A Manual for Making CFRP tubes

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Summary

Carbon fibre tubes are made by wrapping carbon fibre pre-preg around release coated duralumin mandrels and oven curing at 120 deg C. After curing the mandrel is extracted leaving the complete tube.

Tools needed for carbon fibre tube making

Mandrels All of our mandrels were made from standard drawn aluminium tube bought off the shelf. (British standard designation HT 30 TF) (International designation 6082 T6) This is available in diameters from 6mm to 250mm. in 4 and 5m lengths. We used tube with a 10 swg (about 3mm) wall thickness for all of our mandrels. It may be necessary to join lengths of aluminium tubing to make longer carbon fibre tubes. This can be done by machining a joining piece from thick walled (12mm) aluminium tube. This is made a tight sliding fit in the pieces of tube to be joined. It is permanently glued into one of the tube sections, But left free to slide in the other section so that the complete mandrel can be split into two pieces for extraction and storage. See fig 1. This allows the mandrel to be extracted from the cured carbon fibre tube by pulling it out (in two pieces) from either end of the carbon tube. (It can be extremely difficult to pull long mandrels from cured carbon tube and splitting the aluminium mandrel in this way helps since it halves the length that must be extracted at one time.

WARNING 1. The outside diameter of the drawn tube varies so it is important to select pieces of equal diameter when they are to be joined to make a longer length. Failure to do this will result in a step in the tube diameter!

WARNING 2. DO NOT use steel for the mandrels it has a too low a coefficient of thermal expansion and the carbon fibre tubes will ‘FREEZE’ immovably onto it.

Mandrel support jig

The mandrel must be supported between revolving centres during tube manufacture so that the pre-preg can be correctly and easily applied. We made two stepped wooden centres supported on a ball race mounted steel shaft that could be clamped to the work bench. See fig 2. For tubes over 4m long it may be necessary to arrange for additional support at the centre of the tube to prevent excessive sagging of the mandrel this would lead to wrinkles in the wall of the completed carbon-fibre tube with an associated reduction in the tubes strength.

A tool for cutting parallel strips of pre-preg

Typically tubes will have two or more carbon-fibre plys at +- some angle to the tube axis. Knowing the tube diameter, (which increases as carbon-fibre plys are added) and the designed angle of wrap of the carbon-fibre it is possible to calculate the width of pre-preg that must be cut so that each spiral layer will fit exactly at the right angle as it is wound onto the mandrel. To achieve this we made a 5m long cutting board with a aluminium rail along the back edge that has an adjustable cutter (like a BALSA-wood stripper) running on it. This allows accurate parallel strips of pre-preg to be cut. See fig 3.

Carbon fibre tube design

Simple beam theory seems to be adequate for predicting the strength and stiffness of tubular carbon fibre spars. Though the calculation of allowable stress, young's modulus and optimum laminate geometry requires the use of laminate analysis. These methods are detailed in '*THINK COMPOSITES*' book on composites design by Stephen W. Tsai. Think composites also sell software for I.B.M. compatible and Apple microcomputers. They have an on-line version of the book and an EXCEL spread sheet that can be downloaded from their web site at: http://www.thinkcomp.com/index.html However it is difficult to accurately predict the failure loads for these thin walled tubes and structural details (such as the transport joints) present a particular problem. For this reason it is important to verify a proposed design with structural testing. The following points should be considered when designing tubes. Tubes carrying torsional loads should have there innermost ply of carbon fibre applied so that it is in compression and there outermost ply applied so that it is in tension. This will prevent the tube failing by torsional delimitation. Tubes carrying bending loads should have there shear/torsion plys applied at ± 40 degrees to the tube axis. This will improve the tubes bending stiffness without any noticeable effect on the its torsional stiffness.

WARNING As the ply angle is reduced (tubes carrying only axial loads) the tube will contract more radialy as it cools after curing, until at a ply angle of about ±30 degrees it will become permanently 'FROZEN' onto the aluminium mandrel. The only way to remove the mandrel than is by chemical milling using HCl. For this reason it is perhaps worth considering a less then optimum laminate consisting of 2 ± 45 degree plys and 1 or more 0 degree plys. We have successfully extracted 5m lengths of 19mm diameter tube made like this by hand Tube wall thickness is dictated by consideration of local buckling. For this reason a wall thickness of approximately 0.56 mm (4 plys) should be chosen. Thinner tubes will work but should be tested to ensure that they are satisfactory. Sudden changes in the wall thickness should be avoided to reduce stress concentrations. if the wall thickness must be varied than it is advisable to change it gradually. See fig 4. Bending stiffness and strength can be tailored to meet the design requirements by adding 0 degree plys top and bottom (and front and back if the tube is to carry the in plane loads) The number of bending plys is tapered to match the applied load.

WARNING This results in an un symmetrical laminate and the thermal stresses set up as the laminate cools to room temperature after curing will cause the tube to distort to an oval cross-section. See fig 5. This will result in a reduction in the tubes stiffness and strength. We overcame this problem by inserting foam-Balsa wood sandwich bulkheads at 200mm centres to make the tube round. HOWEVER H.P.A's have been built by Wayne Bliesner in the U.S.A. and Peer Frank in Germany that used cantilever tube spars having no internal bulkheads and they have been entirely successful.

Design of joints in tubular spars

The smaller tube should plug into the larger tube for about a distance of 4 times the larger tubes diameter. The smaller tube is held in place by means of 25mm thick ply wood rings at each end of the joint. these are glued to the smaller tube using a high strength Epoxy resin. They are made an easy sliding fit in the larger tube if the joint is to be a transport joint or they are glued if it is to be a permanent joint. The larger tube will require the addition of some hoop plys to at its end to prevent hoop tension bursting. At transport joints it is necessary to arrange to transfer the torsion due to the wings pitching moment across the joint. Fig 6 shows the Airglow transport joints and fig 7 shows the Daedalus transport joints.

Preparation of the aluminium mandrels

The aluminium tube must be cleaned, polished and released ready for laying up the carbon fibre tube. The following procedure has been found to produce good results. (Manufactures Data sheets for the materials used are included in appendix A.)

- ❑ Remove all surface imperfections using 180 grit wet and dry paper used wet.
- ❑ Polish the tube with wet and dry paper (used wet) start with 220 grit and work down to 500 grit paper. Finish with fine wire wool used wet with detergent.
- ❑ De-grease the tube using Trichlorethylene or a similar commercial de-greasing solvent. (Do this out of doors or under an extractor and observe the manufactures safety recommendations)
- ❑ Allow 20 minuets for solvent evaporation. The tube must now be release coated to prevent the cured carbon fibre sticking to the aluminium tube. there are two alternative procedures for this detailed bellow.

1. the tube is coated with a suitable NON-SILICONE release agent Such as AIRTECH Release all #18.

- ❑ support the tube using the revolving assembly jig (clamped to the work bench). Apply a coat of Release all #18 using a soft cloth.
- ❑ It is important to wear rubber gloves to prevent your hands from becoming contaminated with release agent In addition to considerations of safety any release agent transferred to other composite parts will cause there eventual failure by delimitation.
- ❑ Allow 15 - 20 minutes for solvent evaporation and then apply a second coat of release all #18
- ❑ Bake the release agent on to the tube at a temperature of 130 °C for 1 hour.
- ❑ Allow the tube to cool to room temperature and apply a third coat of release all #18.
- ❑ Bake the release agent on to the tube at a temperature of 130 °C for 1 hour.
- ❑ The mandrel is now ready for lay up of the carbon fibre tube.

The extraction of the mandrel will damage the release layer so that it is necessary to re-apply and bake on one coat of release agent before re-use of the mandrel. It is important to take great care in applying the release layer as failure of the release system will result in the loss of both the mandrel and the carbon fibre tube.

