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Design of laminates by a novel “double–double” layup

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ABSTRACT

We introduce the double–double composite layup method and highlight its advantages over the current industry standard layup method. Proof that the double–double (DD) layup method can significantly reduce the required number of plies in laminates and therefore reduce the weight of composite structures is provided. The 4-ply $[\pm\phi/\pm\psi]$ sub-laminates can also make the design and manufacturing processes simpler and less prone to error compared to conventional (quad) layups. Layup homogenization that makes the novel layup method a viable option by mitigating warpage of non-symmetric laminates is also investigated both analytically and experimentally to prove its effectiveness.

1. Introduction

The ultimate goal with composites is to design lighter structural components without compromising strength or stiffness. Generally, there are three approaches to improve the mechanical characteristics of composites: optimizing the material [1–4], the geometry of the component [5–7] or the internal structure (layup) of the laminate [8–14]. Material design and development is more of a material and chemical engineering challenge, and the geometry of the component is often set by considerations other than just strength and stiffness (e.g. aerodynamics). Therefore, it is the optimization of the internal structure – the layup – where structural engineers and designers should have the greatest freedom and potential to exploit the mechanical advantages of composites. Unfortunately, this is also the design step where engineers significantly reduce their own design freedom by following some outdated design guidelines. As we will show, this does not have to be the way forward. We present a more effective design method that can lead to lighter composite structures.

Since the 1960s most conventional layups that are widely used in the industry (e.g. aerospace or wind energy industries) consist of plies with only four fibre orientations. The so-called “legacy quad”, or simply just “quad” layups have plies of 0°, 90°, +45° and −45°. Using quad is only one of the basic layup design guidelines. Seeking layup midplane symmetry is another one. Symmetry has its clear merits as it inherently prevents any warpage that would come from non-symmetric stress distributions through the thickness of the laminate. Also, there is the “10% rule” that prescribes at least a 10% contribution of each of the quad orientation to the total number of plies [15–17]. There are some serious disadvantages of the conventional layup design method using these guidelines. Firstly, these guidelines dramatically reduce the number of potential layup permutations, and therefore reduce the chance of finding the real optimum. Secondly, even with these simplifications, full optimization can be problematic because of the large number of plies in a real composite laminate that increase the number of possible layup permutations to an extent that even high-performance computers cannot handle. Then come ply-drops, where the designer engineer decides about which plies to drop while maintaining symmetry and trying not to sacrifice too much mechanical performance. So engineering judgement historically plays a significant role in the design process, which should be purely based on mechanics for the best results and repeatability. For better layup optimization and lighter composite structures, a different approach is needed.

Instead of optimizing the layup of the entire laminate in one step, the process can be simplified by optimizing the layup of a sub-laminate and then repeating this few-plies thick unit until the desired total thickness is reached. This approach has some key advantages. Full optimization becomes possible because of the significantly reduced number of layup permutations. This also enables us to consider orientations other than the four quad orientations, which is another step towards finding the global optimum. Furthermore, non-symmetric layups become feasible options when stacking identical units (sub-laminates) of them on top of each other. This is called layup homogenization.

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The idea is that an increasing number of sub-laminate repetitions dramatically decrease the effects of sub-laminate asymmetry (e.g. hygro-thermal warping). An additional advantage of homogenized layups is the simplicity of ply-drop design. Symmetry and location of the ply-drop is no longer an issue, and plies can be dropped in finer increments without changing the mechanical characteristics of the laminate (unlike in case of quads) [18,19].

A promising novel layup method uses so-called double–double laminates (introduced by Stephen W. Tsai), where 4-ply $[\pm\phi/\pm\psi]$ sub-laminates are stacked upon each other [18,19]. This leads to mechanically balanced sub-laminates and an easier layup process. The double–double (DD) layup method can be the first approach to significantly change and improve the conventional composite layup design that remained practically unchanged for the past 60 years. It eliminates many hardships imposed by the quad. Instead of 4 fixed angles, mid-plane symmetry, and the 10% rule, we have the use of unlimited number of angles, natural symmetry through homogenization, and thinner building blocks (sub-laminates). Opportunities not hitherto available include large zones (thus mitigation if not elimination of blending), uniform properties across ply drops, aggressive ply drop one at a time in any location, repair by bonded patch same as base laminate, 1-axis layup with minimum scrap and less prone to error, etc. These laminates outperform today's composites in many ways but most importantly lead to lighter composite structures.

As we move forward in the future, DD can be one of the first changes that composites design and manufacturing will adopt. An extension of the DD is the grid/skin concept that one day can replace the frame/stringer concept that was inherited from the metallic structures. Equally revolutionary was the concept of Tsai's modulus [20] that is making changes in data generation and material scaling among composites [19]. DD, as we see it, can have the same effect and in this article, we wish to point out its importance.

