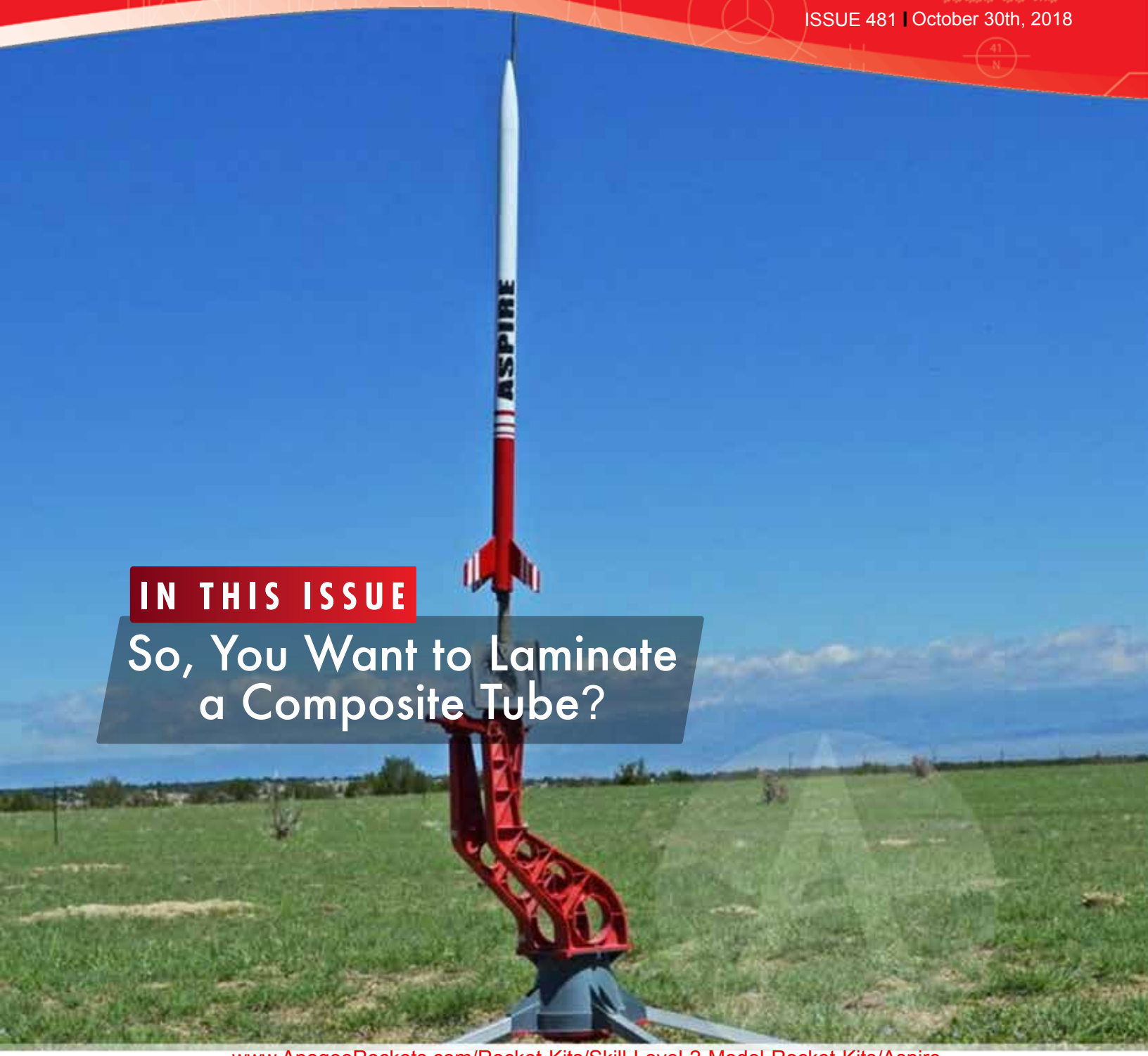
PEAK OF FLIGHT

NEWSLETTER

ISSUE 481 | October 30th, 2018



IN THIS ISSUE

So, You Want to Laminate a Composite Tube?

www.ApogeeRockets.com/Rocket-Kits/Skill-Level-2-Model-Rocket-Kits/Aspire

Apogee Components, Inc.
Your Source For Rocket Supplies That Will Take You To The "Peak-of-Flight"
4960 Northpark Drive Colorado Springs, Colorado 80918 USA
www.ApogeeRockets.com e-mail: orders@apogeerockets.com Phone: 719-535-9335 Fax: 719-534-9050

So, You Want to Laminate a Composite Tube?

