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James Howard

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K. Mukherjee

Major professor

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# LASER MACHINING OF POLYMERIC COMPOSITES FOR JOINT PREPARATION

By

*James Howard*

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# ABSTRACT

## LASER MACHINING OF POLYMERIC COMPOSITES FOR JOINT PREPARATION

By

*James Howard*

Cutting of glass/epoxy composite material with a 2.5 kW $CO_2$ laser and certain cutting parameters such as cutting speed, power used, and cover gas were investigated. Optical microscopy of the cut surface to determine the quality of the cut, and the parameters which gave optimum results were determined. The surface preparation before joining various joint geometries and joining methods were tested. The tensile test was used as a means to determine the best joint configuration and in evaluation of the strength of each joint.

To my family for their support and patience

# ACKNOWLEDGEMENTS

I would like to thank my advisor Prof. Kalinath Mukherjee for his guidance, support, and encouragement during the course of this work and my graduate study.

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# CHAPTER 1

# INTRODUCTION

The increased use of glass/epoxy composites in industry has created the need for different joining techniques. Joints must be strong and meet the specific demands placed on them. They must be as light as possible, without excess amounts of material, and easy to fabricate. The purpose of this investigation was to create such a joint in a thin Sheet Molded Composite (SMC) panel. The goal in joining any material together is to create a joint that is as strong or stronger than the original material. One of the ways this can be accomplished is by backing up the joint area with extra material on each side, a method called a double strap joint. This could become a bulky joint which would be incompatible for certain applications because of the excessive use of material. An alternative method would be to join the 2 halves of the joint without the need for backing on both sides or eliminating the backing completely. The joint must still have adequate strength and integrity by utilizing joint geometry and adhesive strength to accomplish the objective.

One of the challenges in joining 2 pieces of any material together is to find a configuration that will distribute the load over the entire surface without creating a stress concentration at any one point. A joint which will accomplish this must take into account the strength of the adhesive or bolting mechanism and the strength of the material being joined. SMC has one other consideration, the adhesive, glass,

Figure 1.1. Broken SMC.

and epoxy interaction.

Sheet Molded Composite (SMC) is manufactured by alternating layers of epoxy with layers of glass fibers [1, 2]. A thin layer of epoxy is placed in the mold, over this is distributed a layer of short, randomly oriented glass fibers. The glass fibers are coated with a bonding agent to help the epoxy to adhere to the glass [1]. A second layer of glass fiber depending on the specified number of plies will be placed in the mold. The amount of glass fibers and the number of plies are specified by a volume percent glass to epoxy ratio and the number of layers.

The mechanical properties of glass fiber reinforced SMC are affected by the percentage of glass fiber in the panel [3]. An increase in glass content will increase the stiffness of the material. An increase in glass fiber content will also increase the modulus of the SMC [3]. This ability to regulate the mechanical properties of SMC allows it to replace certain sheet metal parts in industries of mass production [3].

The use of composites in mass produced parts and the ability to join SMC parts can be extended if an efficient method of cutting the panel can be found. Three possible methods of cutting are available: Modified conventional tooling, abrasive water-jet cutting, and laser cutting.

Modified conventional tooling uses tool bits which are diamond or carbide cutting coated [4]. Conventional machining techniques such as drilling, milling, and grinding are possible in a glass reinforced SMC. However, the material poses certain problems. The glass fibers, because of the high volume content, causes excessive tool wear and difficulty in machining delicate intricate parts. Tool wear causes dimensional changes as the number of parts cut increases. When the dimensional change is great enough, tool changes are required increasing the cost of production and machine downtime.

Tool wear can cause frictional heat which could damage the surface [5]. As tools become dull they will delaminate the layers. Fiber pullout can occur at the cut or drilled surface [4]. Tool wear means slower cutting speeds so speed would have to be monitored to ensure proper cutting.

The size and shape of contours, holes, or faces would be limited to the availability of proper shaped cutting tools. The smallest radius which can be machined is determined by the smallest bit available [6, 7]. Outside radii are difficult to machine. Combinations of straight surfaces inside radii and contours require several steps to cut.

Clamping or holding the work piece is also a difficulty with conventional cutting. This is an impact process and therefore, if the work piece is not properly secured uneven cuts and vibrational problems can occur.

A second possible cutting method is Abrasive Water-jet (AWJ) Cutting. This method consists of a stream of high pressure water being forced through a nozzle located slightly above the work surface [8]. The water stream is an abrasive powder mixture which in some cases can be 2.0 mm in diameter [9, 10]. The velocity of the water can be 3,000 feet per second [11].

The kerf width is dependent on the nozzle opening. Therefore, a very small nozzle is desired to make intricate cuts. Nozzle wear is one of the problems with abrasive water-jet cutting because of the cutting action of the abrasive powder. To reduce this wear the nozzles are made from sapphire and the water is first conditioned before the abrasive powder is added [8, 12].

AWJ is controlled by a computer numeric control (CNC) which allows for complicated cuts to be performed but the intricacies of the pattern or the size of inside radii is limited by the diameter of the stream. In the case stated above the 2.0 mm diameter would not be small enough for some applications. The accuracies which are obtained with AWJ cutting are $\pm$ 0.38 mm depending on the thickness of the material being cut [13]. The cutting head is normally stationery while the work piece moves under the nozzle. Therefore, the accuracies are partially dependent on the table mechanism.

Some of the problems associated with conventional cutting are eliminated by AWJ cutting but 2 major problems are encountered. It is true that tool wear, heat generation, tolerance problems, and work piece clamping problems are eliminated, however, water absorption at the glass epoxy interface is known to occur [14]. The absorbed moisture causes swelling of the part and during adhesive bonding can cause the adhesive not to adhere to the surface. When water is present in glass/epoxy and the piece is heated in an oven, the moisture will boil off. This will cause bubbles and voids in the adhesive and weaken the bond. One way to correct this would be to dry the part in an oven to remove the moisture before applying the adhesive. However, this would be costly and time consuming. Abrasive particles can become embedded in the surface. These are difficult to remove and will contaminate the surface to be bonded [13].

Cutting shapes and holes in glass/epoxy SMC is possible with a $CO_2$ laser. Laser cutting eliminates the associated problems of conventional milling and the moisture contamination problem of AWJ cutting. It also is a non-contact process. Therefore, simple clamping is all that is necessary to hold the work piece [15]. Lasers will produce very small kerf widths and they are CNC controlled which allows for intricate cuts to be produced [15].

The $CO_2$ laser operates by converting electrical energy into photon energy [16]. This photon energy is given off when the $CO_2$ molecule in its excited state relaxes back to the ground state from either vibrational or rotational energy states. $CO_2$ is a linear triatomic molecule with 3 possible modes of vibration [16, 17]. Symmetric, where both Oxygen atoms are vibrating toward or away from the Carbon atom. Bending where both Oxygen atoms are vibrating perpendicular to the molecule. Asymmetric, where one Oxygen atom is moving toward the Carbon atom and one is moving away from the Carbon atom. To improve the operation of the laser, other gasses are added.

To the Carbon-dioxide is added Nitrogen and Helium to help in the excitation of the $CO_2$. Nitrogen requires less energy to move to the first excited state than does He or $CO_2$ [16]. Nitrogen also retains its energy until a collision with a $CO_2$ molecule rather than giving it off as a photon emission [17]. A third gas, Helium is added to improve operation of the laser by carrying excess heat to the walls of the tube and it deactivates lower energy states which acts to stabilizes the output [17].

The strongest emission of the $CO_2$ gas has a wavelength of 10.6 $\mu$m [18, 16, 17]. This emitted wavelength lies in the infrared region of the electromagnetic spectrum. Many materials readily absorb infrared radiation. Consequently, materials which are not highly reflective to a wavelength of 10.6$\mu$m or have a high thermal conductivity can be easily cut with a $CO_2$ laser [17, 19].

The emitted electromagnetic radiation is highly ordered, monochromatic, and parallel [18, 20]. Therefore, it can be focused to a very small spot size. When the beam is properly focused with fine quality optics it gives a high-energy density sufficient to vaporize most materials quickly [21]. The beam diameter can be as small as 0.15 mm depending on the type and quality of the optics [18, 16].

The optics used to bend the beam to a usable location or focus the beam must have certain characteristics. Ordinary glass or quartz used in lenses and mirrors readily absorb the 10.6 $\mu$m radiation. To be of use in lasers the lenses should be very close to 100% transmissive to 10.6 $\mu$m wavelength if transmissive optics are used [17, 22]. If mirrors are used they must be highly reflective to 10.6 $\mu$m wavelength radiation [22]. At higher powers a very small percent of absorption can be very serious and cause damage to the system. Cooling systems are usually used on the optical components of a laser to reduce the effects of heating by absorption [23, 22].

The optics must also be protected from dirt and contamination [22]. During cutting smoke and debris could get on the lenses. To eliminate this, gas such as air, Argon, or Nitrogen are forced through a nozzle [24, 16]. The laser beam and the gas pass through a small hole in the nozzle slightly larger then the diameter of the laser beam. Since the expelled gas is parallel and surrounds the laser beam it prevents gasses from rising into the nozzle.

Proper alignment of the nozzle and optics is essential to the operation of the laser [16]. If the optical system or focusing mechanism is misaligned, it will distort the beam and power will be lost. Nozzle alignment is critical to the quality of the cut [16]. If the nozzle interferes with the beam it can be melted or distorted and the gas flow will not be parallel to the beam. Nozzles are designed to optimize the gas flow, volume, and speed, into the kerf produced by the laser.