The aim of the paper is twofold. First, we show that discarding all non-symmetric layups in the composite layup design process is an unnecessary simplification. Layup homogenization is presented and studied as a way to overcome issues emerging from the lack of symmetry (e.g. thermal warping). And second, the double–double layup design method as an alternative approach to the conventional quad laminates is investigated. Through examples, we show that we can reduce the required thickness (i.e. fewer plies needed) and therefore the weight of composite laminates using the novel double–double layup technique instead of using the current industry-standard conventional quad layup technique.

2. Layup homogenization

Layup homogenization is the method of repeating identical sub-laminates on top of each other until we reach the desired laminate thickness. This can have multiple benefits. Strength and toughness of the laminate can increase due to the more localized effects of ply-group failure and the better stress redistribution compared to laminates with thicker ply-groups or conventional quad layups. Also, the fewer plies the sub-laminates consist of, the easier the optimization process becomes.

The advantage of homogenization we are focusing on in this paper is its capability of mitigating the unwanted effects of non-symmetric layups. Non-symmetric layups tend to warp (e.g. hygro-thermally), which is the main reason why the industry uses symmetric layups. We show that homogenization is a powerful method to get rid of warping. And with that, the option of working with asymmetric sub-laminates will open new routes for optimizing composite layups, leading to better optimized and therefore lighter structures.

2.1. Plate theory interpretation

Here the effects of homogenization are demonstrated on asymmetric cross-ply laminates with only 0° and 90° plies. The analytical calculations were based on the classical laminate theory and were carried out in MATLAB environment. The ABD compliance matrix values were normalized by the thickness for direct comparability between values from different sub-matrices (α^*_{11} and β^*_{11}) and to avoid any further complications caused by the change in the total laminate thickness when homogenizing the layup. Material data of 0.13 mm thick Hexcel HexTow IM7 UD — HexPly 913 carbon-epoxy prepregs were used for later comparison with experimental results.

Homogenization was carried out by increasing the number of repetitions (r) of a [0/90] sub-laminate. Note, that there is no need to take the change in total thickness into account because of the normalized compliances.

Warpage can be measured and interpreted in many ways. Analytically, there is a simple way to do this by applying uniaxial in-plane tension and taking the ratio of the flexural and the in-plane strains, which equals to the ratio of the corresponding normalized compliance values (β^*_{11} and α^*_{11} accordingly). The result is an index with which the extent of warpage can be quantified. Fig. 1 illustrates the effect of layup homogenization on the extent of warping, based on the analytical calculations. Warping decreases by the negative 1st order with the increasing number of sub-laminates. This means that the more sub-laminates we place on top of each other, the more stable to hygro-thermal stresses the shape of the laminate will be. Even a few repetitions can dramatically reduce warping. For instance, 8 repetitions reduce warping by 85%, based on these analytical results.

2.2. Experimental results

For the manufacturing, the same Hexcel prepreg was used as for the analytical calculations. To achieve the best possible product quality, the flat laminates were cured in an autoclave (7 bar, 125 °C). At this temperature, the laminate is expected to be free of thermal stresses. Five pieces of 150 mm × 150 mm cross-ply laminates were manufactured with different levels of homogenization, but with the same total thicknesses (32 plies, 4.19 ± 0.02 mm) to make them comparable. The five laminates from least homogenized to most homogenized had the following layups: $[0_{16}/90_{16}]$; $[0_8/90_8]_2$; $[0_4/90_4]_4$; $[0_2/90_2]_8$; $[0/90]_{16}$.

To evaluate the extent of warping of each laminate, we 3D scanned their surfaces, imported the measured superficial coordinates into MATLAB, and fitted a surface to them (Eq. (1)). The scannings were carried out at 25 °C, so the temperature difference from the thermal stress-free state was 100 °C. Moisture did not affect the results as it was consistently 15% throughout manufacturing and testing.

$$f(x,y) = p_1 + p_2x + p_3y + p_4x^2 + p_5xy + p_6y^2 \tag{1}$$

where p refers to the parameters (coefficients) of the fitted surface.

To quantify the extent of warping, curvatures were calculated using the first and second derivatives of the fitted surface function. The specimens had double (saddle-like) curvatures and the magnitudes of the perpendicular curvatures were virtually identical (except for their signs). Eq. (2) gives the curvature of the laminate along the x-axis (along one edge of the composite).

$$K(x,y) = \frac{f''_{xx}(x,y)}{\left(1+\left(f'_x(x,y)\right)^2\right)^{\frac{3}{2}}} \tag{2}$$

where K is the curvature, f'_x is the first and f''_{xx} is the second partial derivative of the function *f(x,y)*, by x. The equation would apply to the y-direction (perpendicular edge of the composite) too, but solving for only one direction is sufficient. For simplicity and better comparability between the curvatures of different laminates, y was chosen to be 0.