2. Apply a glass reinforced release fabric such as Airtech TOOLTEC TEFLON release film.
We have not tried this because we thought that a wrinkle, or bubble in the release film would jam the tube on the mandrel. However this technique was used successfully by the builders of the Daedalus HPA. A strip of film is cut the length of the mandrel and about 5mm wider than the tube diameter. this is applied to the mandrel using a suitable high temperature spray adhesive. It is important to achieve a perfect result as any bubbles, wrinkles or surface imperfections will prevent the mandrel being extracted. During extraction the tube should be pulled straight off the mandrel or if it is rotated relative to the mandrel this must be done so that the overlap in the TOOLTEC release film is not peeled back inside the tube. this would jam the tube onto the

mandrel.

Hand lay up of carbon fibre tubes

Before starting the lay up cut out a set of pre-preg parts for the tube. These should be stored flat on a clean bench until they are needed. If it is available then use pre-preg that has a protective film in addition to the usual wax paper backing. This ensures that both sides of the pre-preg are protected and greatly simplifies handling during the cutting and lay up process. Knowing the desired laminate construction and the tube geometry it is possible to calculate the sizes of the pre-preg parts that must be cut out. The following formula allow the sizes of the spiral shear/ torsion plys to be calculated.

L = finished tube length
D = tube diameter (which increases by 2 times the ply thickness each time a ply added to the tube)
ϕ = ply angle (measured from the tube axis)
PL = length of pre-preg to be cut
W = width of pre-preg to be cut
PL = $L/\cos\phi + \pi D \sin\phi$
W = PI D cos ϕ

The ends of the Pre-preg strips should be cut off at an angle (equal to the ply spiral angle) so that the ends of the carbon fibre tube finish square. REMEMBER that plys wound onto the mandrel at + alpha degrees must have there ends cut at the opposite angle to plys wound onto the tube at - alpha degrees. See fig 8.

Lay up of the zero degree plys

The zero degree plys that carry the tension and compression loads due to the wings bending moment should be cut out and assembled ready to be added to the basic tube. The zero degree plys forming the tension and compression “flanges” of the spar beam must have sufficient cross sectional area to meet the wings designed bending moment and stiffness criteria. (To obtain acceptable stiffness the spar will probably need to be stressed for more than 2.5 g.) Remember that the sheer/torsion plys of the basic tube will also contribute a little to the spars stiffness and strength. The “flanges” are built up from a number of plys of different widths. See fig 9. The reasons for doing this are:

To give the spar a smooth cross section resulting in more even consolidation of the laminate during curing. And consequently a stronger more defect free spar.

To concentrate the “flange” cross sectional area as far away from the neutral axis as possible to increase stiffness.

The widest ply should be between 0.5 to 0.7 of the spar diameter and each successive ply should be about 5-10 mm narrower than the previous ply. If the “flange” cross sectional area must be tapered along a spar section to match the applied bending moment then it is best to achieve this by reducing the number of plys in the “Flange” as cutting tapered plys is difficult and time consuming.

Follow the procedure detailed bellow to assemble these parts.

- ❑ The plys are cut out and stored flat ready for use.
- ❑ The widest ply is laid out on the work bench and is stuck down to prevent it from moving. You can do this either using sticky tape at both ends only or two sided sticky tape applied at about 0.6 m intervals.
- ❑ Remove the plastic protective film from the first two plys of the lay up.

WARNING never remove the wax paper baking from the pre-preg until after it has been incorporated in the lay up. The wax paper backing 'stabilises' the pre-preg during handling preventing it from distorting.

- ❑ Stick the second ply down to the ply that has been taped to the work bench. This is best done by two people. start by positioning the plys over each other then using a nylon roller and hot air gun stick one end down. One person should keep the plys separated and prop erly aligned while the other person working from the end that has been stuck down sticks the plys together.
- ❑ Remove the wax paper backing from the top surface of the lay up ready to apply the next lamination.
- ❑ Repeat the previous steps to complete both zero degree ply lay ups.

IMPORTANT ADVICE. The pre-preg is slightly 'tacky' allowing it to be stuck together to construct a laminate. However this tackiness varies with temperature. If the temperature is too low than the pre-preg has insufficient stickiness to adhere to its self and the laminate falls apart as quickly as it is assembled. If the temperature is too high then the pre-preg is so sticky that it cannot be peeled apart and repositioned if a mistake is made. There are two alternative solutions to this problem. 1. Find the 'optimum' temperature and make sure that the workshop is maintained at this temperature during the lay up process. 2. Use a hot air gun to warm the pre-preg so that it sticks to itself properly.

WARNING once the pre-preg is stuck together it is almost impossible to separate if repositioning is necessary.

Lay up of the basic tube

- ❑ The mandrel is supported on the assembly jig which should be clamped to the front edge of the workbench.
- ❑ The pre-preg is wrapped tightly on to the mandrel taking great care to avoid any wrinkles or bubbles. It is usually necessary to hold the ends of the first ply to the mandrel using tabs of masking tape.

WARNING you must remove the masking tape after applying the next layer. If the masking tape is not removed it may be impossible to extract the mandrel after curing the tube.

- ❑ The wax paper backing is removed from about 0.6 m of the first layer at a time and the second layer is positioned and wrapped onto the tube.

REMEMBER that the plys will fit at the right angle so long as there edges are butting exactly. It is for this reason that they have been pre-cut to calculated widths. In practice it is very difficult to obtain an exact butting of the ply edges for the whole length of the tube. For tubes having 4 or

more plys (0.56mm or more) this is probably not too important since the shear/torsion stress in the tube is only going to amount to about 5-10% of the allowable stress for the carbon-fibre. (Tube wall thickness is determined by consideration of local buckling and torsional stiffness)
The solution is to aim for a perfect fit or a small gap between the plys. NEVER allow an overlap as this will make it impossible to add the next layers correctly. The gap can then be filled with a strip of pre-preg though this is probably only important for thin walled tubes (2 or 3 plys thick)
The pre-preg is handled using rubber gloves to prevent contamination of the pre-preg which would later cause delamination. As a further precaution the gloves are changed after the first layer is applied in case they have picked up any release agent from the tube.

Adding the zero degree plys to the basic tube

The zero degree plys are added to the tube taking care to position them correctly. This is best done by two people. DO NOT allow the pre-preg to be 'kinked' as it is quite easy to break the fibres this is especially true for the high modulus carbon fibres.

ADVICE Once the spar has been cured it is difficult to see where the zero degree fibres are the solution is to add a length of KEVLAR roving to the lay up. This is positioned to mark the centre line of the zero degree plys. When the spar is cured it will remain visible as a thin yellow line. See fig 10. Other important features of the lay up can also be marked in this way.

Preparation of the tube for curing

The tube must have a layer of peel ply added to leave a rough surface to allow subsequent bonding on of fittings and wing ribs. Use the finest (lightest weight) peel ply available. There are two ways of applying the peel ply.
1. Use peel ply tape about 100mm wide and spiral wrap it on to the tube. This will help to consolidate the laminate. 2. Use a single sheet of peel ply stretched over the tube surface. It may be necessary to hold the peel ply in place with tabs of sticky tape. The tube is than bound with a layer of low shrink tape (AIRTECH W4500) this provides a release for the outer layer of high shrink tape that is used to consolidate the laminate.

ADVICE The tube can be spun in the assembly jig using a variable speed electric drill (we used a rechargeable drill used on low speed) gripping the tube support shaft directly. This saves the trouble of making a gear box to drive the jig. Finally the tube is bound with 2-3 layers of high shrink tape. (AIRTECH A 575 high shrink tape)

Curing the tube

We cured our tubes using a home made air circulating oven. Fig 11. Shows this and should be self explanatory. Alternately arrange the use of an industrial oven or autoclave. After curing remove the shrink tape but leave the peel ply on the tube to protect the surface during handling. The peel ply is removed just before assembly of the structure and will leave a clean surface for bonding.