Two types of gas nozzles are used on $CO_2$ lasers, subsonic and supersonic [16]. Nozzle design is responsible for the speed and flow pattern of the gas. The speed of the gas affects the cooling rate of the material. The flow pattern affects the way debris and gasses are removed from the kerf on a through cut. Many types of both nozzles have been tested under various cutting conditions [16]. A nozzle which forces a stream of gas into the kerf parallel to the sides with sufficient speed and pressure to keep it clean with the least amount of turbulence seems to be the best [16].

The emitted laser radiation interacts with the material being cut to melt or decompose it [23]. The gas which is injected into the kerf through the nozzle carries molten material and decomposed gas out the bottom of the cut. To be efficient the cut should pierce completely through so the debris can be taken away easily. If the cut is not completely through some pools of molten material and gasses collect in the bottom of the kerf diffusing the energy and absorbing heat which can destroy the surface. This can severely impede the cutting action [18].

The type of cover gas injected into the kerf is dependent on the material being cut. For organic materials such as plastic and wood an inert gas is recommended to reduce the effects of charring [21, 17]. In this investigation there was found no noticeable difference in the amount of charring between air, $N_2$, or $CO_2$ for the cover gas.

The nozzle standoff distance and the distance from the nozzle to the work piece, is an important parameter for proper cutting [5]. The distance must be close enough to ensure an adequate flow of gas through the cut. If the standoff distance is too large the cover gas will spread out over the surface and very little will enter the cut because the kerf is so narrow. If the standoff distance is large it will produce a charred surface and an uneven cut face [18].

The effects of charring are also dependent on the interaction time. For a given power there is a certain speed which will produce the least amount of charring. If the speed is changed the power must also be changed to meet the optimum conditions to produce the least amount of char. Cutting speeds are dependent on the thickness and composition of the composite. Some studies find it is possible to cut 0.254 m/sec for straight cuts and 0.127 m/sec for contour cuts in glass/epoxy [5, 25]. The interaction time affects the heat affected zone which under optimal conditions is very small [17, 5]. The interaction time also affects the slope of the faces of the cut surface [25]. The focal length of the optics will also affect the slope

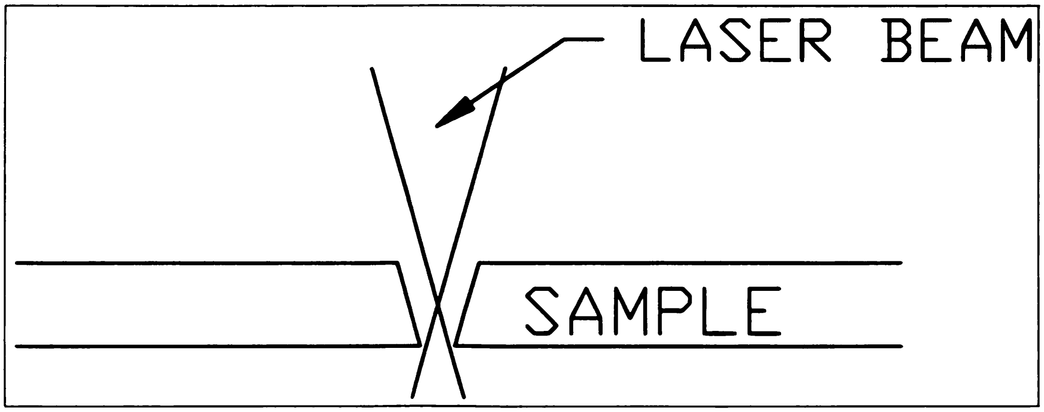


Figure 1.2. Slope of the cut face.

of the surface. This angle ranges from 0.5° to 1.5° depending on the cutting speed [25, 13]. Longer focal length optics produce less angle of cut but have a larger spot size. A shorter focal length will give a sharper spot size but give a steeper angle. The focal point location also affects the quality of the cut.

Some problems associated with laser machining are focal point location, material thickness, properties of the material, and the flatness of the work piece [26]. Setting the focal point on the centerline or slightly below it in the stock being cut is time consuming. Finding the proper speed and power combination to produce a good clean cut is tedious. The flatness of the work piece is essential. The laser used for the experiments was a 2– dimensional laser system meaning the head could not be moved up or down during cutting only in the X–Y direction were possible. The work piece must be flat so the nozzle distance remained close to the stock.

Several advantages exist for laser machining. For small production shops set-up time is very quick for small batch sizes. Laser cutting is safe compared to other methods of machining [9]. Little operator attention is necessary for production work [27]. The ability to cut smaller pieces from a large sheet of stock is an interesting alternative to pre-molded pieces [28].

The ability of the laser to cut intricate joint configurations, and more complex patterns will make it a more competitive manufacturing tool. Other advantages of using a laser in cutting joints are:

- Can be automated by computerized numerical control
- This automation improves precision, repeatability, flexibility and productivity of a joint fabrication.
- Large mechanical forces are not exerted upon the work piece.
- It's inherent ability enables it to machines in locations of difficult accessibility.
- It produces a uniformed finish
- No tool wear
- High processing speed and minimum re-tooling time.

# CHAPTER 2

# JOINT THEORY

Mechanically fastened joints such as bolted joints have three very distinct disadvantages:

- The hole placed in the piece causes a stress concentration which will weaken the joint.
- The bolt must protrude from both sides of the joint eliminating a good flat surface.
- The hole must be very tight fitting or some epoxy must be used to fill the gap between the bolt and the material.

Adhesively bonded joints have a few advantages over mechanically fastened joints as listed below [29, 30, 31]:

- Bonded joints are lighter in weight.
- Capable of bonding small pieces together.
- They distribute the load more evenly across the joint area.
- No necessity to cut holes or drill the composite which saves time.

Along with these advantages a few fundamentals must be taken into account when designing a joint that is to be adhesively bonded, which are adhesive strength, uniform stress distribution, film thickness, and bond area [32].

Adhesives are stronger in shear than in tensile or peel. Therefore, a joint should take advantage of shear strength [32]. An effort should be made to minimize tensile stresses and the tendency for the joint to peel apart. The shear forces of the applied load should be parallel to the bond layer.

Peeling loads are loads that try to wedge the joint apart by placing a strong tensile load on a small portion of the joint. Removing tape from an object demonstrates the weakness of adhesives under peeling loads. Tape cannot be removed by shear forces but is easily removed with a peeling force. Forces which act in a peeling mode should be avoided whenever possible [14].

The lap joint seems to take advantage of the shear property of adhesives (in figure 2.1). The bond surface is parallel to the applied load. The bond area can

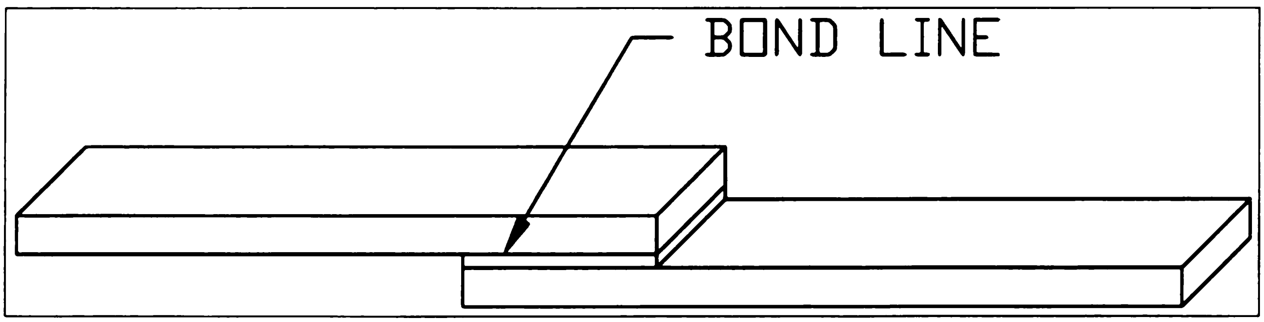


Figure 2.1. Simple lap joint.

be made sufficient to withstand the applied load. The lap joint, when placed in tension, has a bending moment at the joint which places the joint in tension and

peel [33]. Therefore, under a tensile load the lap joint does not take advantage of the adhesive properties and is not an adequate joint for flexible materials.

Adhesively bonded joints should take advantage of adhesive properties [34]. The joint must guarantee the adhesive remains in shear during use [14]. The forces on some joint can be a combination of tensile and shear forces. However, tensile forces should be minimized [35].

Adhesives are not as strong as the composite. Therefore, the area of the joint must be larger than the cross sectional area of the composite [35, 14]. The adhesive does not have the advantage of the glass reinforcement to add strength so it must derive all its strength from the bonded surface area. The bonding area must be greater in shear strength than the maximum expected stresses [34]. In the case of test samples the maximum expected stresses would be that of the composite yielding strength.

The size and shape of the joint should be able to transmit the applied load in a uniform manner [36]. Stress concentrations, sharp corners, and reduction in cross-sectional area should be avoided. Joints should be symmetrical to improve load distribution over the joint area.