By Tomer Simhony

It's the 21st century and composites materials have become ubiquitous. We have gone from using them in niche applications like Formula 1 cars and America's Cup boats to using them in phone covers, sporting equipment, and even toilet seats!

In this article I want to delve into two simple construction techniques to keep your model in the skies rather than being dragged back to the garage for repairs.

1. Perfecting your fibre to resin content ratios
2. Consolidating composite layers together to avoid air entrapment and voids

Background

What is a composite?

A composite material is made from a matrix (e.g. epoxy resin) and reinforcement (e.g. fibre). Composites are known as orthotropic materials, which means that they have different properties depending on your direction of applied loading. This is unlike most metals which are isotropic and so have the same stiffness, strengths, and elongation properties in all directions.

Why use composites at all?

Composite materials can offer many advantages in numerous applications. For a start they are extremely stiff and tough for their weight. **Table 1** shows both the stiffness and the strength, divided by density, of common aerospace materials (these properties are known as specific stiffness and specific strength). As you can see, even once mixed with the relatively weak matrix, a carbon/epoxy composite is leagues stiffer and stronger by weight than any of the commonly used metals.

Where:

- Young's modulus, symbol E, is a measurement of a material's stiffness
- Density, symbol ρ, a measure of mass per given volume
- Specific Stiffness is the Young's modulus divided by the density
- Tensile strength, symbol σ, indicates the force per area a material can accept before failure
- Specific strength is the tensile strength divided by the density

How do rocketeers use composites?

As you are well aware, there currently are no kits available to purchase containing a B motor and a carbon fibre airframe! For low power and medium power rocketry, composites are simply overkill and can be too heavy (not to mention expensive) to consider over paper, cardboard or phenolic tubing.

In high power rocketry…things are a little different. Not only do the rocket loads increase from flying higher and faster, but the search for low aerodynamic drag results in extremely high aspect ratio rockets

Continued on page 3

Material	Young's modulus [GPa]	Density [g/cm3]	Specific Stiffness [$10^6 m^2 s^{-2}$]	Tensile Strength [Mpa]	Specific strength [kN·m/kg]
T700 Carbon Fibre	235	2.15	109	5300	2465
Kevlar 49 (tensile only)	112.4	1.44	78	3620	2514
S-Glass fiber	89	2.5	36	3400	1307
Titanium alloys	112.5±7.5	4.5	25±2	1250	260
Carbon fiber reinforced plastic (70/30 fibre/matrix, unidirectional, along grain)	130	1.6	81	1240	785
Aluminium 7075 T6	69	2.7	26	572	204
Steel	200	7.9±0.15	25±0.5	505	63.1
Balsa	2.3	0.14	21	73	521
Epoxy Resin Newport 301	3.2	1.2	2.6	57.0	46.7

Table 1: Common engineering materials and their properties including corrections for density.

About this Newsletter

You can subscribe to receive this e-zine FREE at the Apogee Components website **www.ApogeeComponents.com**, or by clicking the link here Newsletter Sign-Up

Newsletter Staff

Writer: Tomer Simhony
Layout/Cover Artist: Chris Duran
Proofreader: Michelle Mason

So, You Want to Laminate a Composite Tube?

Continued from page 2

which intensifies bending and buckling loads – thereby requiring very stiff airframes.

As we learned from (**Table 1, Page 2**), composites are uniquely capable of delivering the stiffest and lightest airframes.

Another advantage is that composites are additively manufactured, like 3D printing. This can either be done by hand or by giant filament winding machines (e.g. Boeing Dreamliner or SpaceX BFR), and allows the fabrication of large, continuous structures without the need for welding.

Figure 1 shows fibres loaded in a single direction within the matrix. It is important to consider that brittle reinforcing fibres are much stronger in the direction parallel to the fibre then when loaded transversely to it (this comes from being orthotropic). For example, composites are generally 20-30 times stronger when loaded parallel to the fibre direction than when at 90 degrees to the fibre direction.