Extracting the mandrel

Tubes can often be pulled from the mandrel by hand-but it may take more then two people. Failing this they can be pulled off using a winch. The winch is tied to a (strong-up to 20 loops of roving) loop of KEVLAR rovings that have been lashed to one end of the tube (with EPOXY). The other end of the mandrel is drilled to take a 12mm steel pin. We used two trees as anchor points for tube extraction. REMEMBER to protect the trees so that they are not cut by the winch cable anchors.

Fitting the internal bulkheads

It may be necessary to insert bulkheads to stabilise the thin walled tubes against local buckling or to make them round. The bulkheads can be turned on a lathe. Either individually on a face plate. (hold the blanks in place with two sided tape) Or by turning all the blanks together between centres. (mount them on a threaded rod between clamping plates) The edges of the bulkheads are buttered with epoxy and they are pushed into the tube using the tool shown in fig 12. The bulkheads should have a small hole made in them to allow the air inside the tube to escape.

Bonding on metal fittings

If it is necessary to bond metal fittings into or onto the tube than it is important to insulate them from the carbon fibre to prevent galvanic corrosion. This is done by curing a layer of film adhesive or room temperature curing High strength epoxy to the surface of the metal fitting. This should have a peel plied surface finish to ensure a strong joint. The peel ply is removed from the carbon tube (where the fitting is to be attached, if this has not already been done) and also from the fitting. The joint is made using a suitable high strength epoxy adhesive. It can also be lashed with KEVLAR or Carbon roving to give added security. See fig 13.

ADVICE If fittings must be bonded to the internal surface of a tube than it is possible to put a patch of peel ply onto the mandrel before adding the first ply of carbon fibre. When the tube is cured the peel ply is removed leaving a surface finish suitable for bonding. Note This will only work at the end of the tube where it is possible to get hold of the peel ply to remove it.

Bicycle Frames

After building Airglow Nick Weston thought it would be fun to make a carbon fibre bicycle. The first frame he made was very light, it was possible to ‘squeeze’ the downtube. The lugs were made by wet lay up of carbon fibre cloth with no moulds. After the cloth was laid up it was lashed with peel ply and shrink tape to compact the laminate. The lugs were ugly but the bike worked. Nick built it in ten days finishing on the eve of the start of his first year at university and rode the bike there on his first day. A seventy mile trip with a heavy backpack. Nothing broke. Then Mark and Nick decided to make some frames with moulded lugs. I think the inspiration for this came from an article in Cycling Science describing the construction of the carbon fibre bicycle frames built for the US Olympic cycling team.

Fig 14. Shows a section through the carbon fibre bicycle frames built by Mark McIntyre and Nick Weston. The tubes were made as described in the tube building manual and were wet sanded smooth after curing. The frame tubes were cut to fit and stuck together with epoxy in a jig made from a sheet of fiberlam (used as a flat building board) and wooden blocks that spaced and held the tubes. The drop outs were glued into the chain and seat stays at this stage. The lugs were moulded from carbon cloth as follows. Mark and Nick made wooden patterns for the lugs and cast female moulds from these using tooling epoxy. It would be nice to make these directly from the drawings using an NC mill if one was available. Layers of carbon fibre cloth were cut and wet laid up in the mould sections and then the moulds and cloth were clamped onto the frame and left to cure. Afterwards the lugs were lightly wet sanded to remove the mould flash. The head set inserts, bottom bracket insert, gear bosses and cable guides were glued to the frame. Then the frames were spray painted by a automobile paint shop. The sections of the chain stays are a simple tapering rectangle because this was easily made and the mandrel could be easily extracted from the finished chain stay. The lugs are simple parallel tubes with tapered ends and 1/8 corner fillets again because the parts for the patterns could be easily machined on a lathe and the moulds easily packed with carbon cloth. More sophisticated parts could be designed given NC machinery, injection moulding, woven pre forms etc.

Sources

Think composites.

http://www.thinkcomp.com/index.html
Tsai, Steven. W., Composites Design. P.O.B. Think Composites, P.O. Box 581, Dayton, OH 4519-0581. USA.