A simple scarf joint can reduce the stress of the applied load (in figure 2.2) [34]. It avoids stress concentration, and it is symmetrical. Cutting a scarf joint in glass

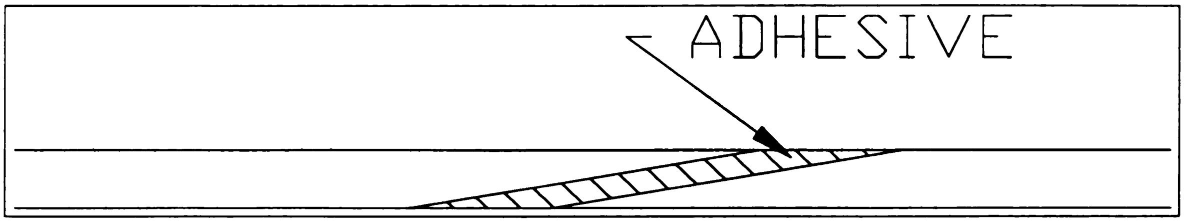


Figure 2.2. Simple scarf joint.

reinforced SMC would be difficult. Machining a scarf joint to a feathered edge causes fraying in soft material [36]. This frayed edge would make it difficult to achieve a uniformed surface.

Besides mechanical design of a joint other factors influence the strength of an adhesively bonded joint [37]. Surface preparation is important in the strength of a joint. The cleanliness of the surface plays a major role in bonding strength [38]. To understand the importance of these two factors an understanding of mechanisms believed to contribute to the adhesive bonding strength are necessary. The 3 mechanisms are: mechanical interlock theory, absorption theory, and the diffusion theory [39, 34]. The exact adhesion process is not completely understood but these theories exist to explain the mechanism [34]. These mechanisms can operate independently of one another, however, it is believed that all 3 theories operate collectively to explain an adhesive joint.

The mechanical interlock theory states that the adhesive will fill the cavities, grooves, or pores in the composite which creates an interlocking effect of the substrate and the adhesive [32]. Adhesive must displace air trapped in the grooves. If the air is present under the adhesive it will prevent proper linking with the substrate. If the surface is not porous it should be abraded in order to create the grooves for the adhesive to bond to. It is believed that by the abrading process the surface properties are changed to increase the strength of the adhesive [34].

Abrading the surface will also remove contaminates which will affect the overall strength of the joint. Mold release is a common agent found in plastic part manufacturing. Mold release, which is used to assist the removal of a part during manufacturing, will prevent the adhesive from bonding if not properly removed [40, 41]. By abrading the surface this is easily removed [38, 31]. Proper abrading of the surface will also remove moisture which will impede adhesion. For laser cut surfaces, abrading will help to remove any char left from cutting. Abrading the surface also has the effects of increasing the surface area and creating a highly reactive surface [34, 42].

In the absorption theory the adhesive molecules and the molecules of the substrate contact and form a bonding force [34]. For proper contact wetting must take place. Wetting is a process by which the surface tension of the substrate is greater than the surface tension of the adhesive. This difference in energy drives the wetting process [31, 32]. For proper wetting the adhesive must not trap air in the cavities or grooves which will reduce the bonding surface area. For heat activated post cure epoxies the air will also expand during curing forcing the adhesive out of the joint.

According to the diffusion theory the long chain molecules of the adhesive and the long chain molecules of the plastic material can move across the interface causing a linking across the boundary [34]. For this to occur the molecules must be able to diffuse into each of the 2 different regions. There can not be a layer of contaminates in the joint area. The surface must have proper wetting to fill all grooves or rough areas of the surface. Therefore, proper surface preparation is essential for proper bonding of joints.

Epoxy adhesives are widely used because they will bond to most materials. Epoxy adhesives will bond to epoxy materials very well. Epoxy adhesives have good gap filling ability and high strength. It will completely fill any irregularities in the surface.

The ideal mode of failure for an adhesively bonded joint is for there to be adhesive bonded to both halves of the joint after failure [34]. Failure should occur in the adhesive layer and not at the adhesive-composite interface. If regions exist which have no adhesive, proper wetting was not achieved or the surface was not properly prepared.

# CHAPTER 3

# EXPERIMENTAL METHOD

The laser used in the investigation was a 2.5 kW $CO_2$ laser capable of both continuous and pulse modes. The laser was able to cut in the X–Y plane only. The composite was positioned and clamped onto a table controlled by a CNC machine.

All the designs for the various joints were drawn on an AutoCad system and converted to the CNC language by a CAM program. This conversion also compensated for the width of the laser beam so the pieces would match the drawing perfectly after cutting.

The laser is capable of very fine cuts if certain parameters are set properly. It can hold close tolerances to within 0.025 mm which is required to cut tight fitting joints [43]. The beam diameter is very small making a kerf of 0.51 mm during cutting. To cut glass/epoxy (SMC) the cutting speed, power output of the laser, the location of the focal point, and the cover gas are very important.

The maximum cutting speed was determined by cutting a 1 inch square with sharp corners and comparing it with a scaled drawing. The speed was increased until a deviation from the pattern was noticed. It was found that the maximum straight cutting speed was 1 m/minute. This was the speed used to cut straight cuts. For contour cuts the same 1 inch square was used but with a radius of 0.76 mm at each corner. Comparisons with the drawing were again made until a deviation was found. This speed was found to be 0.89 m/minute. This was the speed used to cut the curved parts of the joint.

The laser power required to cut the thin section was found by setting the speed to the value for contour cuts as mentioned above and reducing the power until it just made a through cut on the composite. The power to cut different thicknesses of material was experimentally determined and recorded in Table 3.1.

Table 3.1. The power used to cut different thickness of glass/epoxy composite. The same speed and cover gas were used in all tests.

| Material thickness(mm) | Power used(W) | Speed cut(m/min) |
|---|---|---|
| 2.00 | 450 | 0.89 |
| 2.32 | 470 | 0.89 |
| 2.79 | 530 | 0.89 |
| 3.81 | 700 | 0.89 |

The laser beam focal point location and diameter are critical in the cutting with a laser. Therefore careful adjustments of the beam were made. The laser was adjusted so that the focal point was just below the center line of the stock (see Figure 3.1). With the focal spot located on the top surface of the material a satisfactory cut was achieved, however, a slight rounding of the top corner was observed. Focusing the spot on the bottom surface of the material increased the amount of charring and the kerf width.

The type of gas used for cutting was evaluated in terms of the least amount of charring observed on the surface and the best surface appearance after cleaning. A small piece of the material was cut using air as the gas. The thickness of the char could easily be seen using an optical microscope. This layer was measured and a comparison of the char thickness was made after cutting with other inert gases (see

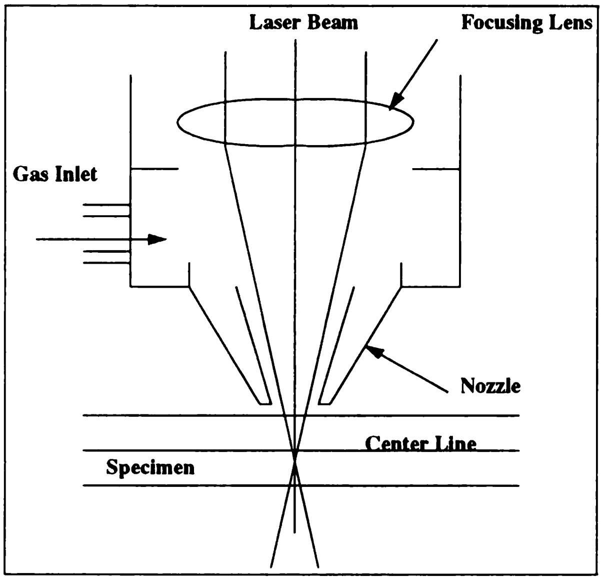


Figure 3.1. A schematic of the laser focusing mechanism.

Table 3.2).

Table 3.2. The measured thickness of the char layer left by the laser during cutting using different cover gases.

| Cover gas | Char thickness(mm) | Gas Pressure(MPa) |
|---|---|---|
| Nitrogen | 0.100 (± 0.029) | 0.58 |
| Argon | 0.130 (+ 0.042 to - 0.034) | 0.58 |
| Air | 0.127 (+ 0.063 to - 0.030) | 0.58 |

Figures 3.3, 3.4, and 3.5 show the cut surface of the material as it came off the laser with no cleaning. Figures 3.6, 3.7 and 3.8 show the surface after cleaning. Figure 3.9 shows the surface cut with a diamond saw and cleaned in the same manner as the other pieces so a comparison in cleaning method could be made.

Comparing Figure 3.9 with Figures 3.6, 3.7 and 3.8 it can be seen that the valleys and peaks are caused by the cutting of the laser and not the cleaning procedure. From the above analysis it was determined the best cover gas to use was air because it produced a relatively uniform surface and it was easy to clean the charred layer.

To clean the surface of the char and melted glass a small brass brush was used. A few strokes with the brush and wiping with a clean cloth and the surface was ready for the application of the adhesive. The flat surfaces had to be sanded lightly with number 240 sand paper as recommended by the adhesive supplier [44] to remove the glossy appearance. The flat surface was sanded very lightly so as not to weaken the cross section.

The adhesive was mixed, applied, and cured according to the manufacturers specifications. The adhesive was mixed 1 part resin and 1 part curing agent (50:50 mix). Both parts were mixed thoroughly in a small aluminum dish, then applied to the surfaces in a smooth layer. The pieces were put in a clamping jig (Figure 3.2) and placed in the oven. The curing time for all of the joints was kept the same, 121°C for 15 minutes.

After the joints were cut and bonded they were tested on an Instron tensile testing machine. All of the joints were tested under the same conditions as set forth in the **Annual Book of ASTM Standards** Section 15, volume 15.03 D3039. The strain rate for the tests was 19 m/ms.

