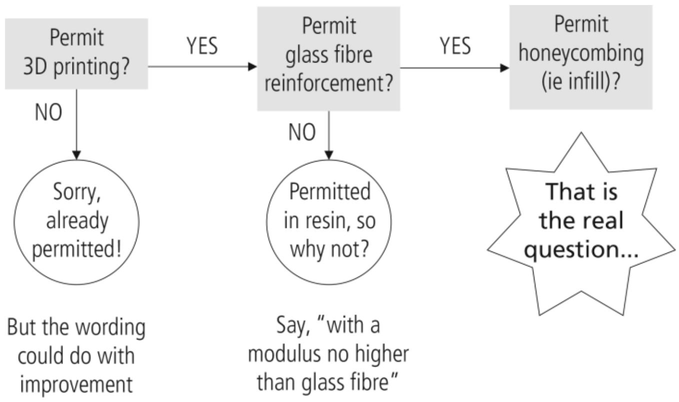
The laws of physics

The question

Some think that glass fibre is currently permitted in 3D printing. Not so. The recent interpretation noted,

*"The fact that the resin (listed in CR D.2.1(a)(3)) may be reinforced with glass fibres means that resin may include glass fibres **but does not mean** that glass fibres are permitted in thermoplastic material. "*

Hence, we begin by assuming that we wish to permit g/f reinforcement in 3D printing filament, and that the real question that needs answering is whether we wish to permit 3D printing where "infill" is less than 100%, that is, honeycombing.



Modulus

The following figures are the E values, modulus of elasticity, quoted in GPa, that reflect the stiffness of various fibres and filament materials. E values do not represent strength, strength to weight, or stiffness to weight, a separate calculation is needed for that, but E is where we'll start.

Material	E
Nylon	2
PLA + 20% wood	2
ABS	2
PLA	4
Nylon + 20% g/f	4
Nylon + 20% c/f	5
Nylon6 + 20% c/f	10
Wood	10
Aluminium	70
D Glass	55
E Glass	72
S & S-2 Glass	89
Dyneema	110
Kevlar	130
Carbon - high strength	230-240
Carbon - intermediate modulus	290-310
Carbon - high modulus	350-400

Honeycombing

Honeycombing and foaming (same idea) is a way to improve stiffness for a given weight over the "solid" version. In addition, a sandwich hull – foamed or honeycombed core – is far more resistant to impact and puncture damage than a single skin hull. That is why honeycombing is such a sensitive topic when looking at IOMs.

Comparison

Let's compare a hull moulded in pre-preg S-glass with a hull 3D printed in nylon with 20% glass fibre infusion. This is a current, generally available, and inexpensive filament with the highest modulus of any that has g/f reinforcement. It is also relatively light (low density) for a thermoplastic.

We compare (a) a pre-preg S-glass moulded solid panel with (b) a g/f nylon 3D printed 'vase' (solid) panel and with (c) a g/f nylon 3D printed honeycombed panel, that is, with 20% infill.

The pre-preg S-glass panel is 1 mm thick. The solid g/f nylon panel is around 2.5 mm thick. The honeycombed panel is 3 mm thick with two skins each 0.8 mm thick, giving the honeycomb in a 1.4 mm core. We'll see why these are convenient thicknesses to compare in a moment. You can use any other numbers you like, the results will be in proportion.

The pre-preg S-glass has a modulus E of around 64 (*), and a density of 1.6, while the g/f nylon has E = 4 and density 1.2. The honeycomb core, 20% infill, has a density therefore of 0.24.

We are going to work with an engineering parameter called the second moment of area symbolised "I". The usefulness of I is that it is the engineering measure of the resistance of a panel to being deflected or bent. For our use here, the second moment of area is the second moment of the cross-section of the panel we are thinking about. The second moment of area is in proportion to the cube of the panel thickness, and has an appropriate deduction if the panel is 20% infill because that is 80% fresh air.

Thicker is much stiffer. This is the important point about a honeycombed or foamed panel, because it is the very clever way to get a thicker panel without using extra material. If the panel is twice as thick, it is 8 times stiffer (the thickness cubed).

