60
35.20
30.80
26.40
22.00
17.60
13.20
8.800
4.400
0
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

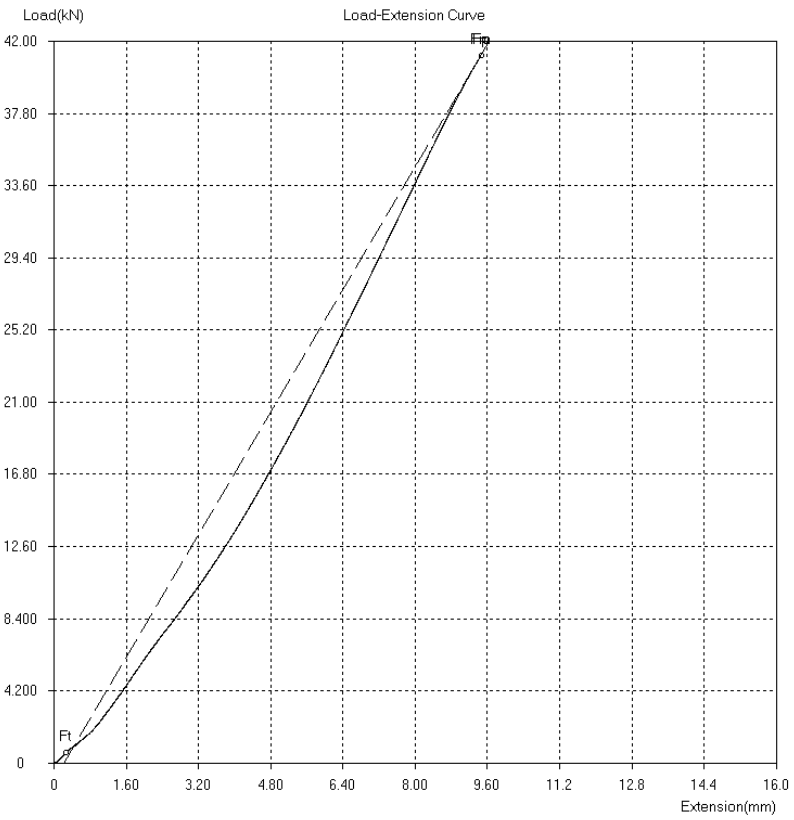
P 1-1


Load(kN)
Load-Extension Curve
Fm
Ft
38.00
34.20
30.40
26.60
22.80
19.00
15.20
11.40
7.600
3.800
0
0
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
Extension(mm)

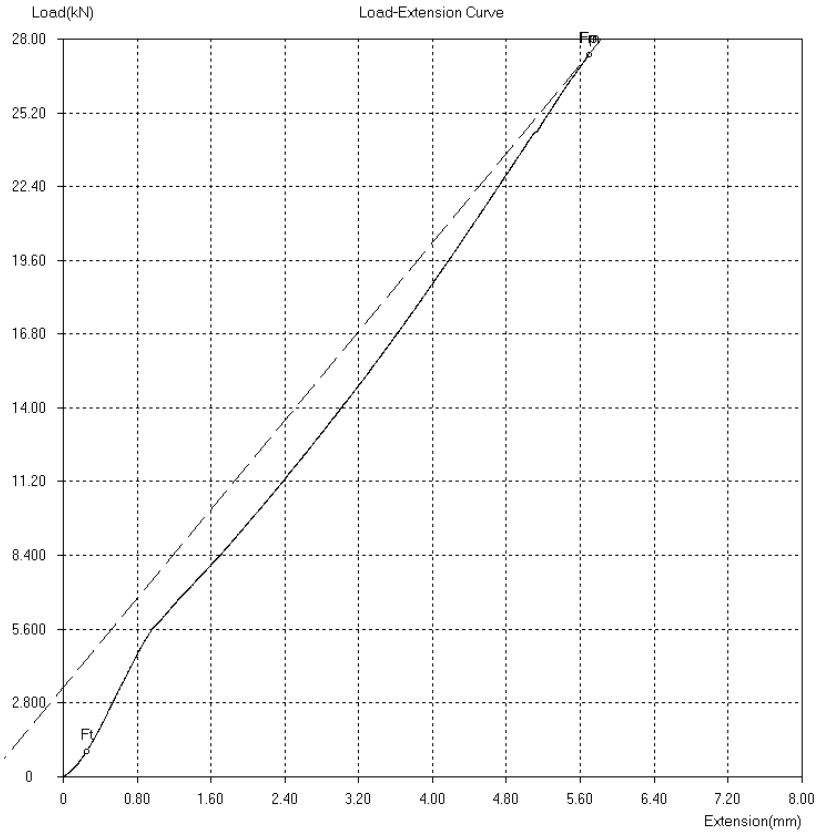
P 1-2


Load(kN)
Load-Extension Curve
41.00
36.90
32.80
28.70
24.60
20.50
16.40
12.30
8.200
4.100
0
Ft
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

