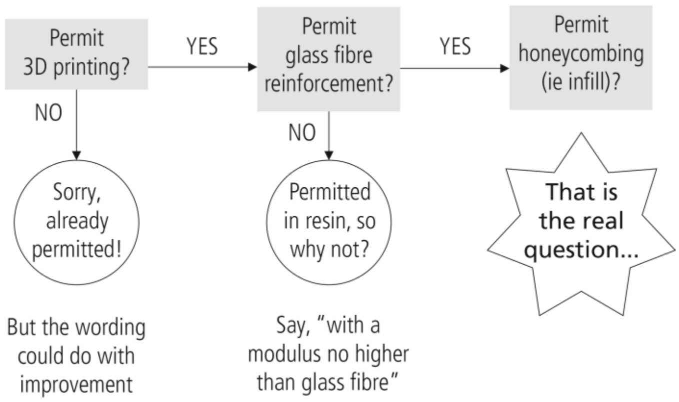
The laws of physics

The question

We begin by assuming that we wish to permit glass fibre 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%, a form of honeycombing.



Modulus

We start with the modulus of elasticity, E, that reflects the stiffness of various fibres and filament materials.

Honeycombing

Honeycombing (and foaming, expanding, micro-ballooning, etc, these are all the same idea of introducing voids into a material) is a way to improve stiffness for a given weight compared with the "solid" material. In addition, a sandwich hull with a 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 A – Normal glass hull vs 3D printed hull

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 normal glass laminate with (b) a 3D 'vase' printed laminate and (c) a 3D printed honeycombed laminate, that is, with 20% infill.

We assume the pre-preg S-glass has a modulus E of around 60 (*), 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.

Let's make the pre-preg S-glass hull 1 mm thick, the 3D 'vase' print hull around 2.5 mm thick, and the honeycombed 3D print hull also 2.5 mm thick, in this case with two skins each 0.8 mm thick and a 20% infill 0.9 mm thick core. These are convenient 'round number' thicknesses to compare.

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 adjustment 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).

To find the actual stiffness we 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 2.5 mm honeycombed g/f nylon panels is 5.0, 5.2, and 5.0. That's why we chose the thicknesses of the various panels that we did, they have very similar stiffness as expressed by EI.

The panel weight is interesting. For the 1 mm S-glass, 2.5 mm solid g/f nylon, and 2.5 mm honeycombed g/f nylon panels, weight is in proportion to 1.6, 3.0, and 2.1 respectively. The solid g/f nylon 2.5 mm panel is more or less twice the weight of the 1 mm S-glass, while the 2.5 mm honeycombed panel is between the two.

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. We want that for our hulls as well as stiffness. 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, and multiplied by E gives us a measure of the relative 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, 4.2, and 3.7 respectively. So the S-glass is 240% stronger than the 'vase' print and 270% stronger than the honeycombed print.

	Input values			**Output values**					
	Glass skin thickness	Core thickness	3D skin thickness	Total thickness	Stiffness	Relative Strength	Relative Weight	Stiffness to weight	Strength to weight
normal' resin-glass	1.0			1.0	5.0	10.0	1.6	3.1	6.3
3D 'vase' print			2.5	2.5	5.2	4.2	3.0	1.7	1.4
3D honeycomb print		0.9	1.6	2.5	5.0	3.7	2.1	2.3	1.7

Conclusions for comparison A

We can 3D print a nice honeycombed (20% infill) hull in g/f nylon filament with the same stiffness and only 30% heavier compared to 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 g/f hull. This is simply due to the laws of physics.

If we'd like our 3D print honeycombed hull to be just as strong as pre-preg S-glass, it will be 4.8 mm thick and 70% heavier. It will be nice and stiff, though, around 180% stiffer.

If we don't want a honeycombed 3D print, a 'vase' printed solid hull 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 3.9 mm thick and 2.6 times the weight. It will be twice as stiff.