Rather than a weakness, in the construction of composites, each layer of fibre can be placed in the orientation that best suits the load directions, leading to a very optimised airframe structure.

What kind of strengths might we achieve using composites?

Engineering for composite materials can certainly be daunting at times, especially when it comes to predicting their point failure. Since composites are made of extremely brittle fibres, there is virtually no deformation (on the order of 0.5 %) before a part catastrophically fails without warning.

To get an intuitive understanding of how a composite material works, it is beneficial to learn about the Rule of Mixtures. This simple theorem (containing many simplifying assumptions) is a good introduction to composite engineering. First, we will need to define what a fibre volume fraction is.

A fibre volume fraction (**Eq. 1 and Fig 1**) is the ratio of fibre volume to matrix volume in a composite. Generally speaking, the higher the fibre volume fraction (i.e. the closer the fibres are packed within the resin) the stiffer and stronger the composite material will be. Typical fibre volumes achieved are shown in **Table 2**.

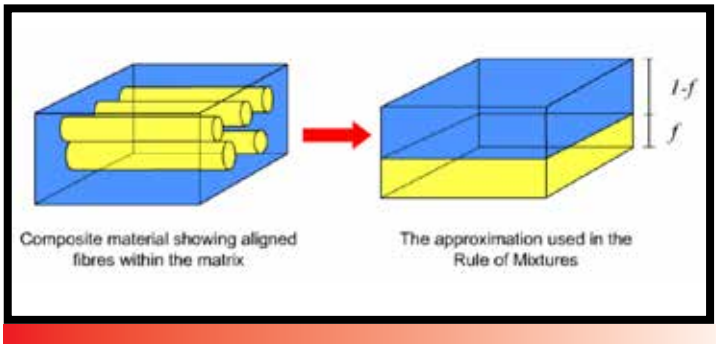


Figure 1: Rule of Mixtures simplification of fibre volume ratio [1]

$$\text{Eq. 1} \qquad \nu_f = \frac{Fibre\ volume}{Total\ volume}$$

$$\text{Eq. 2} \qquad E_{composite} = E_f \nu_f + E_m \nu_m$$

Equation 2 shows the Rule of Mixtures demonstrating the stiffness of a composite based on the volumes and stiffnesses of fibre and matrix respectively. In fact, other properties such as ultimate failure strength, density or many others can all be found by substituting "E" for the parameter of interest. This simple equation is incredibly powerful in determining the basic properties of any combination of two separate materials!

Let's test it out by comparing how a glass-epoxy laminate with fibre volume fraction of 0.6 stacks up against the venerable Aluminium 7075.

Continued on page 4

Check out our Facebook page
www.facebook.com/ApogeeRockets

So, You Want to Laminate a Composite Tube?

Continued from page 3

Solution:

Fibre volume fraction, $\nu_f = 0.65$

It follows that the matrix makes up the rest of the volume, so $\nu_m = 1 - \nu_f = 1 - 0.6 = 0.4$

From **Table 1** (**Page 2**), Young's modulus of glass fibre and Newport 301 epoxy resin are 89 and 3.2 GPa respectively.

The stiffness of the composite is therefore:

$$E_{composite} = E_f \nu_f + E_m \nu_m$$

$$E_{composite} = 89 \times 0.6 + 3.2 \times 0.4 = 54.7\ GPa$$

To find the density of the composite, we need to perform the equation again.

$$\rho_{composite} = \rho_f \nu_f + \rho_m \nu_m = 2.5 \times 0.6 + 1.2 \times 0.4 = 1.98$$

The density is 1.98 g/cm^3, therefore the specific stiffness is 27.6 $10^6 m^2 s^{-2}$.

In comparison, your homemade glass composite tube is 6% stiffer than the aerospace grade AL 7075 T6, without requiring any welds or fasteners! As an exercise to prove you understand the concept, you can repeat the steps above to determine the Tensile Strength of a Kevlar-Epoxy composite of $\nu_f = 0.65$

Answer = 2370 MPa

As can be seen in the examples above, the fibre volume fraction is a critical metric in the properties of the composite part. A lot of time and effort has been devoted over the last 50 years to improve fibre volume fractions' contents through innovative composite construction techniques.