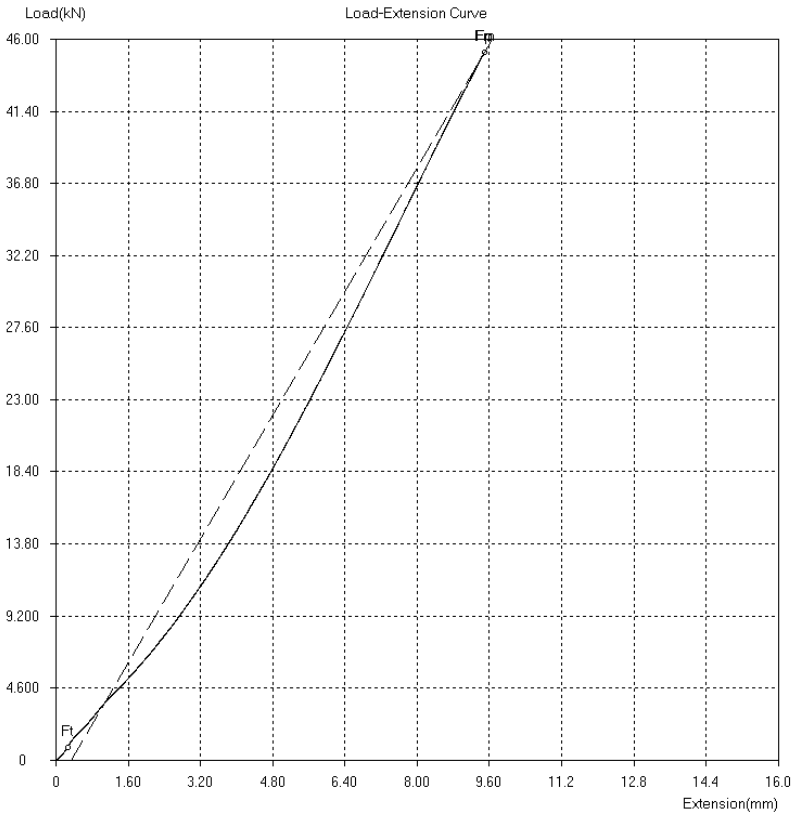
P 1-3


Load(kN)
Load-Extension Curve
42.00
37.80
33.60
29.40
25.20
21.00
16.80
12.60
8.400
4.200
0
Ft
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