Greenwood, J. H. German work on grp design. Composites, July 1977, 175 pp

DRAWING SHOWING HOW TO JOIN THE MANDREL TO MAKE LONG CARBON FIBRE TUBES

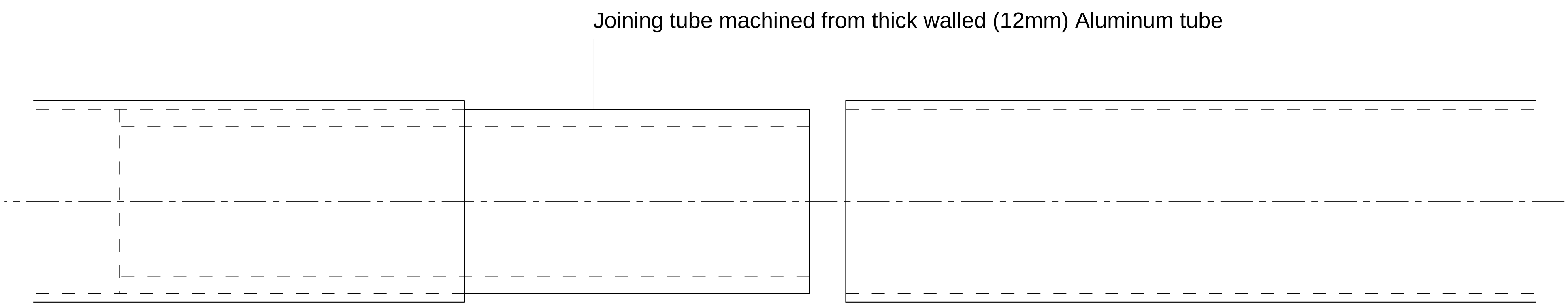


Fig 1

TUBE SUPPORT JIG

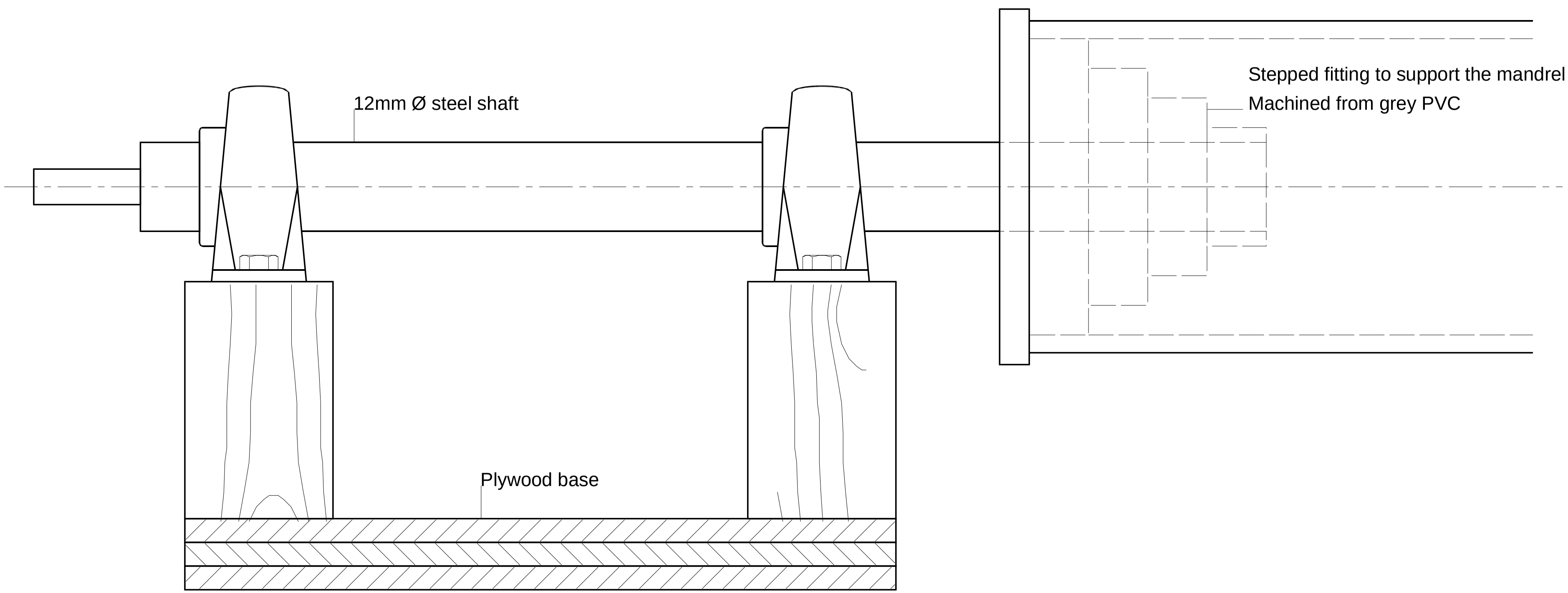


Fig 2

PRE PREG STRIPPER

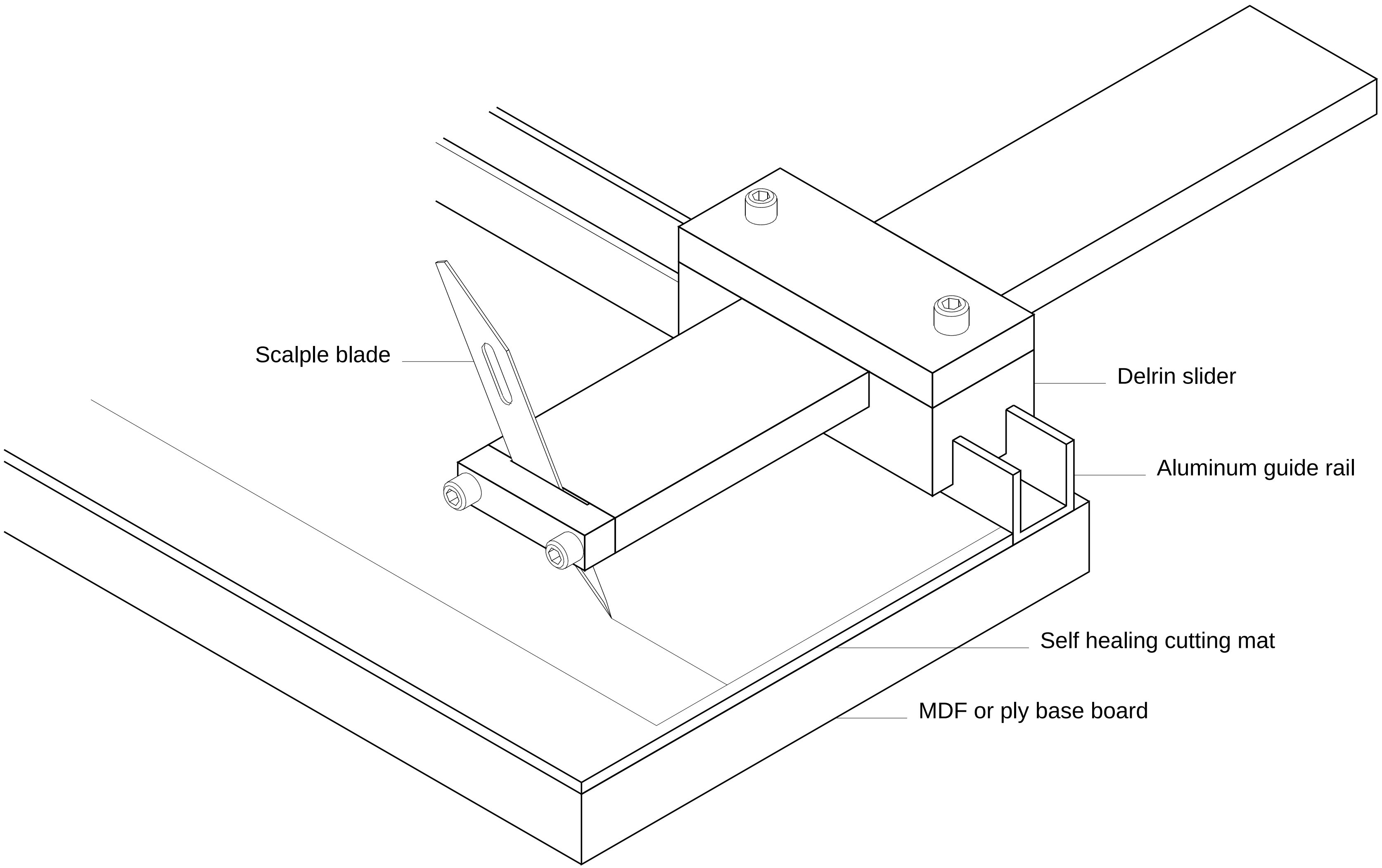


Fig 3

DRAWING SHOWING HOW THE WALL THICKNESS OF THE SPAR SHOULD BE STEPPED
IN THICKNESS TO REDUCE STRESS CONCENTRATIONS

When the wall thickness of tubing must be increased in areas of higher stress change the thickness gradually to reduce stress concentration.

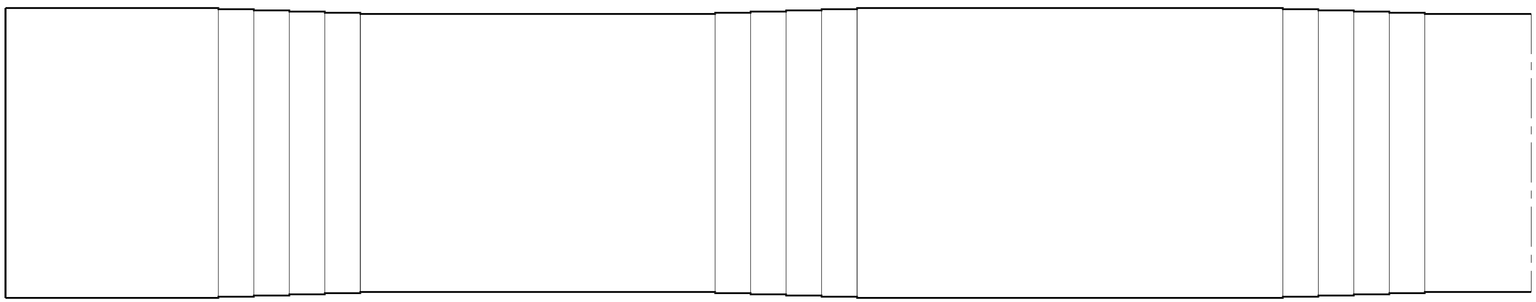


Fig 4

DRAWING SHOWING HOW THE UNSYMMETRICAL LAMINATE USED IN THE SPAR BEAM DISTORTS THE TUBE TO AN OVAL CROSS SECTION

This is the main reason that it is difficult to extract the mandrel from the complete spar. (The drawing is exaggerated.)