1. Fibre wet out

In the composites world, there is little room for artistic flair with regards to mixture ratios. If you have either too much or too little resin you will get a weaker product liable to fail without warning. Luckily there is a way to calculate the exact amount of resin required so you never have to guess again.

As can be seen in **Table 2**, the fibre volume fraction varies greatly depending on construction method. These are the main composite construction techniques that we should be aware of before going any further. I will explain how each of these methods can be used to make a simple composite plate (which can be used for fins, bulkheads, flaps or whatever your mind dreams up!)

Method	Typical max. ν_f
Hand lay-up	0.4-0.5
Vacuum Bag	0.6
Infusion	0.6-0.65
Prepreg/Autoclave	0.65-0.72

Table 2: Fibre volume fractions achievable through common construction methods [2]

Hand lay-up

Composite construction in its simplest form. To make our flat plate, one lays a single dry fibre layer (known as lamina) onto a flat table with mould release. Laminating resin is mixed thoroughly with its hardener and poured onto the lamina and spread evenly, ensuring there are no dry patches. Resin is normally spread with a soft squeegee, paint brush or roller depending on its viscosity (thickness).

Hand lay-up has the advantage of being the cheapest and easiest construction methodology. No consumable products or operation of pumps are required which also makes it a fast method. Its disadvantages are the inconsistency of the laminators and the ease of which air bubbles and distortion of fibres occur. This results in a low fibre volume fraction and therefore a weaker final product.

Continued on page 5

Join Tripoli.org
Mention Apogee Components

So, You Want to Laminate a Composite Tube?

Continued from page 4

Vacuum Bagging

Vacuum bagging is such a proven and effective technique that it features on all the following construction methods. The basic idea is to increase the quality of the composite part by compressing it after lamination is over, by using the weight of the atmosphere! So how to achieve the entire weight of the atmosphere? As the name suggests, one seals a bag around the perimeter of the laminate with one hole which is fed into a vacuum pump. The pump evacuates the air inside the bag, which compresses the laminate under 14.7 psi or 1 bar of pressure.

To stop the resin from being totally sucked out of the composite and into the vacuum pump, several consumable layers (i.e. layers that are thrown away after curing is complete) are needed. These layers are designed to slow down the resin suction, ensure vacuum is carried everywhere evenly, and to soak up any excess resin that makes its way to the top of the laminate so that a resin rich layer is not formed.

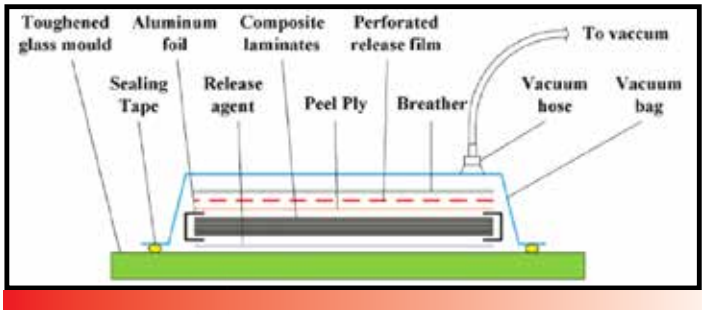


Figure 2: Vacuum bag set up with consumable layers [3]

The compression achieved in vacuum bagging forces out any voids and flattens wrinkles or bridging that can occur over complicated moulds which greatly improves the fibre volume fraction and therefore strength of the plate. Importantly, it also improves the toughness of the laminate by reducing the voids which cause failure points.

Infusion

Infusion is the most elaborate methodology commonly used in composite construction. It has many critical variables that need to be characterised and planned for in order to achieve good quality parts. The principle of infusion is to draw resin through a dry fibre stack with a vacuum pump as shown in **Figure 3**.