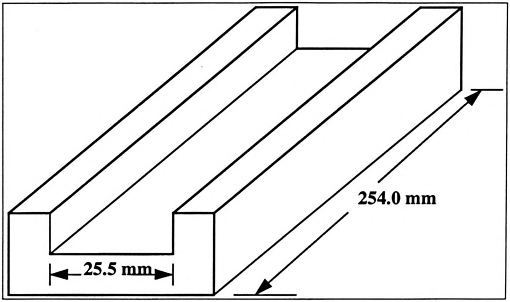


Figure 3.2. Clamping jig to align the pieces during curing.

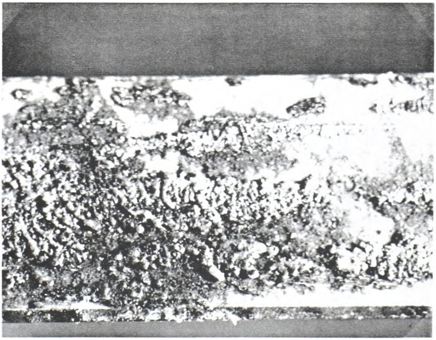

Figure 3.3. The surface after cutting with no cleaning, using air as the cover gas. The char is evident along with melted glass.

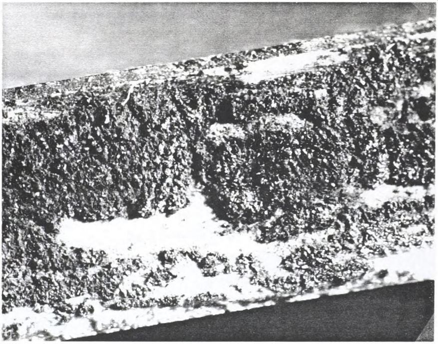

Figure 3.4. The cut surface using Nitrogen as the cover gas.

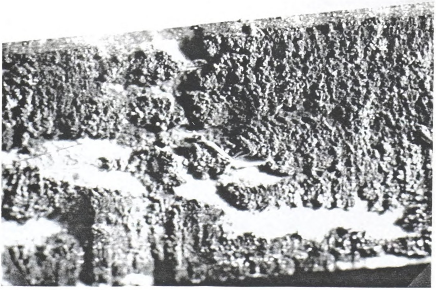

Figure 3.5. The cut surface using Argon as the cover gas.

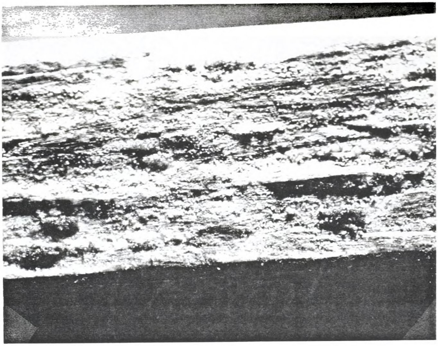

Figure 3.6. The surface after cleaning. Air was the cover gas.

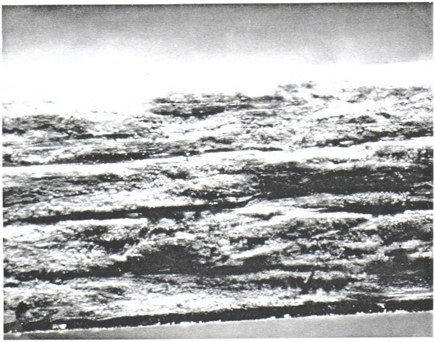

Figure 3.7. The cut surface cleaned with brush. Nitrogen was the cover gas.

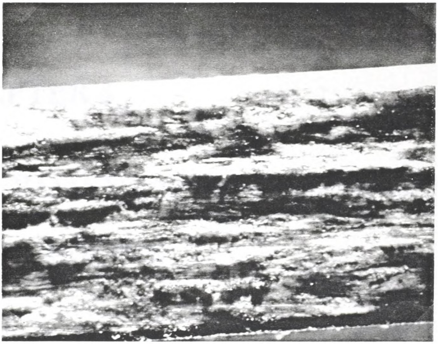

Figure 3.8. The cut surface after cleaning with brush. Argon was the cover gas.

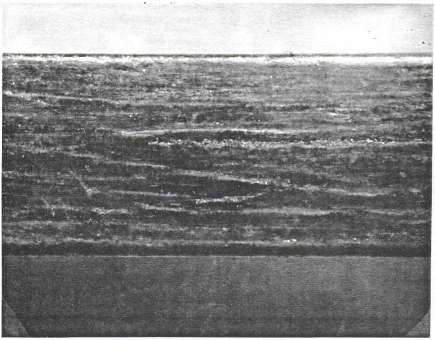

Figure 3.9. Composite cut with a diamond saw and then brushed in the same manner as the previous samples.

# CHAPTER 4

# EXPERIMENTAL RESULTS AND DISCUSSIONS

Prior to making any joints the materials strength had to be known so that a base line for comparison could be found. Samples were prepared as shown in Figure 4.1 to the specifications of the ASTM standards. They were tested and the results were recorded in Tables 4.1 and Table 4.2. Figure 4.2 shows a plot of the tensile test of the sample.

Table 4.1. The experimental results of a tensile test on a standard sample of 2.32 mm thickness.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 2.82 | 2.09 |
| 2 | 3.53 | 3.26 |
| 3 | 3.14 | 1.92 |
| 4 | 3.19 | 2.25 |
| 5 | 3.578 | 2.04 |

A common joint used is a simple lap joint (Figure 4.3). It has an area of bonded

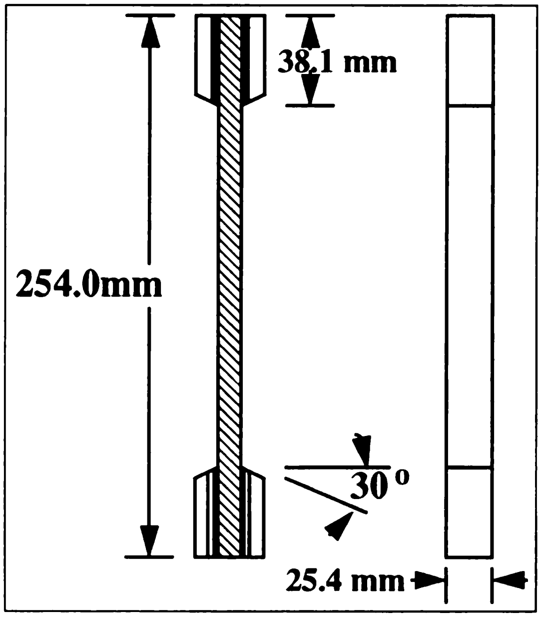


Figure 4.1. ASTM standard test sample.

Table 4.2. Results of a tensile test of a standard sample 2.80 mm thick.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 4.80 | 2.50 |
| 2 | 4.32 | 2.14 |
| 3 | 4.91 | 2.19 |
| 4 | 4.21 | 2.05 |
| 5 | 4.73 | 2.63 |

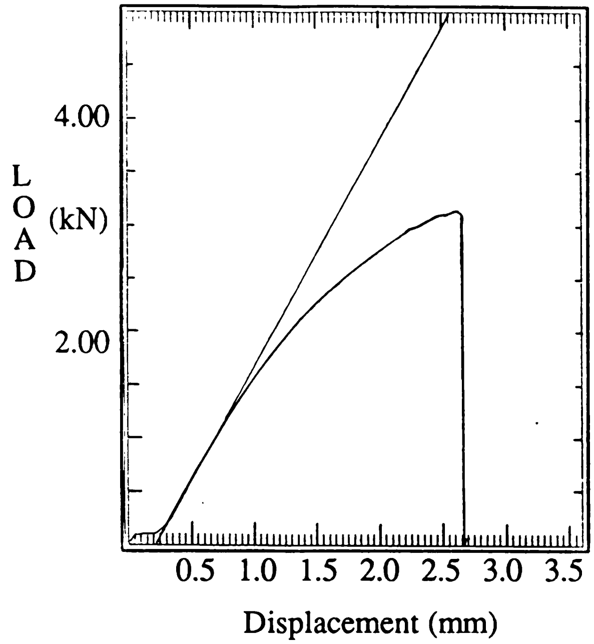


Figure 4.2. Plot of a tensile test for a standard sample.

surface which is parallel to the applied stress. This area is provided by part of one surface overlapping the opposite surface. The stresses generated by the load however, are not uniform over the entire area (figure 4.4) but are concentrated at each end of the lap, with very small stresses in the center.

It has been stated that the stress in the center is only about 1/5 of the stresses at the end of a lap joint [45]. The minimum stress on a lap joint being in the center and the maximum at each end give rise to the idea that a longer lap joint is not better than a shorter one. There is a limit to the effective length which gives an increase in strength [45]. A better way to increase the strength of a lap joint is to increase the width instead of the length [45].

The lap joint has one critical disadvantage. When a load is applied the joint will bend as if a moment was being applied to the specimen (Figure 4.5). This bending motion causes the joint to peel apart and severely reduce the strength. The results of the tensile test are shown in Table 4.3. Figure 4.6 is a plot of the tensile test

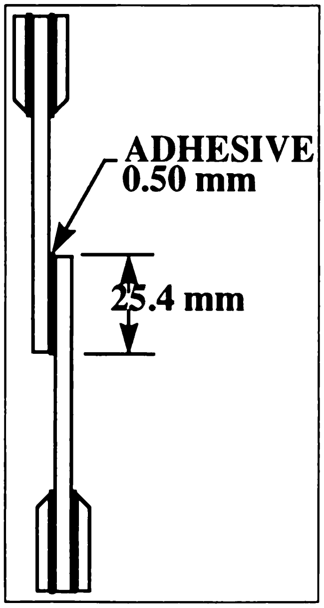


Figure 4.3. A simple lap joint before testing.