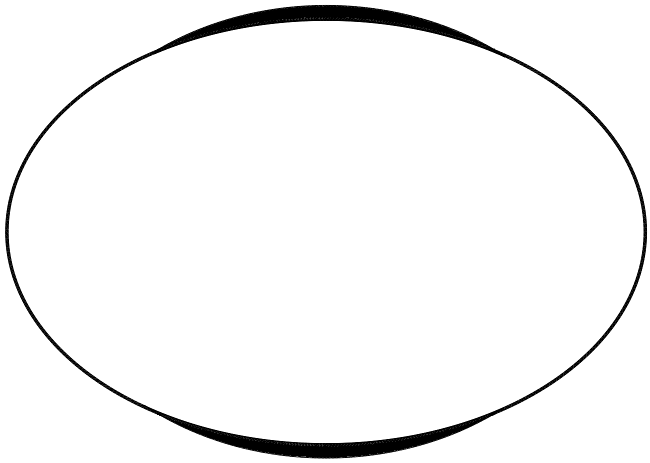


Fig 5

Airglow WING PANEL JOINTS

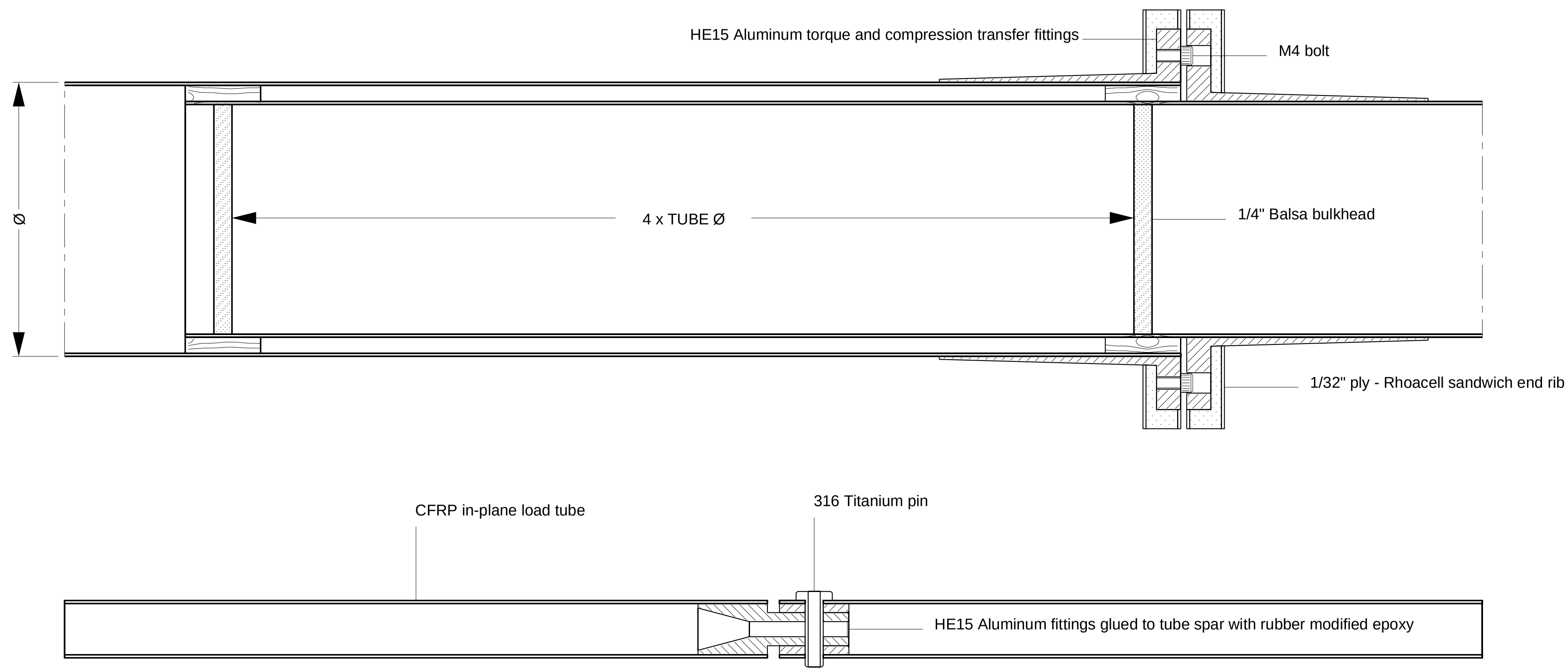
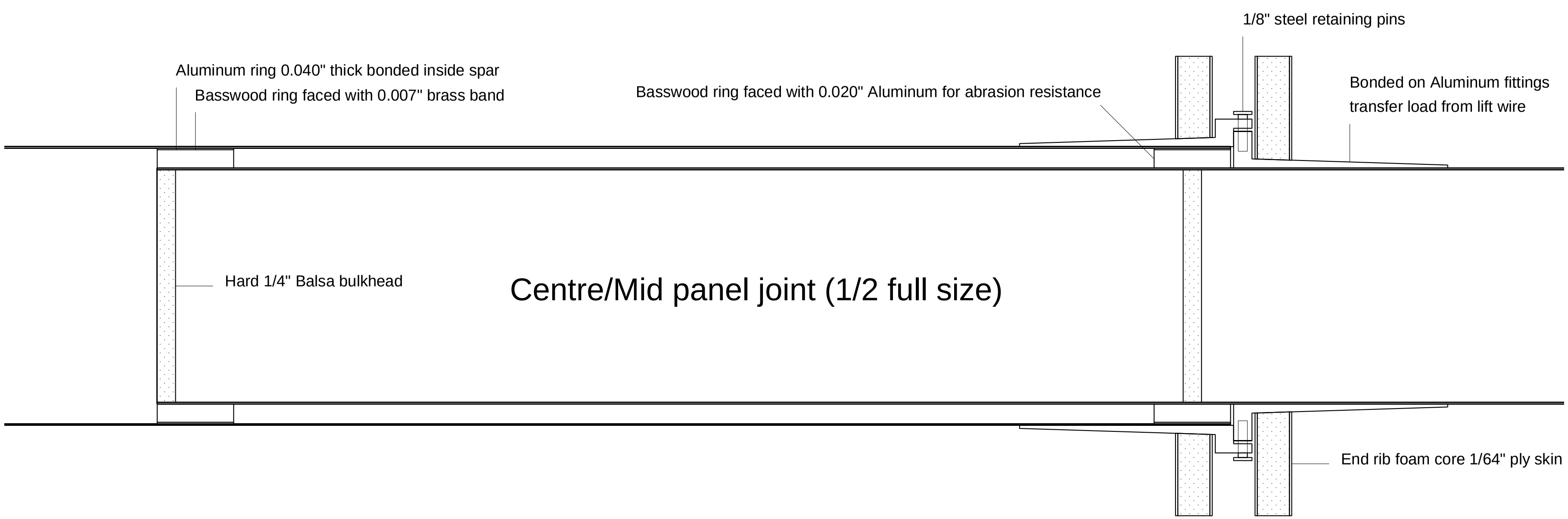


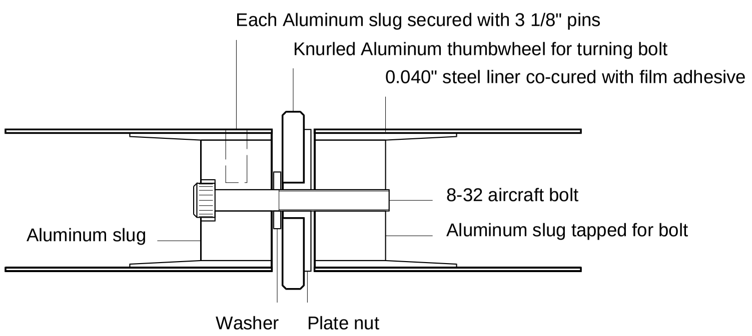
Fig 6

DAEDALUS WING PANEL JOINTS

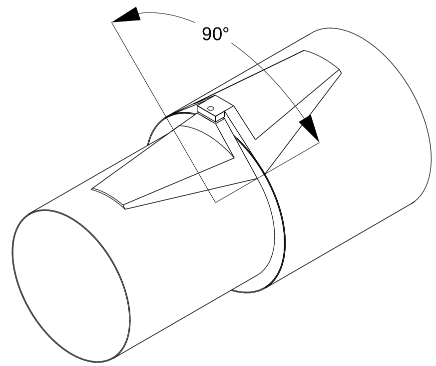
Copied from a drawing by Mark Drela 7 May 1998



Centre/Mid panel joint (1/2 full size)