Variables required to achieve a consistent fibre volume fraction throughout the entire part include: resin viscosity, resin cure time, laminate thickness, lamina orientation, number and position of inlets/outlets, the amount of resin in each inlet bucket, consumable layers to help distribution, mould leakage and the list goes on…

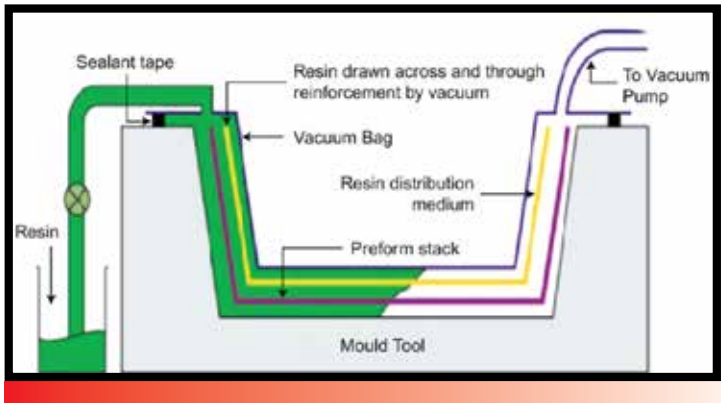


Figure 3: Infusion process. Preform stack refers to a dry fibre laminate, while resin distribution medium is likely three or four different consumable layers. [4]

Infusion processes have only marginally higher costs than conventional vacuum bagging and can achieve higher fibre volume fractions. For homemade composite parts, the added complexity is rarely worth the steep learning curve until parts can reliably be made to a high standard and so this one is better left for the professionals.

Prepreg/Autoclave

Prepreg construction is the top of the line when it comes to composite construction. Prepreg is a portmanteau (a word formed by merging the sounds and meanings of two different words) of pre-impregnated fibre which means that the resin and fibre are already combined before you begin laminating. Not only

Continued on page 6

So, You Want to Laminate a Composite Tube?

Continued from page 5

is the resin impregnated within the fibre, but the hardener is as well! This resin has some special characteristics such as a high viscosity and very slow cure time at room temperature. Chemistry can't be denied for long however, so prepreg composites are kept frozen at -19°C (-2.2°F) until needed and have a shelf life of about one month.

Prepreg construction is almost always combined with vacuum bagging and autoclave curing. An autoclave is a pressurised oven with a maximum internal pressure typically around 5-6 bar. As I will explain later, this extra consolidation helps to eliminate failure through crack propagation by reducing voids.

The primary advantages of prepregs is their ease of lamination. They are slightly tacky which helps stick them down to the surface of your mould or mandrel, they do not fray when cut, which makes the final product much more aesthetically pleasing, and the resin is already perfectly mixed in without possibility of human error or troublesome exotherming. The major downside of prepreg is their cost of fibre and equipment such as autoclaves, their limited shelf lives and their necessary heat cure (minimum of 180°F/80°C).

DIY Resin Calculations

Although fibre volume is a handy metric in design, it is much easier when building to measure weight rather than volume, and therefore a weight fraction is more practical.

$$\text{Eq. 3} \quad \omega_m = \frac{\rho_m \nu_m}{\rho_m \nu_m + \rho_f \nu_f}$$

Where density is given by the Greek letter rho, ρ, the volume fraction is given by the Greek letter nu, υ, while subscripts m, and f refer to matrix (aka resin), and fibre respectively. The equation states that the weight fraction of the resin in the composite is just a percentage of the total weight (density times the volume) of the composite.

Noting that the fibre and matrix together make up the entire composite ($\nu_f + \nu_m = 1$), **Equation 3** becomes **Equation 4**:

$$\text{Eq. 4} \quad \omega_m = \frac{\rho_m(1-\nu_f)}{\rho_m(1-\nu_f) + \rho_f \nu_f}$$

Using the matrix weight fraction, the final weight of resin can be figured out for a calculated matrix weight fraction and given fibre weight using **Equation 5**.