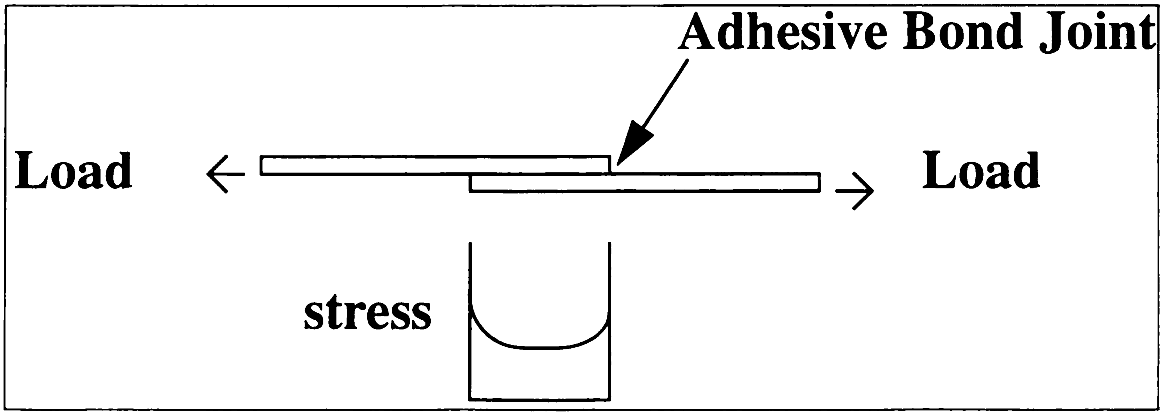


Figure 4.4. The stress distribution associated with a simple lap joint. Higher stresses are found to develop at the end of the joint and lower stresses at the center.

showing load versus displacement.

Another common joint used for soft materials is a strap joint (Figure 4.7). This joint is like placing 2 lap joints together and has the same disadvantage of the bending motion when a load is applied (Figure 4.8). Failure on this joint was also from the composite peeling apart. The maximum load and displacement are given in table 4.4 and figure 4.9 shows a plot of the tensile test results.

One common joint that provided the strength necessary to break the sample in a location other than the joint was the double strap joint (Figure 4.10). It had enough strength on each side of the specimen to equalize the stress and eliminate the bending which occurred in the single strap joint and the simple lap joint. The data for the tensile test is shown in Table 4.5. Figure 4.11 is a plot of a typical tensile test of the double strap joint.

A joint could be made like a strap joint by eliminating the break in the middle, which would distribute the load as in a solid piece. The strap joint has the advantage of a back-up strip on one side and yet provides a smooth surface on the opposite face. The back–up strip provides strength and keeps the top surfaces aligned during gluing.

It was determined that in order to create such a joint the 2 pieces would have to be joined and then a back-up strip applied over the joint area. This was determined by cutting several joints, gluing them, and then testing on a tensile testing machine.

Table 4.3. The results of a tensile test on a simple lap joint.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 2.27 | 0.98 |
| 2 | 1.65 | 0.71 |
| 3 | 2.12 | 0.97 |
| 4 | 2.00 | 0.83 |
| 5 | 2.33 | 0.86 |
| Average | 2.074 | 0.87 |

Table 4.4. The results of a tensile test of a single strap joint.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 1.79 | 1.35 |
| 2 | 1.67 | 1.46 |
| 3 | 1.74 | 1.08 |
| 4 | 1.78 | 1.00 |
| 5 | 2.06 | 1.34 |
| Average | 1.81 | 1.25 |

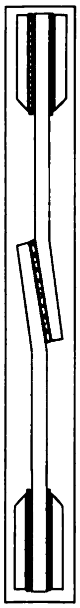

Figure 4.5. A simple lap joint during testing.

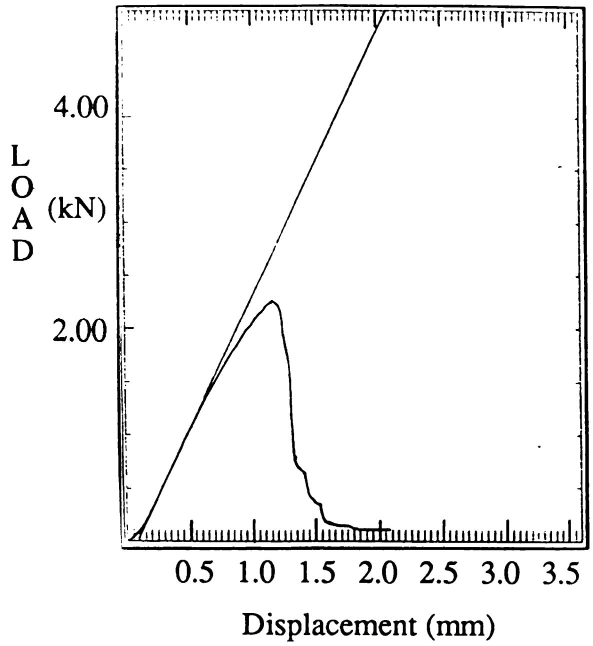


Figure 4.6. Plot of a tensile test of a simple lap joint.

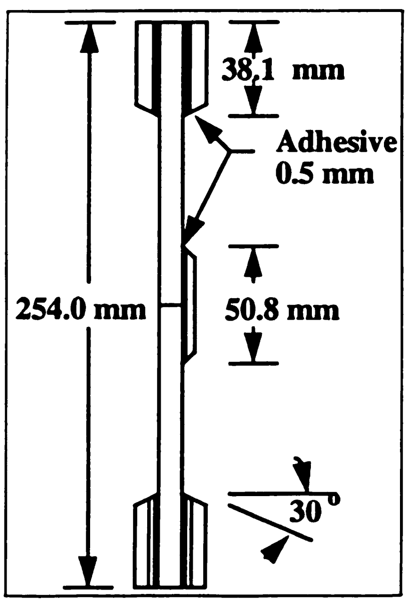


Figure 4.7. A single strap joint before testing.

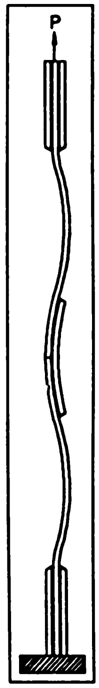


Figure 4.8. Single strap joint during tensile test.

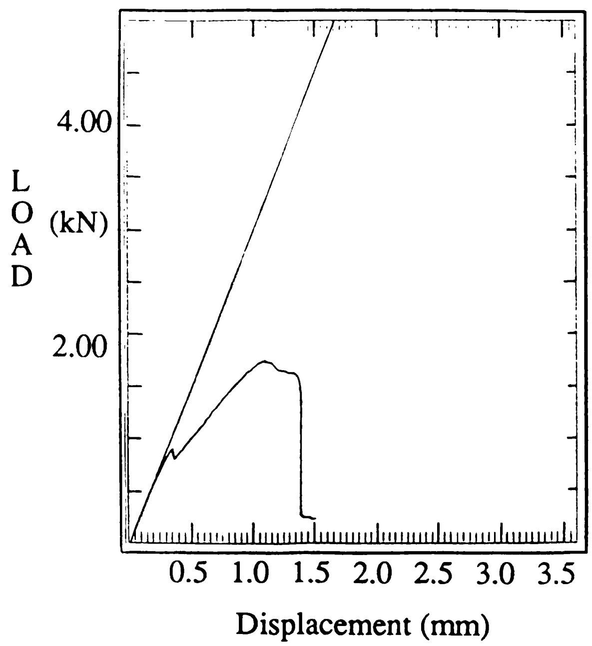


Figure 4.9. Plot of a tensile test of a single strap joint.

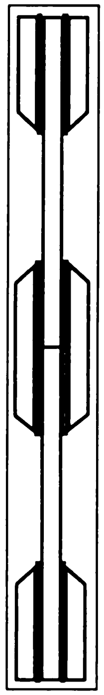

Figure 4.10. In a double strap joint the stresses are equalized on both sides so no bending occurred during testing.

Table 4.5. Test results of a double strap joint with a material thickness of 2.79 mm.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 4.79 | 2.58 |
| 2 | 3.78 | 2.13 |
| 3 | 4.70 | 2.51 |
| 4 | 4.29 | 2.04 |
| 5 | 4.96 | 2.84 |
| Average | 4.50 | 2.42 |

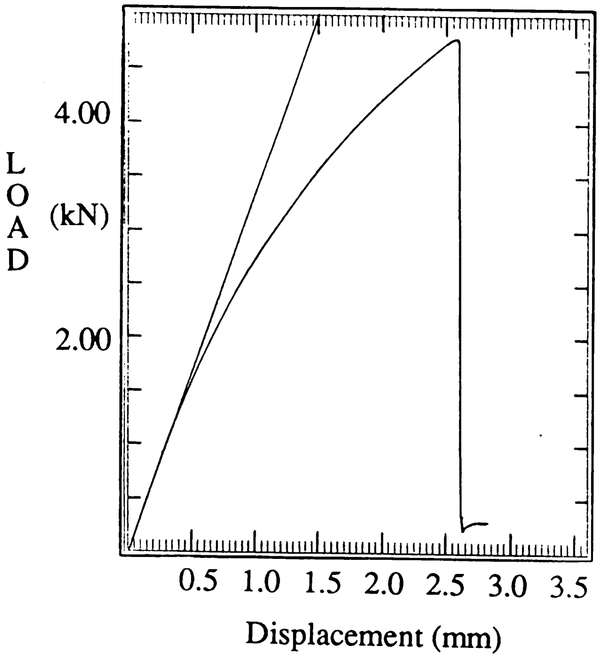


Figure 4.11. Plot of a tensile test of a double strap joint.