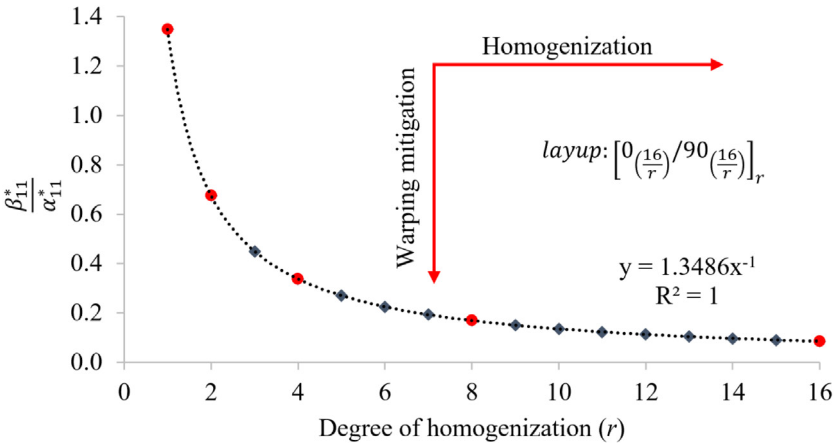

Fig. 1. Warping as a function of layup homogenization — analytical results. Red markers: values for direct comparison with later experimental results.

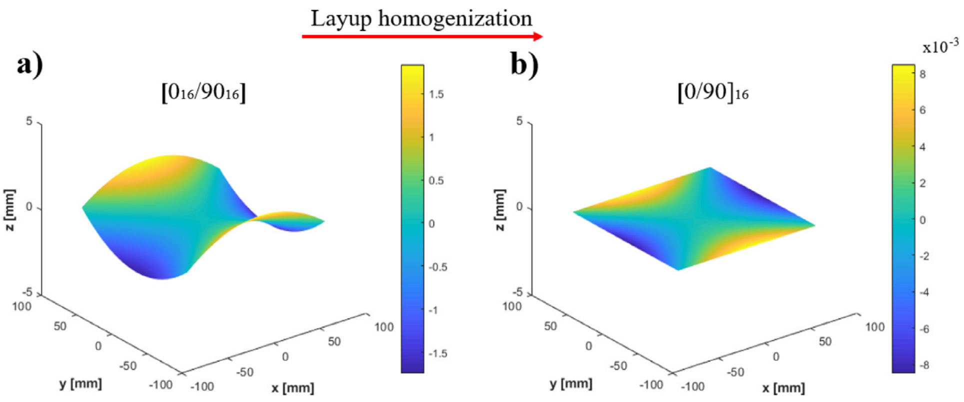

Fig. 2. Fitted surface of the least homogenized (a) and the most homogenized (b) 32-ply cross-ply laminates.

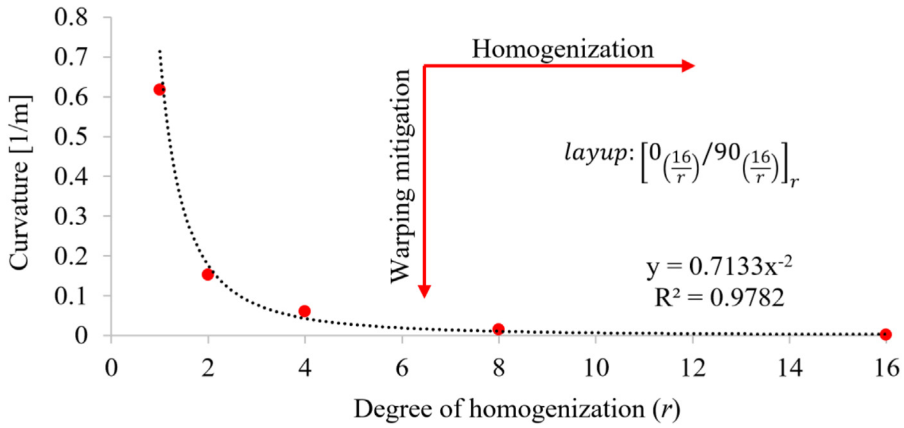

Fig. 3. Warping (curvature) as a function of layup homogenization — experimental results.

This gets rid of the y term. As the rosette was defined to be in the middle of the laminates, the zero y value means that the curvature was evaluated on the xz plane that cuts the laminate in half (halfway along y).