Comparison B – Normal glass hull vs glass sandwich with 3D filament or balsa wood

Let's have a look at what might happen if a 3D core was used between two S-glass skins. We'll look at three versions of this sandwich, one where the core is solid filament, one where the core is completely honeycombed at 20% infill, that is, without any 3D printed skin, and one where the core is balsa wood. As before, the 3D filament is Nylon6 with 20% glass fibre infusion. The balsa wood is given E = 10, and density = 0.9.

We'll use thinner glass now, two skins each 0.25 mm thick, giving a total glass skin thickness of 0.5 mm. The solid 'vase' core, the 20% infill 3D core, and the balsa wood core are all the same, 0.55 mm thick. These convenient numbers give us the same or almost the same stiffness as previously, 5.0, 5.0, and 5.1 for the 'vase' core, the 20% infill core, and the balsa wood core.

The relative weights are very interesting, but come with a significant health warning. For the 'vase' core, the 20% infill core, and the balsa wood core, weight is in proportion to 1.5, 0.9, and 1.3 respectively. These are all lower, one much lower, than the 1.6 relative weight recorded for the 'normal' glass hull. The health warning, though, is that these values take NO account of the adhesive which is needed to bond the sandwich core to its skins. But you can see how attractive the honeycombed core looks.

Relative strength is in proportion to 8.2, 8.0, and 8.5 respectively for the 'vase' core, the 20% infill core, and the balsa wood core. This is pretty good and only 20% lower than the 'normal' glass hull.

	Input values			**Output values**					
	Glass skin thickness	Core thickness	3D skin thickness	Total thickness	Stiffness	Relative Strength	Relative Weight	Stiffness to weight	Strength to weight
'vase' sandwich	0.5		0.55	1.05	5.0	8.2	1.5	3.4	5.6
3D core sandwich	0.5	0.55		1.05	5.0	8.0	0.9	5.3	8.6
balsa core sandwich	0.5	0.55		1.05	5.1	8.5	1.3	3.9	6.6

Conclusions for comparison B

The sandwiches are very interesting, they have competitive stiffness, strength, and weight. They ARE going to obsolete the fleet and threaten anyone with a g/f hull, BUT ONLY if the core can be bonded to its skins with negligible adhesive.

Conclusions

Permitting honeycombed (foamed, expanded, micro-ballooned, voided anything, etc) materials in any form of sandwich is likely to be disruptive.

Permitting solid materials in any sandwich looks perfectly safe, as safe as the current permission for wood in a sandwich.

Permitting 3D printed hulls with less than 100% infill seems perfectly safe, the weight penalties to achieve any reasonable stiffness or strength are severe.

Appendix

A downloadable worksheet calculates stiffness, and estimates relative strength and weight, of a laminate made up from any or all of the following components: (A) an outer skin (S- or E-glass, etc.); (B) a variable infill core (3D print using PLA, Nylon6 with 20% g/f, etc); (C) an inner skin to the core (3D print).

Laws of physics

Review the "Instructions and Explanations" worksheet.

Input parameters and values where shown in bold and blue. DO NOT change values in any other cells!

Major output shown in orange.

NB - NO ACCOUNT IS TAKEN of the extra adhesive needed to bond the 3D core and/or the 3D skin to the glass skins in any sandwich.