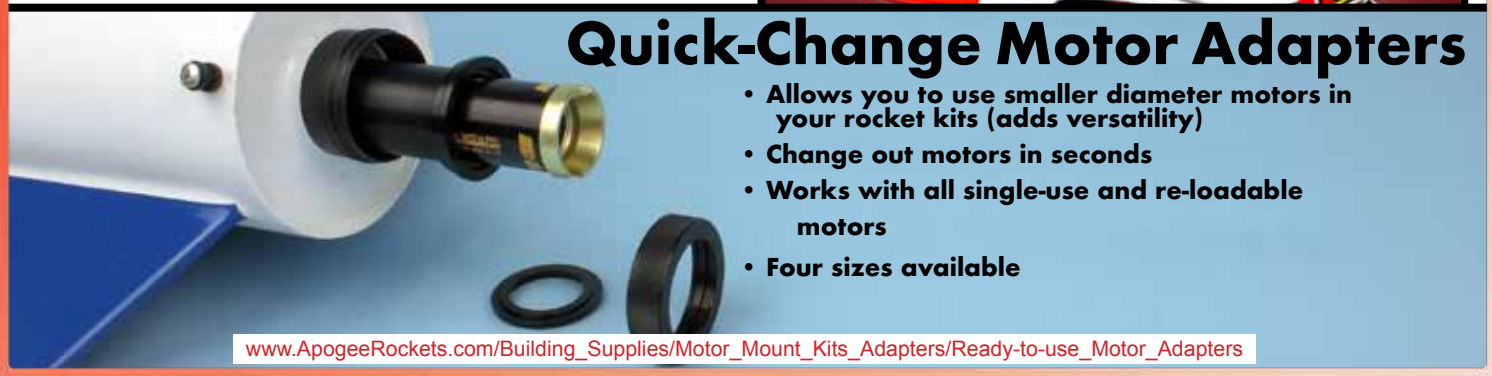
$$\text{Eq. 5} \quad W_m = \frac{\omega_m W_f}{1-\omega_m}$$

Let's put this in practice. After setting up your mould (aka as mandrel) with appropriate mould release such as PTFE tape, cut lengths of carbon cloth and wrap them around the mandrel until your desired laminate thickness is achieved. Carefully remove the fibre and weigh it to figure out the exact weight of resin to mix!

For example: Your resin density is 1200 kg/m^3 and you have splurged on carbon fibre of density 1800 kg/m^3. You do not own a vacuum pump and so you are using the hand lay-up method (**Table 2**), therefore, you are shooting for a fibre volume fraction of 0.5. Plugging in these values to **Eq. 3** gives a matrix weight fraction of 0.4. You have removed the fibre from your mandrel after trimming it to length and found it to weigh 120g. Using **Eq. 4** gives the resin weight to be 80 g.

Caution: **Equation 4** calculates the total resin weight. This must be split into resin and hardener according to the manufacturer's exact specifications. A typical 4:1 mix results in 64 g of resin and 16 g of hardener.

Continued on page 7



So, You Want to Laminate a Composite Tube?

Continued from page 6

2. Consolidation

Consolidation is extremely important in maximising the longevity and fracture strength of your project. Each tiny void is a potential crack propagation site! Consolidation is the compression of the composite layers onto the surface of the mould to eliminate air entrapment. We can actually compress our lamina onto our mandrel from both directions if we use a bit of trickery.

Figure 4: Peel-ply absorbing laminating resin [5]

For thicker laminates, I would add a consumable layer to the end of my laminate which is called Peel-Ply.

Peel-Ply (**Figure 4**) is an absorbent cloth which does not adhere to epoxy and is widely used in the composite manufacturing world as the last layer in a laminate. Removing the Peel-Ply removes a lot of excess resin which makes sanding much faster!

To compress the lamina from the outside, my tip would be to wind plastic around the mandrel being careful not to distort the fibres. By using a 1" strip, we can wind around our mandrel in a self-overlapping way, which presses the carbon tightly onto the mandrel.

But how can we compress the lamina from the inside, you ask? The secret is heat and a bit of material science. Unlike Tim, my preferred mandrel material is aluminium, not steel! The reason is the thermal expansion coefficient of these materials. Most materials expand upon being heated. However, we can exploit that not every material expands at the same rate. What Table 3 shows is that an aluminium mandrel will expand between 1.5 and 6 times more than a carbon weave when heated. Units are in inch / inch F° but are not as important as the comparison.

Material	Coefficient of Thermal Expansion, α.
Steel	7
Aluminium	13
Kevlar	< 3
Carbon Woven Cloth	< 2
Carbon Uni directional	-1 to 8
Fibreglass	7 to 8

Table 3: Coefficient of Thermal Expansion for different materials [6]