## 4.1 EXPERIMENTAL JOINTS

The fact that the joint alone with no support plate had to withstand 1/5 of the strength of material or greater and that the adhesive would play a vital role, it became necessary to determine the shear and tensile strength of the adhesive. To do this a single finger joint was cut and glued (Figure 4.12 a). A second finger joint with 2 fingers (Figure 4.12 b) was cut and joined. A third finger joint was also made (Figure 4.12 c).

The width of the stock remained constant along with the thickness. With these dimensions kept constant the only difference in the final strength would be due to the increase in shear area of the adhesive.

The tests were performed using the same ASTM test rate as before. Table 4.6 shows the results of the test. Five samples of each joint were tested and the average values are given in the table. The difference between the peak load of the 1 finger joint and the 2 finger joint was found to be 0.648 kN. Since the cross-sectional area

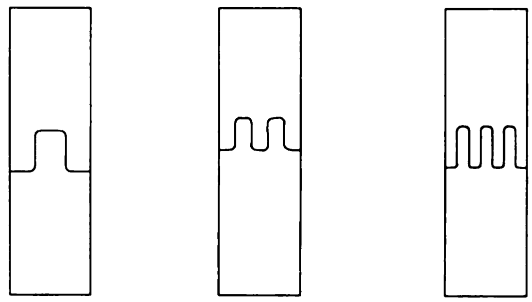


Figure 4.12. (a) A single finger joint, (b) finger joint with 2 fingers, and (c) a 3 tab finger joint.

Table 4.6. Results from tensile test of finger joints.

| Number of fingers | Shear area($mm^2$) | Tensile area($mm^2$) | Load at peak(kN) |
|---|---|---|---|
| 1 | 60.0 | 60.0 | 0.777 |
| 2 | 120.0 | 60.0 | 1.425 |
| 3 | 180.0 | 60.0 | 1.610 |

remained the same the only change was in the adhesive area subjected to pure shear load. Therefore, the shear load of the adhesive was 0.648 kN for this particular shear area. Dividing 0.648 kN by the shear area, the shear stress can be found in $kN/mm^2$. Subtracting the shear load of 0.648 kN from the maximum load of the 1 finger joint a value for the tensile strength of the adhesive can be found. The following calculations show shear and tensile strength taken from the values in Table 4.6.

1.425 kN – 0.777 kN = 0.648 (total shear load of the adhesive)

0.777 kN – 0.648 kN = 0.129 (total tensile load of the adhesive)

Dividing by the shear and tensile areas respectively

$0.648 kN/60\ mm^2 = 0.0108\ kN/mm^2$

$0.129 kN/60\ mm^2 = 0.00215\ kN/mm^2$

The value for the 3 finger joint could not be used in the calculations because during the test the 3 fingers were pulled off the sample. This indicates that the shear strength of the adhesive was stronger than the tensile strength of the composite.

Once the adhesive strength was known several joints were tried. In designing these joints it was assumed that the center of the joint would only have to carry 1/5 of the total load. However an attempt was made to maximize this value so the joint could withstand greater loads than that of the composite.

A single dovetail joint (Figure 4.13) with a tail of 9.5 mm in length and a width of 8.5 mm was cut and tested. The results are shown in Table 4.7. Failure always occurred in the outer tab at the narrow point after the adhesive failed.

A circular dovetail joint was made in an attempt to maximize the shear area of the adhesive (Figure 4.14). This consisted of a 9.5 mm diameter circular section in the center and a straight tab. The results of the tensile test are shown in Table 4.8. The failure of this joint was the same as for a simple dovetail joint but with a lower

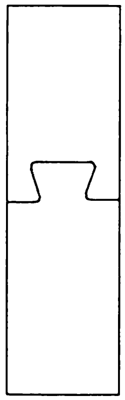

Figure 4.13. Single dovetail $20^0$ angle.

Table 4.7. Single dovetail tensile test results.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
| --- | --- | --- |
| 1 | 0.966 | 0.410 |
| 2 | 1.028 | 0.440 |
| 3 | 1.295 | 0.590 |
| 4 | 1.218 | 0.560 |
| 5 | 1.252 | 0.620 |

value for the peak load.

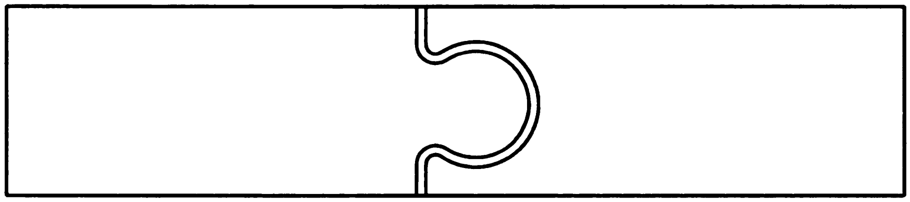

Figure 4.14. Circular dovetail.

Table 4.8. Circular dovetail test results.

| Specimen number | Load at peak(kN) | Displacement at peak( mm) |
|---|---|---|
| 1 | 1.046 | 0.460 |
| 2 | 1.141 | 1.100 |
| 3 | 1.160 | 0.740 |
| 4 | 1.145 | 0.720 |
| 5 | 1.295 | 0.590 |

To increase the surface area further 2 dovetails were cut in the width of the specimen (Figure 4.15). The tails were 12.5 mm long. This did increase the shear strength, but it also weakened the tabs. As a result, there was a reduction in tensile strength. The tails were shortened in an attempt to add strength to the tabs (Figure 4.16), however there was no substantial improvement in the strength. The results of the tensile test are shown in Table 4.9. A plot of load versus displacement is depicted in Figure 4.17. The failure of this joint was due to the center tail pulling off during testing.

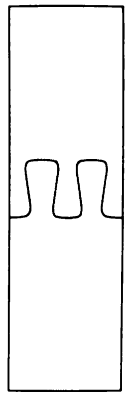

Figure 4.15. Double dovetail with $10^0$ angle.

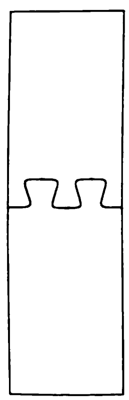

Figure 4.16. Double dovetail with $20^0$ angle.

Table 4.9. Short double dovetail

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 0.769 | 0.410 |
| 2 | 0.885 | 0.410 |
| 3 | 0.928 | 0.640 |
| 4 | 0.638 | 0.700 |
| 5 | – † | – * |
| Average | 0.805 | 0.540 |

† excluded, bad set-up in Instron
* excluded ...

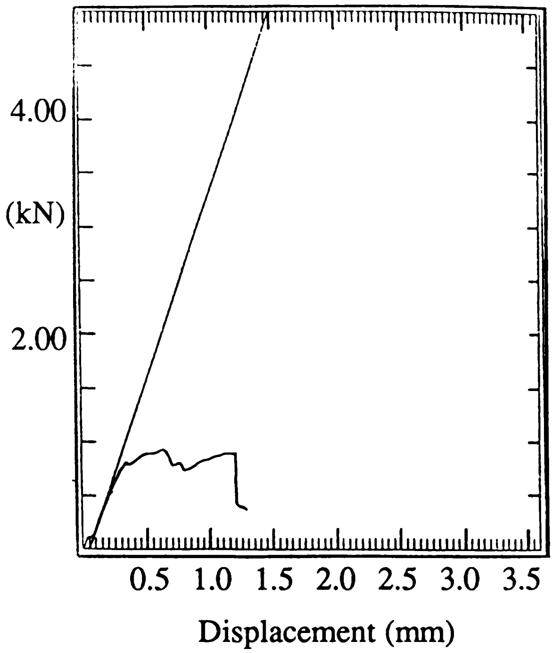


Figure 4.17. Plot of a tensile test for a small double dovetail joint.

Other joints were tried but the results were the same. No joint could withstand the stresses needed to obtain a satisfactory joint. It became apparent that no joint would even come close to the 3 tab finger joint used to determine the strength of the adhesive so that became the choice to try with a back–up strip.

Five 3 tab finger joints were cut and glued. A back–up strip of the same material 2 inches long and of the same width were glued across the back of the joint (Figure 4.18). These were tested in the same manner as the other joints. This time the joint failed outside the joint area. The results of the tensile test are shown in Table 4.10. Figure 4.19 is a plot of the tensile test of load versus displacement.

These joints were like a strap joint/finger joint combined. They did not exhibit the same bending as the strap joint. They remained straight during the test. All of the failed composite samples displayed fiber pull out and separation of the material. More tests were made of the same joint and the results were the same.

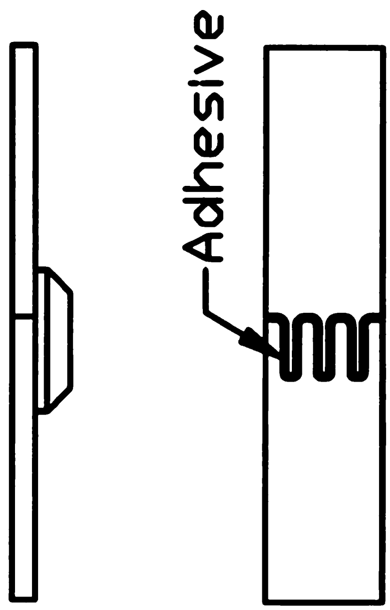


Figure 4.18. Finger/Strap joint.