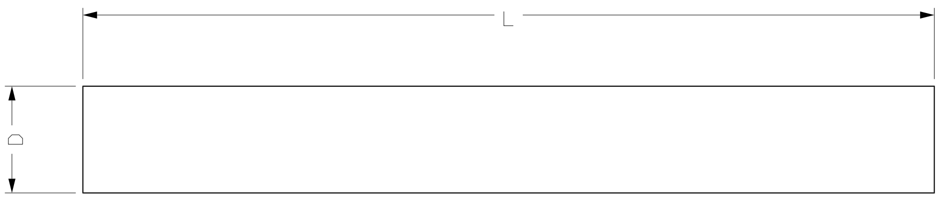
Rear spar joint (full size)



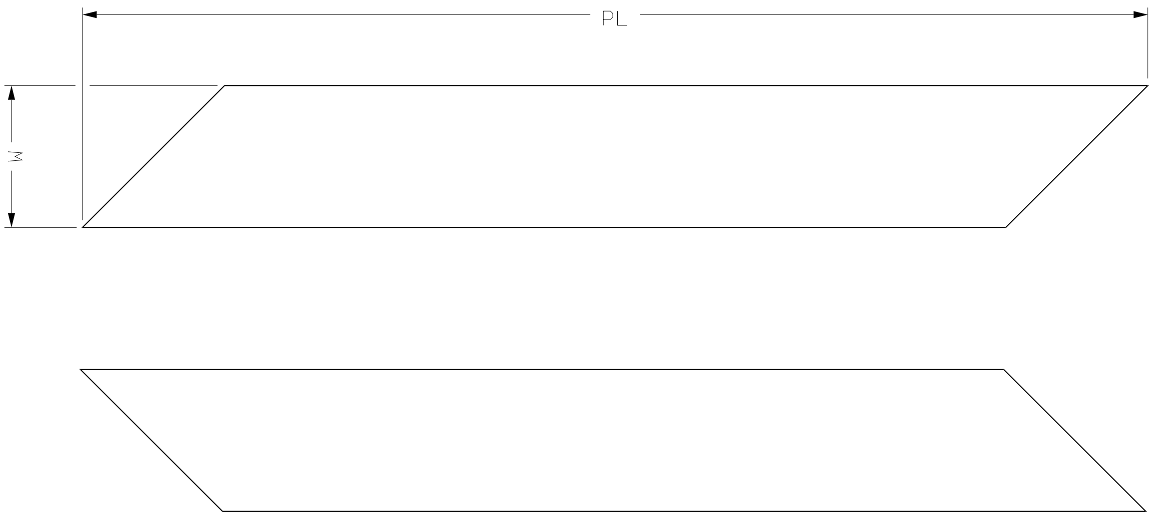
Sketch of Aluminum fitting on top of spar

Fig 7

DRAWING SHOWING HOW TO CALCULATE THE CORRECT SHAPE TO CUT OUT THE SHEAR/TORSION PLYS



Required tube size



Remember that the plys come 'left' and 'right' handed depending on whether they are wound onto the tube at + or - the designed ply angle

Fig 8

LAMINATE CONSTRUCTION OF THE 0° PLYS USED IN THE SPAR FLANGES

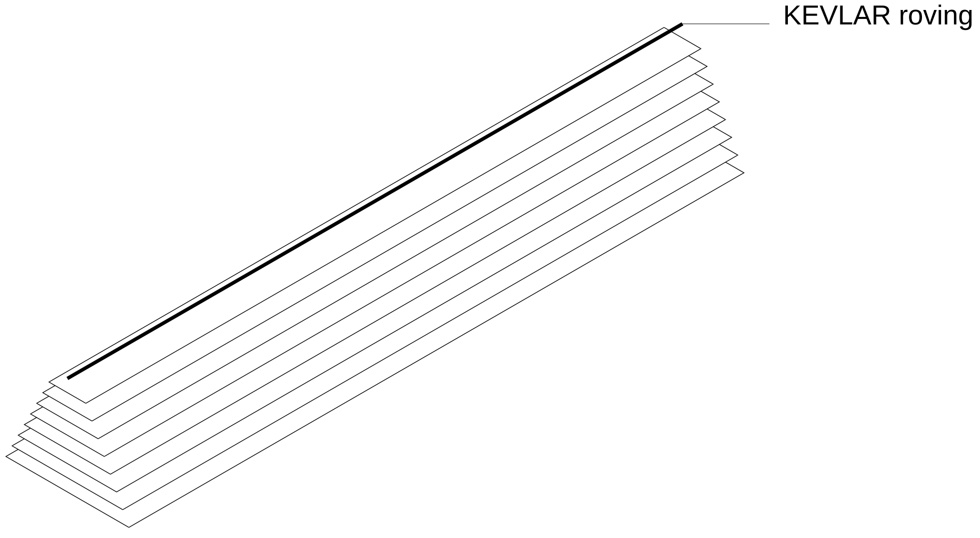


Fig 9

ADDING THE 0° PLYS TO THE SPAR TUBE

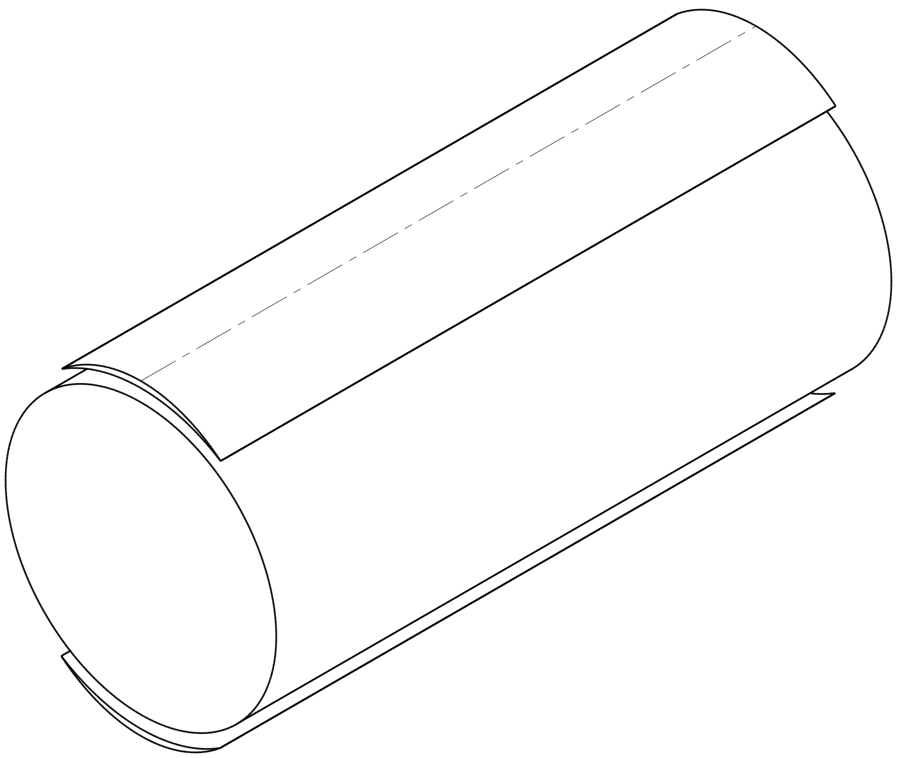
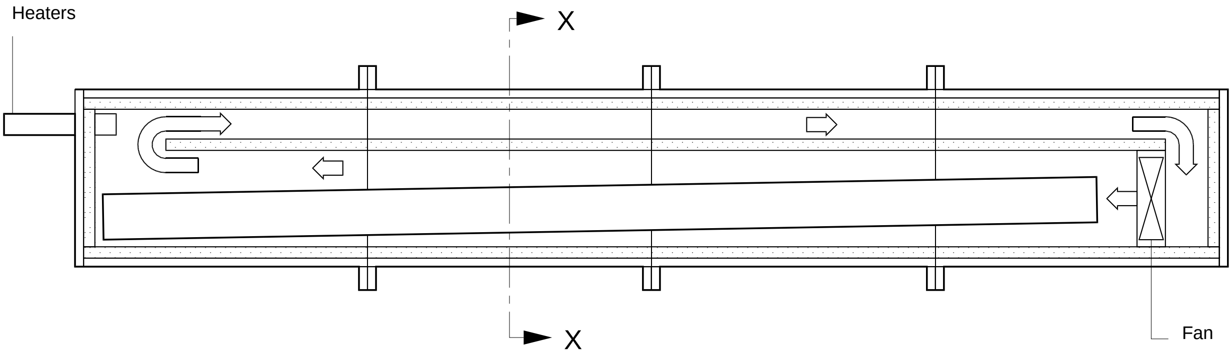