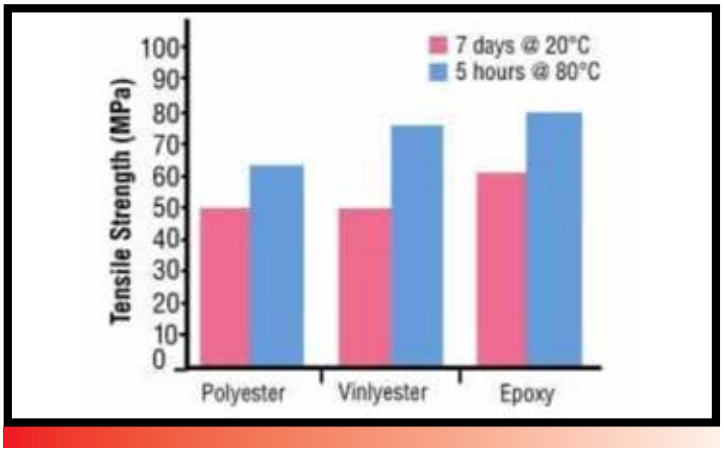


Figure 5: Temperature is vital in maximising matrix strength [7]

Continued on page 8

So, You Want to Laminate a Composite Tube?

Continued from page 7

All this expansion will occur against our tightly wrapped laminate on the outside of the mandrel, pushing the fibres closer together and hopefully stretching any misalignment back into beautiful straight unidirectional fibres.

Figure 5 (**Page 7**) is yet another reason to heat your part during its cure. This shows a typical epoxy energy barrier where it will not fully cure regardless of time, if the temperature is not sufficiently high.

To heat your composite part safely, ensure you are using a high-temp resin (NOT 5-minute variants). A regular home heater can be placed inside a makeshift tent to cure the resin at an increased temperature. Ensure the heater does not touch the sides of the tent and maintain close supervision. As **Figure 5** shows, temperature is much more important than time in determining our matrix strength.

The advantages of curing your part with heat are numerous and substantial.

1. The resin will cure at a high temperature, vastly improving its strength (**Figure 6**).
2. The composite will be consolidated from within, pushing out voids and improving toughness.
3. The composite will cure at the expanded position of the mandrel; upon cooling the mandrel will shrink, leaving a small gap between it and the laminate. This will make removing the tube much easier!

Composites offer distinct advantages over traditional engineering materials in the application of high-power rocketry yet are inherently more difficult to work with. In this article I have introduced simple analysis techniques such as the Rule of Mixtures, briefly commented on advanced construction techniques, demonstrated how to calculate the perfect amount of resin for a given fibre volume ratio and discussed the importance of proper consolidation and some techniques to practically achieve it on a mandrel tool.

Figure 6: Mandrel wound, thin-walled composite tube [8]

Fortunately (or unfortunately!) this is just the tip of the iceberg when it comes to composite analysis and design. There is a lot of science and construction techniques to learn before perfecting your first composite parts, but don't let that stop you! The best way to learn is to try, fail and try again!

Figure 7: Cheap heat tent made from plastic [9]

Continued on page 9

So, You Want to Laminate a Composite Tube?

Continued from page 8

About the author:

Tomer is a Composite Design Engineer at a marine company based in Auckland, NZ with a passion for things that go fast, optimising design, and teaching. He loves mental and physical challenges in the form of outdoor sports, rocketry and playing music.

Got any questions? Want some more reading resources? Please email him at tomer.simhony@gmail.com

[1] Rule of Mixture
https://www.doitpoms.ac.uk/tlplib/bones/derivation_mixture_rules.php
[2] Fibre Volume Fractions
http://www.tecnologiadematerias.com.br/mt/2015/cobertura_paineis/nautico/apresentacoes/barracuda.pdf
[3] Vacuum Bagging
https://www.researchgate.net/publication/281521950_Effects_of_temperature_profiles_of_microwave_curing_processes_on_mechanical_properties_of_carbon_fibre-reinforced_composites/figures?lo=1
[4] Resin Infusion
https://www.nal.res.in/en/techniques/vacuum-enhanced-resin-infusion-technology
[5] Peel Ply
http://buildingkira.com/2010/04/
[6] Coefficient of Thermal Expansion
https://www.christinedemerchant.com/carboncharacteristics.html
[7] Resin Cure vs Temperature
https://netcomposites.com/guide-tools/guide/resin-systems/strength-stiffness/
[8]
https://watersportsadventure.en.alibaba.com/?spm=a2700.details.cordpanyb.1.4ab8d464HuO1qY
[9] Heat tent
https://www.clcboats.com/shoptips/epoxy_and_fiberglass/epoxy_cold_weather.html

Figure 8: Author Tomer Simhony