Fig. 2 illustrates how layup homogenization mitigates warping by visualizing the fitted surface for the least homogenized (Fig. 2/a) and the best homogenized (Fig. 2/b) laminates (note the different limits on the legends).

The least homogenized laminate came out from the autoclave significantly warped. The best-homogenized laminate remained flat. Fig. 3 shows the extent of the warping as a function of the homogenization (sub-laminate repetitions).

The results show a dramatic and rapid reduction in warping with an increasing level of homogenization demonstrating the validity and significance of the layup method. The curvatures of the plates change by the negative 2nd order with the increasing number of sub-laminates. This is a much more rapid reduction than what the analytical model predicted, partly because of the different definitions of warping (analytical and experimental) and partly because of the simplifications the classical laminate theory relies on. Warping was mitigated by 75% for only 2 sub-laminate repetitions, by 90% for 4 repetitions, by 97.5% for 8 repetitions and by 99.7% for 16 repetitions. Placing the 150 mm × 150 mm panels on a flat surface, even the third most

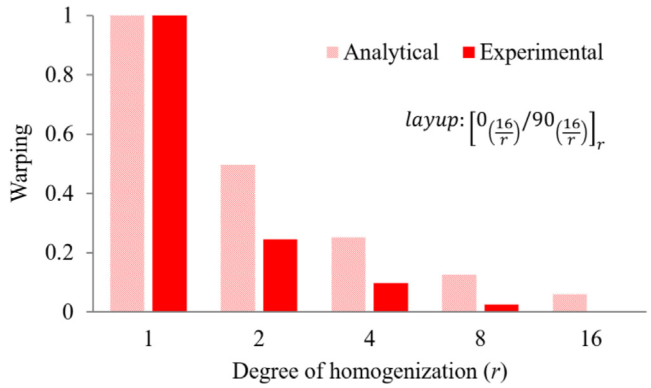

Fig. 4. Warping as a function of layup homogenization — analytical and experimental results. Warping of the least homogenized laminate is unity, all other values are normalized accordingly.

homogenized laminate (with 4 repetitions) could not be differentiated from flat.

Fig. 4 compares the analytical and the experimental results by normalizing the magnitude of laminate warping by the warping of the least homogenized laminate in both cases. The experimentally observed decay of warping was so rapid that warping for the most homogenized laminate (16 repetitions) was not even visualized by the software.

It is clear how powerful layup homogenization is when it comes to warping mitigation of asymmetric sub-laminates. The conclusion is that composite design does not have to be restricted to symmetric composites only. Homogenization enables the selection of asymmetric laminates as optimums without having to deal with the disadvantages normally associated with layup asymmetry.

3. Double–double layups and their advantages

The double–double layup method is a Stanford University innovation (patent pending) utilizing layup homogenization. Double–double laminates consist of 4-ply [$\pm\varphi/\pm\psi$] sub-laminates and offer multiple significant advantages over the current industry standard – so-called quad – laminates with only 0°, 90° and ±45° fibre orientations. In the following sections, we highlight some of the main benefits of double–double laminates.

3.1. Layup design

Designing the layup of a double–double laminate is a two-step process. First, the optimal 4-ply sub-laminate needs to be found that will later be the building block of the laminate. Secondly, the factors of safety (R values) have to be calculated for the part or different zones of the part based on the complex loads and the material properties. From the factors of safety, the required thickness and therefore the number of sub-laminate repetitions can be calculated. When calculated for zones, a full tapering map can be obtained from these results.

The DD design has several advantages over the quad design. We have more freedom with ply orientations, as no orientation is set and each orientation has to compete for its place in the layup. Also, we do not have to worry about layup symmetry. This is because layup homogenization with thin 4-ply DD sub-laminates is very effective even for laminates with only 10–20 plies in total, leading to mitigated warping. Quad layups have much thicker sub-laminates and therefore layup homogenization is not possible for thin laminates, so they have to maintain symmetry. In this paper, we compare 4-ply DD sub-laminates with 6-ply, 8-ply and 10-ply quad sub-laminates, which really are 12-, 16- and 20-ply sub-laminates to fulfil symmetry. Quad laminates also follow the 10% rule, as in the industry.

3.2. Strength and stability

Strength and buckling stability are two key properties of structural materials, so it is important to evaluate those for double–double laminates and compare the results to the strength and stability of quad layups. We developed an analytical tool (Lam search) that finds the strongest laminate (both DD and quad) based on a set of inputs (e.g. material properties and a set of complex loads). The calculations are based on the classical laminate theory (CLT) and the default failure criterion is maximum strain, first ply failure (although other failure criteria can be added, e.g. Tsai-Wu). The analytical buckling calculations are for uniaxial compression of a simply supported rectangular laminate. Buckling calculations can be extended to other loads, e.g. combined compression and shear.