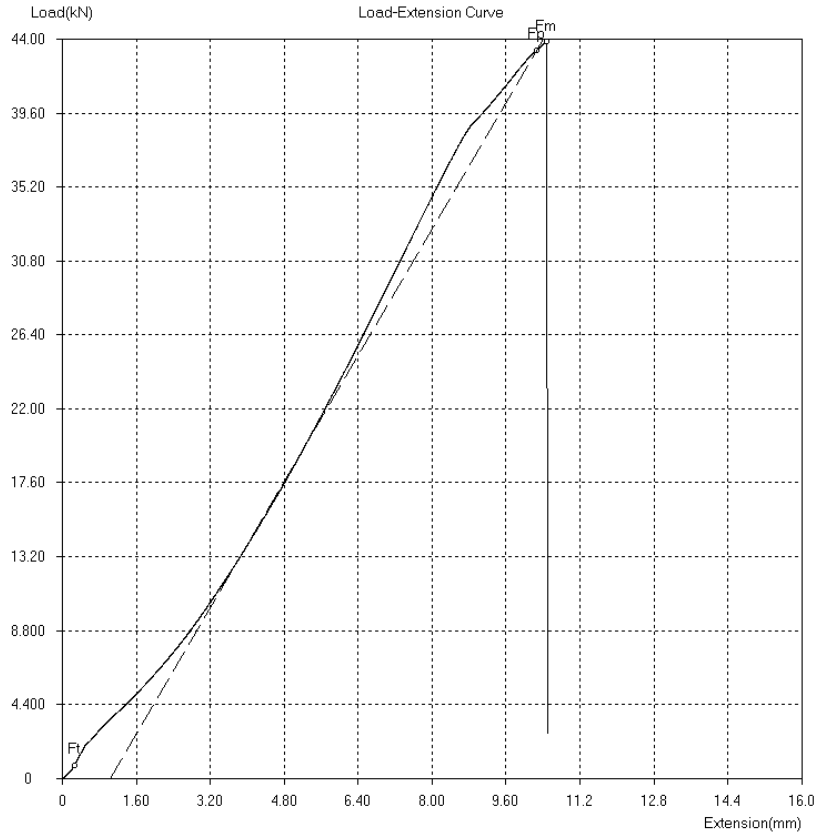
P 1-4


Load(kN)
Load-Extension Curve
28.00
25.20
22.40
19.60
16.80
14.00
11.20
8.400
5.600
2.800
0
Fm
Ft
0
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
Extension(mm)

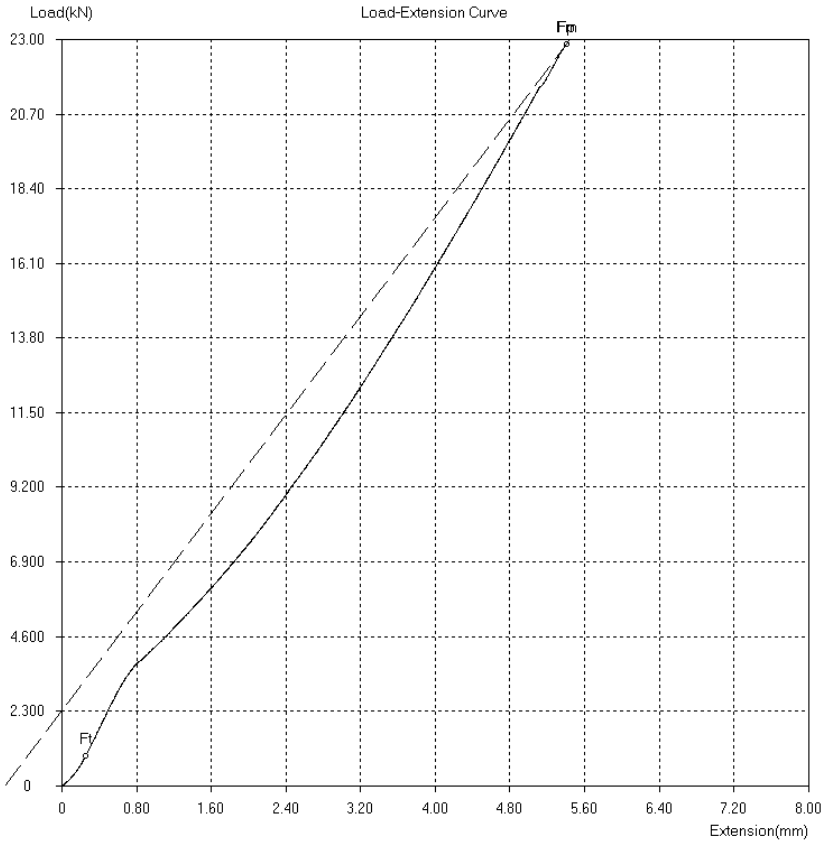
P 2-1


Load(kN)
Load-Extension Curve
46.00
41.40
36.80
32.20
27.60
23.00
18.40
13.80
9.200
4.600
0
Fm
Ft
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

P 2-2


Load(kN)
Load-Extension Curve
Fm
Fp
Ft
44.00
39.60
35.20
30.80
26.40
22.00
17.60
13.20
8.800
4.400
0
0
1.60
3.20
4.80
6.40
8.00
9.60
11.2
12.8
14.4
16.0
Extension(mm)

P 2-3


Load(kN)
Load-Extension Curve
Fm
Ft
23.00
20.70
18.40
16.10
13.80
11.50
9.200
6.900
4.600
2.300
0
0
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
8.00
Extension(mm)

P 2-4

Appendix 7: 3-point flexure failure (macro)

Appendix 8: tensile test failure (macro)