Table 4.10. Tensile test from a finger joint with a back up strip. The material thickness was 2.32 mm.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 4.196 | 2.960 |
| 2 | 3.584 | 2.810 |
| 3 | 3.779 | 2.620 |
| 4 | 3.793 | 2.630 |
| 5 | 3.525 | 2.530 |

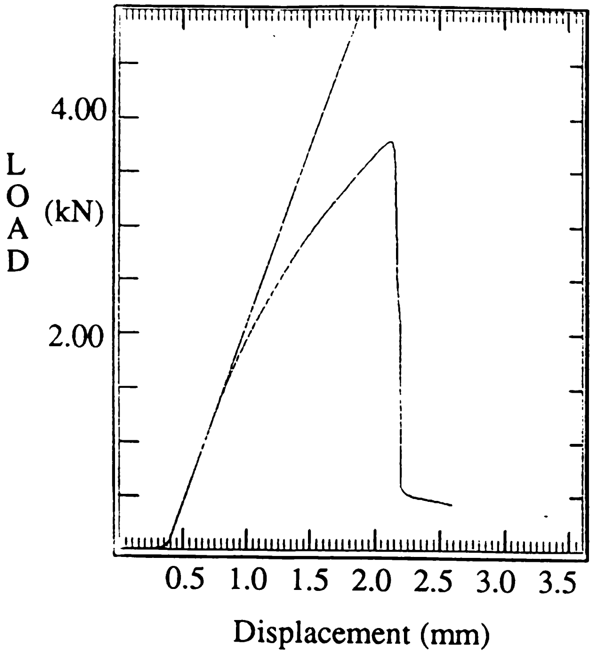


Figure 4.19. Plot of tensile test of a finger/strap joint.

## 4.2 JOINTS

Minor modifications of joint design, based on shear length, lead to improved strength levels in joints without any backup support plate. Joints were also much easier to align and glue, when the backup plate was not required. All the joints were prepared with a laser system equipped with circular polarizer, transmissive optics (5 inch focal length) and a beam expander of 1:2 expansion ratio. Strength values reported in the previous chapters were from joints made with a laser system equipped with reflective optics (10 inch focal length). The laser beam was randomly polarized for the previous experiments. All these new changes lead to finer kerf width (because of finer spot size) and less charring of the cut surfaces. In addition to the design modifications, the changes made to the laser system might have contributed to the increase in tensile strength of the joints reported here. Because of better focussability and low energy losses of the beam possible with transmissive optics, joints were made with less amount of laser energy than in the previous study.

Thermal damage of the material along the cut surfaces would be small, if the laser energy used to cut was low. This would have an influential effect on strength of the joints.

Among the various types of joints reported in the previous section, it was found that finger joint had the optimal strength properties. In section 4.1, the intra-facial distance between the teeth was the limiting factor (see figure 4.20). This

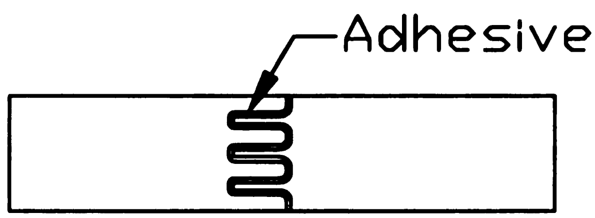


Figure 4.20. Finger joint from previous section.

determined the area over which shear stresses act. It was concluded previously that optimal strength values could be obtained when the area over which shear stresses act is high. This factor was taken into consideration in the modification of the finger joints. In order to increase the area over which shear stresses act, a computer program was used to determine the shear length and the number of tabs required to yield strength values comparable to samples without any joint in them, as reported in table 4.1. Hence modified finger joints, which do not have inter-facial width limitations were tested and the results were reported here (see figure 4.21). One problem with such a joint is, what angle would give maximum strength and also increase the shear area for the adhesive.

The composite strength was determined, for a 2.32 mm thickness specimen, to be between 2.82 - 3.58 kN. The joint had to withstand close to this and preferably

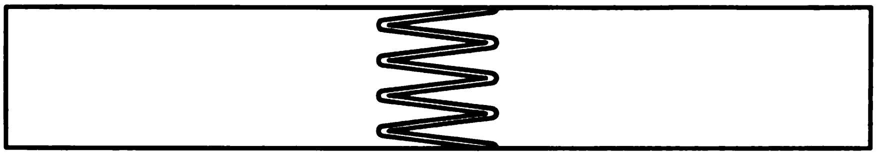

Figure 4.21. Modified finger joint.

greater loads before failure. The adhesive shear strength was found to be 0.0108 $kN/mm^2$ and the tensile strength was 0.00215 $kN/mm^2$. Working with the total strength of the composite, and the strength of the adhesive, a joint could be designed around these parameters.

Using the strength parameters a computer program was written which would vary the number of teeth in the joint and the angle of each tooth. It used the laser beam diameter, being the minimum at the base of each tooth, as the critical restraint on the angle for each tooth of the joint. The program used the maximum value of 3.5 kN load for a 2.32 mm thickness of material and simple trigonometry to calculate the shear length, area, and strength for each tooth (see figure 4.22). By varying the number of teeth and the angle of each a series of possible joint geometries were produced. Table 4.11 shows the possible combinations for the joint.

Table 4.11. Number of teeth vs angle of cut.

| Number of teeth | Angle in degrees | Shear length/tooth |
|---|---|---|
| 2 | 9 | 71.6 mm |
| 3 | 8 | 50.0 mm |
| 4 | 7 | 39.6 mm |
| 5 | 6 | 33.8 mm |
| 6 | 6 | 25.7 mm |

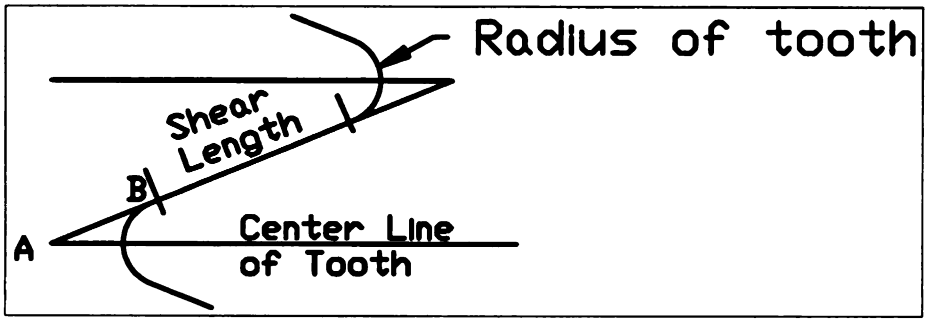


Figure 4.22. Tooth geometry for calculation.

The 2 teeth saw joint was cut using a 2.5 kW laser with a X-Y numeric controlled table. The quality of cut has been improved by the use of a transmission lens which has a shorter focal length and a sharper focal point spot size. A different nozzle for the cover gas was installed which improved the gas flow into the kerf of the laser cut. These and other improvements produced a better quality of cut and a smoother surface in which to apply the adhesive to.

The angle of each tooth of the 2 teeth saw joint was 9 degrees and a 0.38 mm radius at the base of each tooth (see figure 4.23 ). This provided the necessary shear

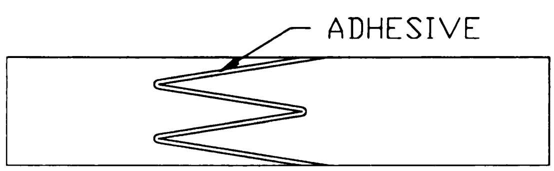


Figure 4.23. Two tab saw joint.

length however it was very long. It was cleaned and glued using the manufactures recommendations, the same as previously reported.

The results of this joint were better than previous joint without a backup plate however they did not withstand more than the composite. The results are shown in table 4.12. The average strength of the joint, without a backup strip was 86% as strong as the composite.

Table 4.12. Results of the tensile test of a 2 tab saw joint.

| Sample number | Maximum load (kN) | Displacement at break (mm) |
|---|---|---|
| 1 | 2.47 | 1.77 |
| 2 | 2.98 | 2.71 |
| 3 | 3.18 | 2.37 |
| 4 | 2.86 | 2.08 |
| 5 | 4.48 | 2.08 |

A 3 tab saw tooth joint was cut according to table 4.11 (see figure 4.24) with an eight degree angle. This joint proved stronger than the 2 tab design. The results

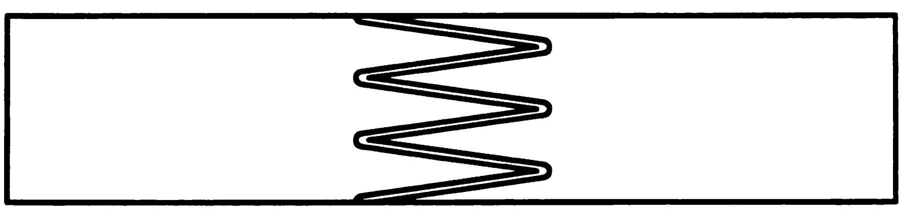

Figure 4.24. Three tab saw joint.

are shown in table 4.13. The average strength of this joint compared with the mean of the standard sample of the same thickness was 94% as strong.