The program calculates strength and stability for all possible double–double layups and all possible quad layups. Six laminate families were optimized and the best performing laminates from each family were compared to each other based on strength and buckling stability:

- Quasi-isotropic quad (QI) - 25% [0°], 50% [±45°] and 25% [90°] as a benchmark
- Quad with 6-ply sub-laminate (6QD)
- Quad with 8-ply sub-laminate (8QD)
- Quad with 10-ply sub-laminate (10QD)
- Quad with user defined field increment (FieldQD) - number of layups depends on the quad field increment in [%]. If quad field increment is 5%, then the laminate can consist of 10%, 15%, …, 85%, 90% [0°] or [90°] plies and the remaining plies are [±45°]
- Double–double with 4-ply sub-laminate (DD) - number of layups depends on the DD orientation increment in [°]. If DD orientation increment is 2.5°, then $\pm\varphi$ and $\pm\psi$ can be ±0°, ±2.5°, …, ±87.5°, ±90°, independently of each other.

The layup optimization tool is a self-developed MATLAB based program with a clean and easy to use graphical user interface. The user can decide about the following inputs:

- Material — moduli, Poisson's ratio and failure values (e.g. max. strains)
- Complex loads - a set of user defined in-plane longitudinal, transverse and shear stress (1–49 load cases)
- Ply thickness, DD orientation increment and quad field increment
- Failure criterion — maximum strain, first ply failure as default
- Random load generation — based on the user defined loads (1–5 main loads), 44 additional loads can be generated, whose stress component values will be between the extremums of the user defined loads. This is a feature for extra safety and can be enabled or disabled.
- Laminate edge length and maximum number of half waves in load direction (for buckling)

Provided the inputs, the tool offers an objective, full and quick (few seconds) analytical layup optimization. The input variations are endless and so are the possible outputs, so in the followings, we present some arbitrarily chosen case study examples to show that double–double laminates can in fact be superior to quad laminates based on strength and stability.

The case studies differ only in the applied complex loads to imitate different composite components. All other input was kept unchanged as follows: material – T300-F934 (Cytec) prepreg, ply thickness – 0.125 mm, DD orientation increment – 5°, quad field increment – 5%, failure criterion – max. strain first ply failure, random load generation – disabled, laminate edge length – 100 mm on both edges, maximum number of half waves in load direction – 10.

Case study 1 – composite shaft

Stress components are defined as unit stress, so their absolute value is unity at most. This way the factor of safety values (R) will represent

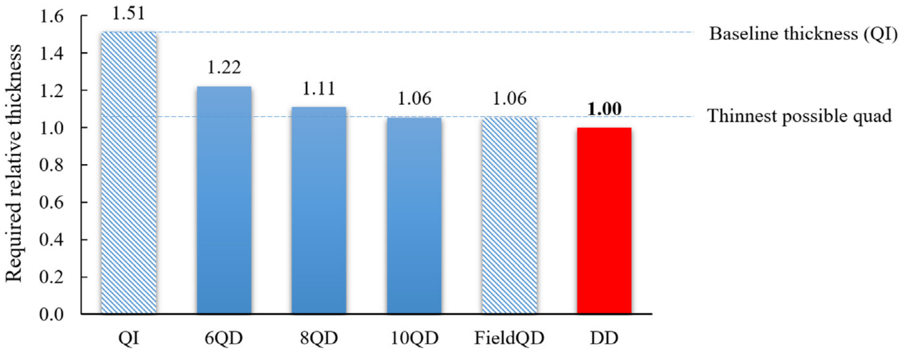

Fig. 5. Required relative thicknesses of the best layups from each layup family — composite shaft.

Table 1
Complex loads acting on a composite shaft, and damaging potential ($R/R_{control}$) of the individual loads compared to the most dangerous (control) load.

Load	σ_1	σ_2	σ_6	$R/R_{control}$
Load 1	0.0	0.0	1.0	0.91
Load 2	0.2	0.0	1.0	1.00
Load 3	0.2	−0.2	1.0	0.94
Load 4	0.0	0.5	0.0	0.87
Load 5	0.5	0.0	0.5	0.78

Table 2
Optimal (strongest) layups from each layup family — composite shaft.

Layup family	Layup of the strongest laminate from family (0°/±45°/90° ratios for quad layups)
FieldQD	10/80/10
QI	25/50/25
6QD	17/67/17
8QD	13/75/13
10QD	10/80/10
DD	[±30.0°/±50.0°]

the strength of the laminate. Table 1 shows five example main loads that are expected to act on a composite shaft (σ_1 - longitudinal in-plane stress, σ_2 - transverse in-plane stress, σ_6 - in-plane shear stress). The last column of Table 1 displays the relative damaging potential of each load compared to the controlling load, which is the most dangerous of all. In this case study, the second load is the controlling load. These values were calculated for the strongest double–double laminate.