Item	Symbol	Formula	Components: Outer skin(s) Glass fibre pre-preg	Components: 3D print Nylon6 + g/f Core 20% infill	Components: 3D print Nylon6 + g/f Skin(s)	Resulting laminate Outer skin(s) Inner skin(s) Core	Notes
Illustrative input values						**Output values**	
material stiffness (modulus)	E		**60**	0.8	**4**		1
thickness			**0.5**	**0.8**	**0.6**		3
density	ρ		**1.6**	0.24	**1.2**		4, 5
Calculations							
material 0.2% proof stress	s		*60*	*0.8*	*4*		2
thickness of component as if solid	t		*1.9*	*0.8*	*1.4*		
I as if solid		t^3/12	*0.6*	*0.04*	*0.23*		6
gap between component skins	g		*1.4*		*0.8*		
I of gap		g^3/12	*0.2*		*0.04*		
resulting I	I	(t^3-g^3)/12	*0.3*	*0.04*	*0.19*		
strength index as if solid		t^2/6	*0.6*	*0.1*	*0.3*		8
strength index of gap		g^2/6	*0.3*		*0.1*		
resulting strength index	i	(t^2-g^2)/6	*0.3*	*0.1*	*0.2*		
total thickness of laminate						1.9	
stiffness (EI)		E*I	*20.6*	*0.03*	*0.74*	21.4	7
relative strength	si	s*i	*16.5*	*0.1*	*0.9*	17.5	9
relative weight	w	ρ*t	*0.8*	*0.2*	*0.7*	1.7	
stiffness/relative weight		EI/w	*25.7*	*0.2*	*1.0*	12.5	
relative strength/relative weight		si/w	*20.6*	*0.4*	*1.2*	10.2	

Notes

(1) Young's modulus E, Gpa. Reduced by infill percentage, if any.

(2) Stress parameter for purposes of strength estimates taken as equal to modulus E

(3) Two outer skins, each 0.25 mm thick. 3D print has 0.3 mm inner skin either side of 0.8 mm honeycomb core

(4) Density, g/cm^3

(5) Core density estimated as material density * percentage infill

(6) Second moment of area, a parameter of resistance to deflection, proportionate to thickness cubed

(7) EI, a measure of 'actual' stiffness given the modulus and the thickness of the component

(8) First moment of area, an index of resistance to breaking or failure, proportionate to thickness squared
That is, proportionate to I/t

(9) Relative strength, a measure of 'actual' strength given the index and the thickness of the component

Instructions and explanations

The "Physics" worksheet calculates stiffness, and estimates relative strength and weight, of a laminate made up from any or all of the following components:

(A) an outer skin (S- or E-glass, etc. See note for pre-preg or resin plus glass mat construction)
(B) a variable infill core (3D print using PLA, Nylon6 with 20% g/f, etc)
(C) an inner skin to the core (3D print)

Each component is characterised by three parameters:
(a) E, Young's modulus for the material
(b) thickness of the component
(c) density of the component

Six interesting laminates can be investigated (for a hull):

To estimate stiffness and strength of hull made from:	Component(s)	Set required thickness of:			Set zero thickness for:			Set core infill:
(1) 'normal' resin-glass lay-up	A	glass skin				core	inner skin	n/a
(2) 3D 'vase' print	C			inner skin	glass skin	core		n/a
(3) 3D honeycomb print	B, C		core	inner skin	glass skin			eg 20%
(4) sandwich of a 3D 'vase' print with glass skins	A, C	glass skin		inner skin		core		n/a
(5) sandwich of a 3D honeycomb print with glass skins	A, B, C	glass skin	core	inner skin				eg 20%
(6) sandwich of a 3D 'pure' honeycomb with glass skins	A, B	glass skin	core				inner skin	eg 20%

Note: The worksheet assumes pre-preg glass, where the resin + glass reinforcement is treated as a single component.
It is necessary to estimate the parameters of the whole component if values are only known for its glass reinforcement element.
The guide values for E, below, use 67% E for pre-preg, and 50% E for resin + glass mat. Use any other values as preferred.

Note: Thickness of any skin is the total thickness. It does not matter if this total in fact concerns two skins or only one.
The worksheet assumes that there are two skins for the purpose of Note 3,
but this assumption merely reflects the probable intent of the laminate, it has no effect upon the calculations.

Note: NO ACCOUNT IS TAKEN of the extra adhesive needed to bond the core or inner 3D skin to the outer glass skin in any sandwich.