Sample number 2 from table 4.13 actually broke outside of the joint area, ap-

Table 4.13. Results of the tensile test of a 3 tooth saw joint.

| Sample number | Maximum load (kN) | Displacement at break (mm) |
|---|---|---|
| 1 | 3.05 | 1.98 |
| 2 | 3.29 | 2.93 |
| 3 | 2.91 | 1.70 |
| 4 | 2.95 | 2.10 |
| 5 | 3.16 | 1.48 |
| Mean | 3.07 | 2.04 |

proximately 25 mm from the joint. The maximum load for the 3 tab joint was very close to 3 kN whereas for the 2 tab joints some of the values were much below 3 kN. It seems that the 3 tab joint is stronger than the 2 tab joint.

Other saw tooth joints were tested to determine if an increase in strength was due to more fingers with a shorter length. To determine this, joints with 4, 5, and 6 teeth were cut and bonded as described previously. The method of cleaning and testing procedure were kept the same. The shear areas of all the modified finger joints varied slightly from 143 mm to 163 mm. The only difference in them was the angle of each tooth and the number of teeth for each joint.

A 4 finger joint shown in (figure 4.21) has a shear length for each tooth of 39.6 mm. As can be seen from (table 4.14) strength of this joint is slightly better than the strength of the 2 and 3 finger joints. The maximum load applied to a joint was 3.31 kN for sample 2 and a minimum load of 2.88 kN for sample 3. It can be seen that these values are within the error band of the composite. Therefore, this 4 finger joint is quite close to the value needed.

A 5 finger joint has a change in the angle of the teeth and the length is reduced even further. The angle was reduced to 6 degrees and the shear length for each tooth was 33.8 mm. Table 4.15 shows that the 5 finger joint was not quite as strong as the 4 finger joint. The mean load at peak was 2.57 kN which was much lower than

Table 4.14. Test results from a four tab saw joint.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 3.203 | 1.86 |
| 2 | 3.31† | 2.40 |
| 3 | 2.89 | 1.73 |
| 4 | 3.12 | 1.90 |
| 5 | 3.13 | 2.10 |

† the sample broke outside the joint area

needed. A 6 finger joint was also tested and the results were shown in table 4.16. The 6 finger joint, even though the results were less than expected, did have 2 samples fail outside the joint area.

Table 4.15. Test results from a five tab saw joint.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 2.59 | 2.22 |
| 2 | 2.61 | 2.10 |
| 3 | 2.28 | 1.74 |
| 4 | 2.78 | 2.02 |
| 5 | 2.58 | 1.87 |

All of the joints tested were very close to the average strength of the composite for the same thickness of material(see figure 4.25). In some joints the teeth pulled off the sample, while in other cases the adhesive separated from the composite. Some of the joints failed because of improper cleaning of the surface. A look at the surface after failure revealed that some voids were present in the adhesive.

One possible explanation for the increase in strength of the joints could be that the glass fibers in the joint area are helping to increase the strength of the adhesive

Table 4.16. Test results from a six tab saw joint.

| Specimen number | Load at peak(kN) | Displacement at peak(mm) |
|---|---|---|
| 1 | 2.71 | 1.94 |
| 2 | 2.78 | 2.18 |
| 3 | 3.26† | 2.77 |
| 4 | 2.58 | 1.67 |
| 5 | 2.79† | 1.98 |

† the sample broke outside the joint area

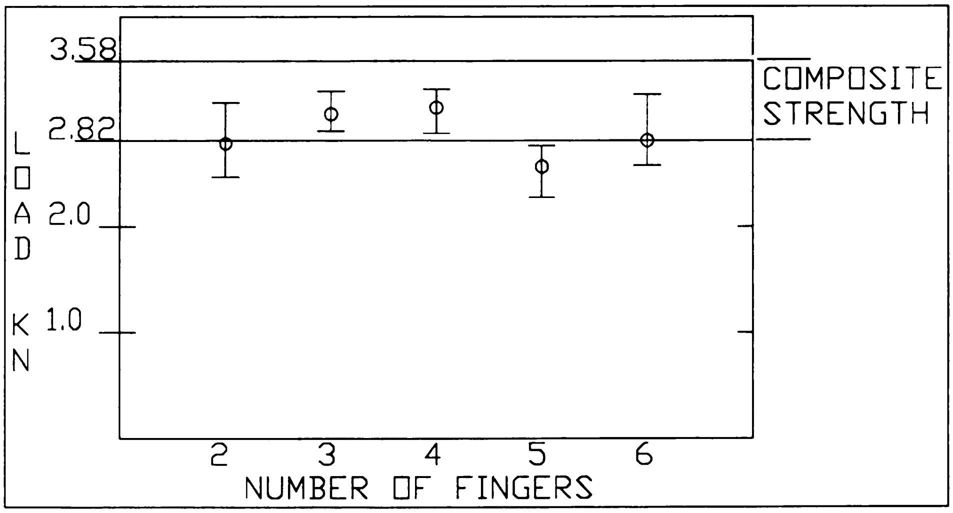


Figure 4.25. Strength of each type of joint compared with the strength of the composite.

(see figures 4.26, 4.27, and 4.28). It can be seen that the glass fibers are actually sticking into the joint between the 2 surfaces. When the adhesive is applied to the faces it can bond to these fibers and the composite which will increase the strength. It can be seen from these pictures that the glass does in fact protrude into the joint area. Further investigation into this will have to be conducted.

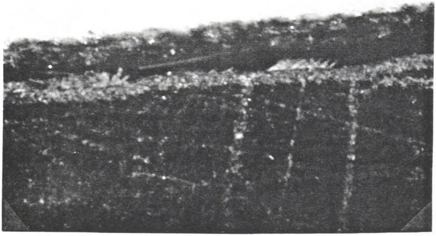

Figure 4.26. A photograph showing the glass fibers which protrude into the joint area.

One of the possible reasons for the difference in the 2 joints could be the variation in total length of each tab. The composite will elongate more than the adhesive due to the difference in the modulus of each. This could cause a stress concentration along the composite/adhesive interface. This stress concentration would exceed the strength of the adhesive causing failure. The failure in all of the 2 tab joints was caused by adhesive failure. The failure during testing seemed to be in small

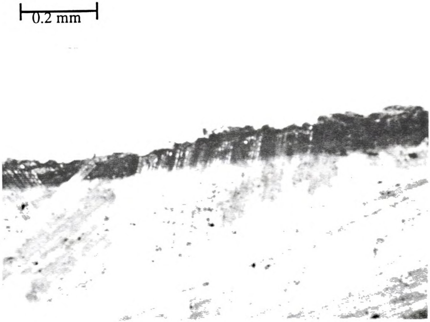


Figure 4.27. Glass fiber after laser cutting without cleaning the surface.

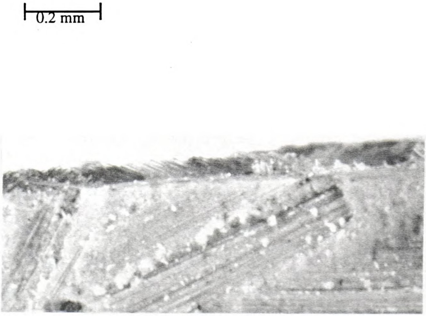


Figure 4.28. Glass fiber after cleaning the surface.

increments. Initially small cracks occurred at the tip of each tooth and proceeded down the length of each tooth until the joint failed completely. The shorter 3 tab joint was not affected as much by the modulus mismatch and therefore was able to withstand a greater load before adhesive failure. This joint did not exhibit the same mode of failure as the previous joint.

Future testing of various angles and lengths should be conducted to determine if there exists an optimum length which would give a joint stronger than the composite it is created in, possibly a 4 or 5 tab joint which is shorter. Finite element modeling of this joint to determine if a stress concentration exists at the interface of the adhesive would help determine if the length of the joint plays a critical role. Testing of different adhesives with different moduli on these joints would give valuable information.

# CHAPTER 5

# CONCLUSION

A joint can be made with sufficient strength to withstand mechanical loads more than the glass/epoxy composite with no joint. As the width of the sample increases the number and size of the fingers should be increased to maintain optimal strength levels, in-order to obtain joints with higher strength than the parent composite material with no joints. Therefore the strength of the joint would always be greater than the composite. If the thickness were to increase the shear area of the adhesive and the tensile strength of each tab would also increase and make the joint stronger.

For a finger joint the optimum size of the joint can be calculated knowing the shear strength of the adhesive. For the joints that were made it was found that the strength of the adhesive would equal the strength of the composite when the tabs were 5.0 mm in width and 2.32 mm in thickness. The strength of the tabs would be 1.25 kN and the strength of the adhesive would be 1.27 kN. The optimum size for any thickness or size of joint could be found by comparing the shear strength of the adhesive and the strength of the composite.

Putting a back-up strip on the finger joint greatly increased the strength of the joint, because the shear on the backs of the fingers have a tendency to hold them in place. The tabs which get interlocked across the face will distribute the shear across a larger area. The joint being symmetrical about the center line keeps even tension on both sides of the joint, thereby preventing twist.

For the saw tooth joints the angle of each tooth and the length seem to play an important role. It might be possible to increase the length of each tooth but care must be taken not to make them too long and actually weaken the joint. One advantage of this joint is it provides a smooth surface on both sides of the strip which might be desirable in some circumstances. The saw tooth joint is also easier to assemble and align for gluing. These advantages make this joint desirable for further investigation.

The laser is a viable method for cutting a glass/epoxy composite. There is no tool wear, and there is no observable separation of the glass from the epoxy during cutting. Accuracy of 0.025 mm is more than enough to cut the configurations described in this report. The surface was flat enough to bond the pieces together. The laser spot size would remain the same because there is no wear to change it. Once the programs for each joint were written the set-up time would be minimal.

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