Table 2 comprises the optimal layups from each of the six layup family, based on strength (max. strain FPF). The strongest layups are the ones with the greatest factor of safety value calculated for the controlling load in each case.

For the quads, ±45° dominates in each case. The optimal double–double laminate for strength is [±30.0°/±50.0°]. This is close to ±45°, but the difference shows that quads can only approach an optimal layup that much.

Fig. 5 is a comparison graph of the required thickness of the best (strongest) laminates from each layup family, relative to the best double–double layup. Field quad and quasi-isotropic quad are distinguished for a reason. Field quad is more of a theoretical layup family than a practical one. The reason for this is its thick sub-laminates (20-ply thick in this case study) that limit its usage in thin and/or tapered laminates. It is therefore included as a lower (theoretical) limit for required quad-thickness. The quasi-isotropic laminate is the upper limit, although not a theoretical, but a practical one. Required thicknesses for the 6-, 8- and 10-ply quads are expected fall between the thickness values of these two limits or be equal to them, however, thickness values greater than of the quasi-isotropic quad is also possible. The optimal 10-ply quad is stronger than the optimal 8-ply quad, which is stronger than the optimal 6-ply quad. This tendency is not universal but depends on the loads. The last (red) column in Fig. 5 shows the required relative thickness of the best double–double laminate (baseline thickness for best comparability). The required thickness of the best double–double layup is about 6% lower than for the best quad layup, and more than 50% lower than for the quasi-isotropic laminate. This means that for this complex load case, double–double is 6% stronger than quad, or from another perspective, double–double can provide the same strength as the best quad, only at a lower weight (ca. 6% weight saving). Furthermore, these results do not yet consider other factors (e.g. aggressive tapering of double–double laminates) that can further increase the advantage of DD laminates over quads.

Table 3
Required thickness and number of sub-laminate repetitions of the strongest layups from each layup family to withstand loads. NA: not applicable (not practical laminates, only limits) – composite shaft.

Layup	FieldQD	QI	6QD	8QD	10QD	DD
Required thickness [mm]	7.6	10.9	8.8	8.0	7.6	7.2
Number of sub-laminate repetitions	*NA*	*NA*	11.7	8.0	6.1	14.3

Table 3 contains two additional important pieces of information about the strongest laminates from each family: the required absolute thickness to withstand the applied load and the number of sub-laminate repetitions needed to reach that thickness. Generally, the fewer plies a sub-laminate consists of, the better, because then more repetitions are needed to reach the total thickness of the laminate. A greater number of repetitions allows for more effective layup homogenization and tapering. Also, as it can be seen in Table 3, the number of repetitions are not integers, so a round-off is necessary. With more repetitions, the round-off to integer is a much finer increment than in case of only a few repetitions. Furthermore, tapering of the laminate is key for weight reduction, and double–double laminates are superior to quads in that regard, too. More on tapering in the next section.

Buckling stability is critical in most industrial applications, especially for compressed skins/shells. Therefore, selecting the best laminate purely based on strength is not sufficient; buckling has to be taken into account, too. As buckling stability is dependent on the stacking sequence of non-homogenized quad laminates, we calculated the critical buckling load for every quad layup permutation. Fig. 6 illustrates the critical buckling load and the strength of all quad and double–double layups. Layup selection is a complicated process specific to each individual part and application, but generally the greater the strength and the critical buckling load are, the better. Two layups seem to perform the best, both DDs: [±30.0°/±50.0°] and [±35.0°/±50.0°]. To summarize, a composite shaft that is loaded according to Table 1 can be significantly lighter when built with the double–double method instead of the quad method. More than 6% weight reduction can be realized when considering the strength only. This weight-saving can be significantly improved when considering tapering, too (more on this later).

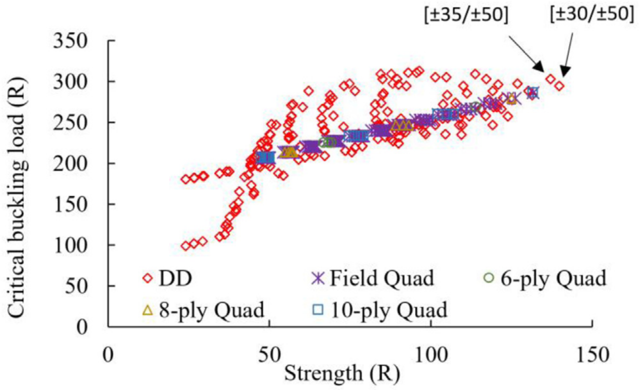

Fig. 6. Critical buckling load vs. strength (factors of safety - R) graph of quad and double–double laminates — composite shaft.