The parameter "I" for 1 mm S-glass, 2.5 mm solid g/f nylon, and 3 mm honeycombed g/f nylon panels is 0.1, 1.3, and 1.4 respectively. To find the actual stiffness we must multiply I by the modulus E of its material. Hence the actual stiffness of the 1 mm S-glass, 2.5 mm solid g/f nylon, and 3 mm honeycombed g/f nylon panels is 5.3, 5.3, and 5.5. That's why we chose the thicknesses of the various panels that we did, they are more or less identically stiff as expressed by E•I.

The panel weight is interesting. For the 1 mm S-glass, 2.5 mm solid g/f nylon, and 3 mm honeycombed g/f nylon panels, weight is in proportion to 1.6, 3.0, and 1.5 respectively. That's another reason to choose our panel thicknesses. It turns out that the 3 mm honeycombed panel is much the same weight as the 1 mm S-glass, while the solid g/f nylon 2.5 mm panel is more or less twice the weight of each.

Now for the important bit. Stiffness and strength are two different things, and strength is the resistance of a panel to breaking, yielding, or being permanently deformed. It is what we want from our hulls. Roughly, we can take the modulus E of the materials we are using as an indicator of their modulus of strength. Strength is in proportion to the square of thickness, not the cube. So we take I, and divide it by the thickness (**), to get an index of the strength of the panel, and then multiply that by E to get a measure of the actual strength of the panel. For the 1 mm S-glass, 2.5 mm solid g/f nylon, and 3 mm honeycombed g/f nylon panels, their relative strength is in proportion to 10.7, 4.2, and 3.6 respectively.

Conclusions

We can 3D print a nice honeycombed (20% infill) hull in g/f nylon filament with the same stiffness and same weight as a pre-preg S-glass hull but it'll have one third the strength. So this is not going to obsolete the fleet or threaten anyone with a nice g/f hull. This is simply due to the laws of physics.

If we'd like our hull to be just as strong as pre-preg S-glass, it will be 4.3 mm thick and twice the weight.

If we don't want a honeycombed 3D print, the hull in solid (100% infill) g/f nylon 2.5 mm thick is around 40% the strength of the pre-preg S-glass and has similar stiffness at twice the weight. If we want it as strong, then it'll be 4 mm thick and three times the weight.

Notes

(*) Though S Glass is listed as E = 89, when mixed with resin this is discounted to E = 64 for our calculations.
(**) Half the thickness, actually. Apparently, that's the formula.

Laws of physics			Illustrative Values		
			Thin panel solid pre-preg S-glass	Thick panel solid nylon6 20% g/f	Thick panel honeycombed nylon6 20% g/f
material stiffness (modulus)		E	64	4	4
material 0.2% proof stress		s	64	4	4
overall thickness of panel		t	1	2.5	3
core thickness		t(c)	0	0	2.2
skin thickness		t-t(c)	1	2.5	0.8
density of skin		ρ	1.6	1.2	1.2
density of core		ρ(c)	1.6	0.24	0.24
notional I of a solid panel	I	t^3/12	*0.1*	*1.3*	*2.3*
notional I of core	I(c)	t(c)^3/12	*0.0*	*0.0*	*0.9*
notional I of cored panel	I(cp)	I-I(c)	*0.1*	*1.3*	*1.4*
notional E•I (stiffness) of cored panel		EI(cp)	*5.3*	*5.2*	*5.5*
notional weight of skin	w	ρ(t-t(c))	*1.6*	*3.0*	*1.0*
notional weight of core	w(c)	ρ(c).t(c)	*0.0*	*0.0*	*0.5*
notional weight of cored panel	w(cp)	w+w(c)	*1.6*	*3.0*	*1.5*
stiffness/weight		EI(cp)/w(cp)	*3.3*	*1.7*	*3.7*
strength index I/y (y = ½t)		I(cp)/y	*0.2*	*1.0*	*0.9*
relative strength		sI/y	*10.7*	*4.2*	*3.6*

I — second moment of area
measure of resistance to deflection