Fig 10

CFRP TUBE CURING OVEN

The oven is built from 12mm plywood lined with 25mm Cellotex 'RR' Aluminum foil faced insulation board. Air is circulated by a fan driven by an external electric motor.
Heating is provided by two 1500 Watt 'hot air guns' controlled by a PID or on/off temperature controller.
- Cellotex 'RR' insulation board is available from insulation suppliers.
- The oven was built in 4 2m sections that bolt together.
- The curing temperature of the pre-preg was 120 degrees C.



SECTION X-X

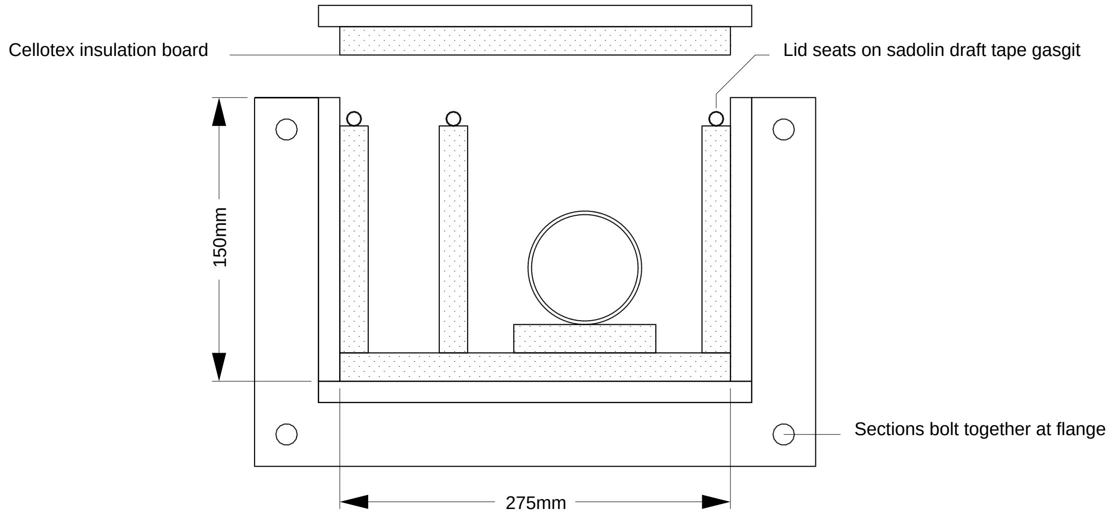


Fig 11

DRAWING SHOWING HOW TO INSERT THE BULKHEADS USED TO MAKE THE SPAR ROUND AND TO STABILIZE IT AGAINST LOCAL BUCKLING

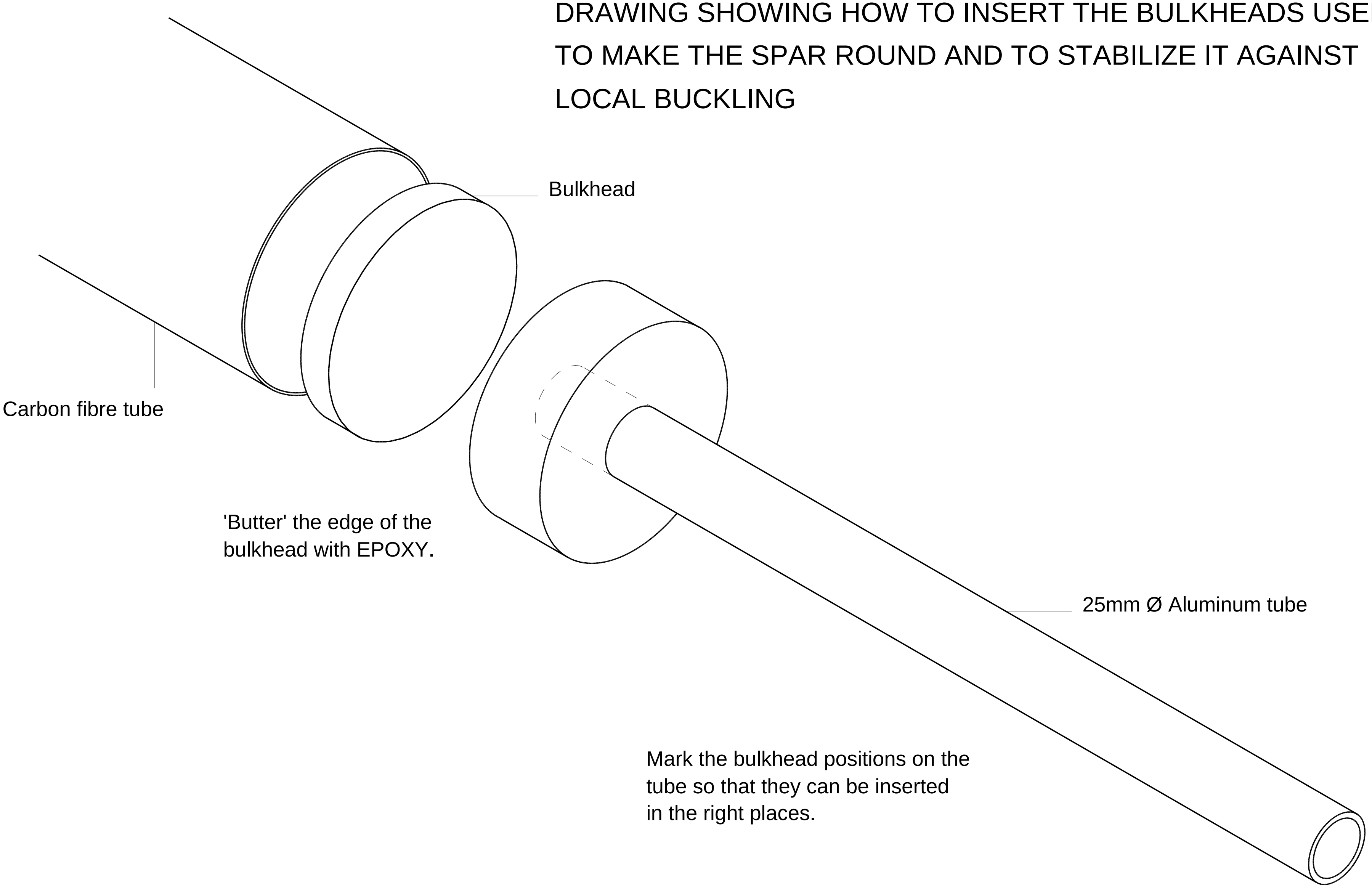
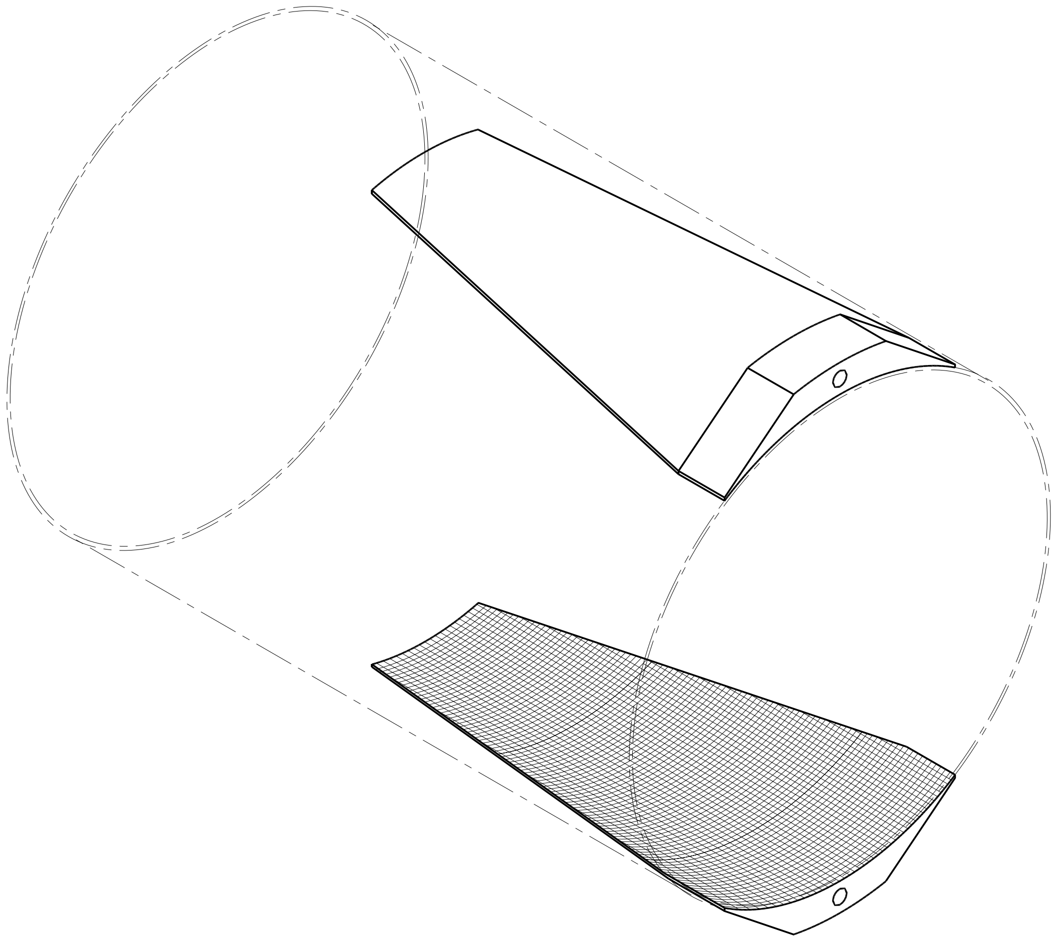