Table 4
Complex loads acting on a composite bulkhead, and damaging potential (R/R$_{control}$) of the individual loads compared to the most dangerous (control) load.

Load	σ_1	σ_2	σ_6	$R/R_{control}$
Load 1	1.0	1.0	0.0	0.79
Load 2	1.0	1.0	0.2	1.00
Load 3	0.8	0.0	0.2	0.98
Load 4	0.0	0.3	−0.2	0.50
Load 5	−0.5	0.4	0.0	0.52

Table 5
Optimal (strongest) layups from each layup family — composite bulkhead.

Layup family	Layup of the strongest laminate from family (0°/±45°/90° ratios for quad layups)
FieldQD	20/65/15
QI	25/50/25
6QD	17/67/17
8QD	25/50/25
10QD	20/60/20
DD	[±25.0°/±65.0°]

Case study 2 – composite bulkhead

Table 4 shows five main example loads that a bulkhead is expected to experience during its lifetime. The controlling load case (Load 2) is a bi-axially heavily pulled and slightly sheared load.

Table 5 comprises the optimal layups from each of the six layup family for maximum strength.

As mentioned in the previous case study, the required thickness of the quasi-isotropic quad is not a theoretical but a practical extremum. Fig. 7 clearly illustrates that the best quad with 6-ply sub-laminate is weaker (thicker) than the quasi-isotropic quad. This can happen because certain orientation ratios cannot be realized with only a few plies in the sub-laminate (Table 5). On the other hand, the best double–double laminate outperforms the best quad laminate once again, by about 6%.

Table 6
Required thickness and number of sub-laminate repetitions of the strongest layups from each layup family to withstand loads. NA: not applicable (not practical laminates, only limits) – composite bulkhead.

Layup	FieldQD	QI	6QD	8QD	10QD	DD
Required thickness [mm]	7.2	7.5	7.8	7.5	7.2	6.8
Number of sub-laminate repetitions	*NA*	*NA*	10.4	7.5	5.8	13.6

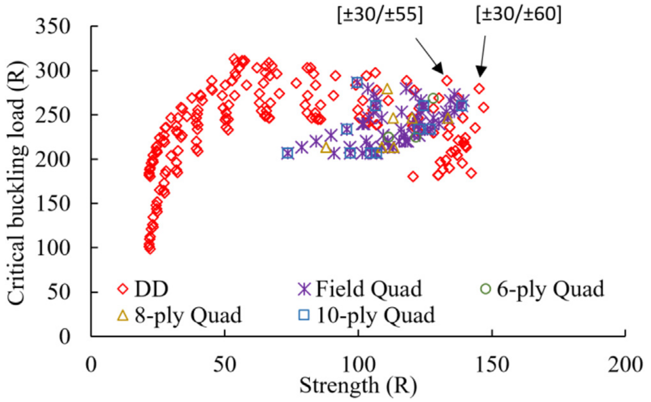

Fig. 8. Critical buckling load vs. strength (factors of safety -R) graph of quad and double–double laminates — composite bulkhead.

Table 6 shows a similar tendency to the first case study. Double–double laminates can be made thinner and still provide the required strength. A weight saving of about 6% can be realized by this alone, but tapering can further increase the advantage of DD laminates because of the thinner sub-laminates and the freedom to disregard symmetry when tapering (this is due to layup homogenization).

Strength and stability should complement each other in case of a bulkhead, too, and the two best layups seem to be DDs again: [±30.0°/±55.0°] and [±30.0°/±60.0°] (Fig. 8). Numerous double–double layups in Fig. 8 perform well for strength or buckling but underperform in the other aspect. This is shown by the wide spread of red diamond-shaped markers across the graph. However, we only need to focus on the best performing layups of which our composite part will be made. The two case studies show that double–double laminates can be a better choice than quads when considering strength and buckling. The extent of weight saving depends greatly on the complex load case but weight reductions from a few percent to more than ten percent can be realized. And this is before taking tapering into account which is significantly more efficient for double–double laminates than for quads and therefore can further increase the advantage of DD layups.