Fig 12

BONDING FITTINGS TO THE SPAR

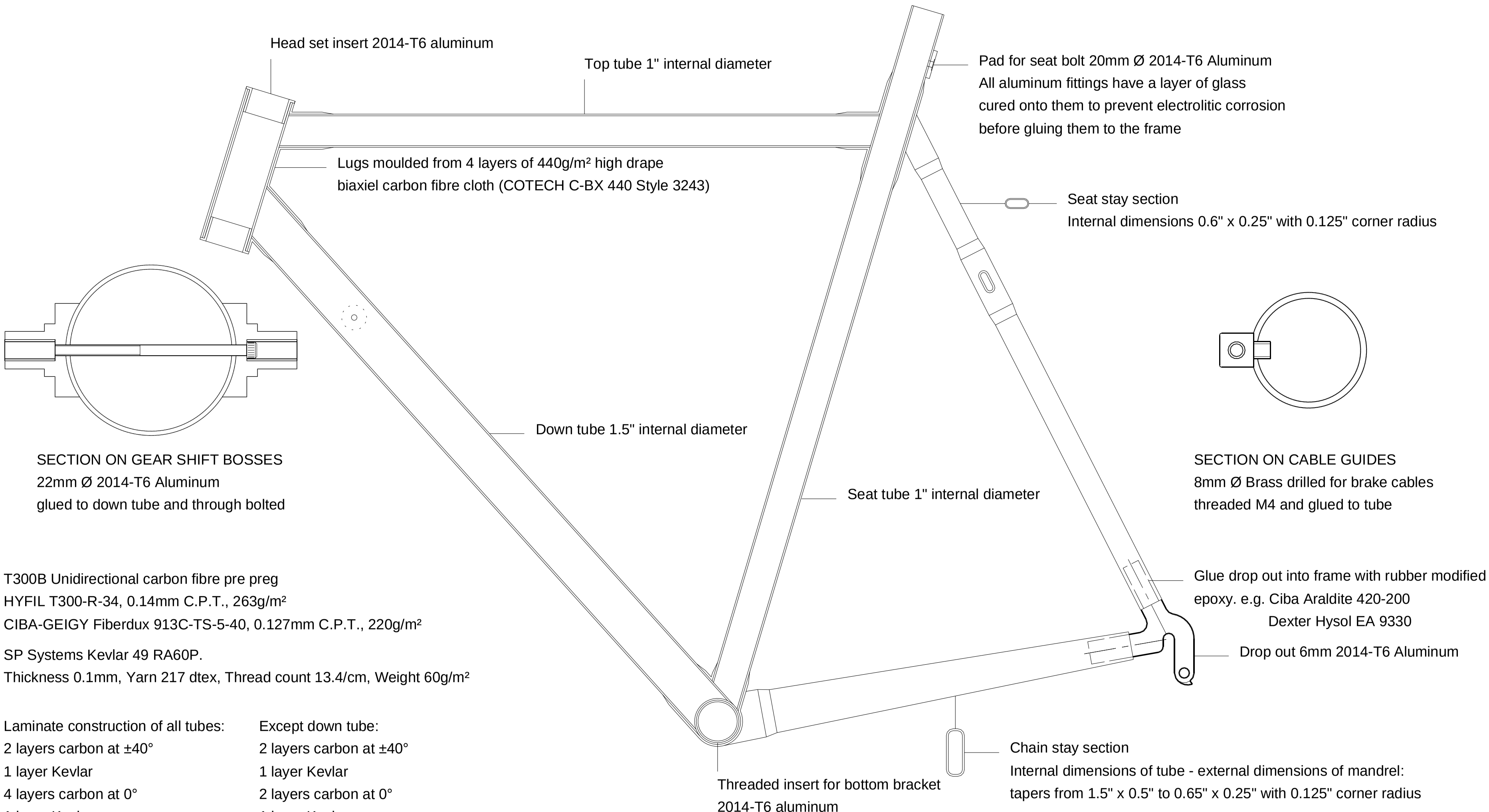


Cure film adhesive on to the Aluminum fittings to electrically insulate them from the carbon fibre tube before gluing them in place with a rubber modified epoxy. Use peel ply when curing the film adhesive to get a good mechanical bond.

Fig 13

CARBON FIBRE BICYCLE FRAME

SCALE 1:5



T300B Unidirectional carbon fibre pre preg
HYFIL T300-R-34, 0.14mm C.P.T., 263g/m²
CIBA-GEIGY Fiberdux 913C-TS-5-40, 0.127mm C.P.T., 220g/m²

SP Systems Kevlar 49 RA60P.
Thickness 0.1mm, Yarn 217 dtex, Thread count 13.4/cm, Weight 60g/m²

Laminate construction of all tubes:	Except down tube:
2 layers carbon at ±40°	2 layers carbon at ±40°
1 layer Kevlar	1 layer Kevlar
4 layers carbon at 0°	2 layers carbon at 0°
1 layer Kevlar	1 layer Kevlar
2 layers carbon at ±40°	2 layers carbon at ±40°
1 'sacrificial' 0° layer of carbon fibre	1 'sacrificial' 0° layer of carbon fibre

Fig 14