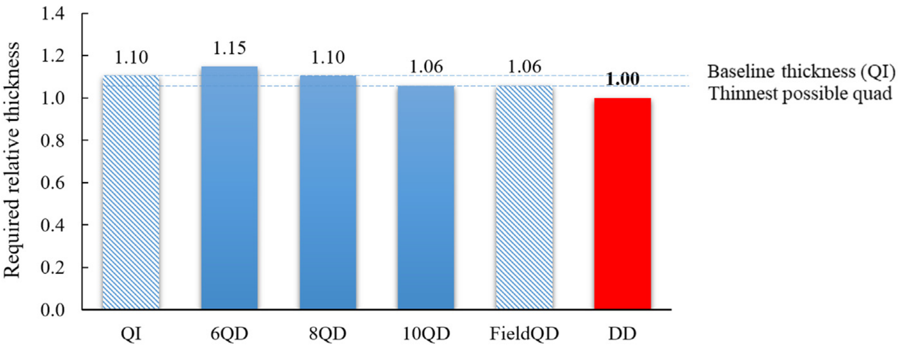

Fig. 7. Required relative thicknesses of the best layups from each layup family — composite bulkhead.

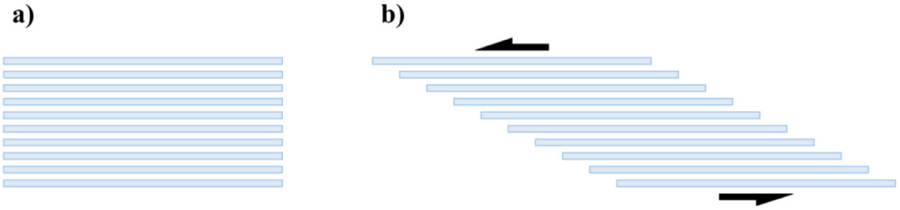

Fig. 9. Schematics of a composite laminate with (a) no tapering (b) card sliding double taper (possible with double–double laminates).

3.3. Tapering

Efficient tapering is one of the greatest strength of double–double layups with which the weight of composite components can be further reduced. As DD layups with about 5 repetitions and above are naturally symmetric, tapering can be done ply-by-ply with single ply drops without worrying about mid-plane symmetry as in case of quad layups. Also, any ply at any location can be dropped without significantly altering the mechanical characteristics of the laminate. This is a significant designing and manufacturing advantage over quads, where ply drops are usually based on subjective engineering judgement trying not to change mechanical characteristics too much and maintaining mid-plane symmetry. Double–double tapering leads to lighter structures, is simpler to design, easier to manufacture and less prone to error compared to quad tapering.

Placement of the ply drops within the laminates can be critical, and DD laminates give almost absolute freedom in this regard. Placing ply drops along the natural axis can get rid of stress caused by bending, so no knockdown factor is necessary. Alternatively, plies can be dropped on the exterior surfaces, ready for inspection and avoiding fibre breakage in the interior of the laminate. An example of the exterior ply drop is the Stanford proprietary card sliding tapering method for double–double laminates (as introduced by Stephen W. Tsai, patent pending) (Fig. 9). This is a double-sided external tapering method useful for laterally loaded components (perpendicular to the plane of the panel). The sliding method makes tapering simple to design and manufacture and leads to significant weight saving and minimum scrap while reducing the likelihood of free edge delamination. We carried out static and cyclic dynamic bending tests on a double cantilever beam with all the ply-drops on the exterior surface and found those not to be the weak link.

3.4. Manufacturing

Double–double laminates can not only be lighter and simpler to design than quad laminates, but they are easier to manufacture, too. This is due to the single 4-ply building block and the simple tapering. Double–double sub-laminates can be pre-manufactured into 4-ply thick non-crimp fabrics (NCFs). This makes one-axis layup process possible when laminators do not have to worry about different orientations as each fabric is placed along the same axis. The only real task becomes placing the right number of NCFs to reach the desired thickness in each zone. This not only makes the manufacturing process simpler and faster but significantly less prone to errors, too, compared to ply-by-ply layup, let alone complex quad layups.

4. Conclusions

First, we showed that layup homogenization is a powerful method to mitigate the warpage of asymmetric layups. Only 8 repetitions of highly asymmetric cross-ply sub-laminates reduced warpage by 97.5% compared to the same cross-ply laminates without homogenization. Layup homogenization is an integral part of the novel double–double layup method presented in this paper, as the 4-ply building blocks of these laminates are usually asymmetric. With double–double layups, we showed that the laminate design and manufacturing processes can be simpler and less prone to error compared to those of conventional quad layups. More importantly, significant weight savings can be realized with the novel method that we demonstrated through case studies. Weight savings with double–double laminates have two main reasons. Firstly, unlike in the case of the conventional quad layups, there are no set fibre orientations and each orientation needs to compete to earn its place in the laminate. This leads to a better exploitage of the mechanical potential of the fibres and therefore fewer plies are required in the laminate that saves weight, ultimately. When optimizing layups for strength and buckling stability for two example composite components (shaft and bulkhead), the best double–double layup was able to meet the mechanical performance of the best quad layup while offering a 6% weight reduction in both cases. The other reason why weight can be saved with double–double laminates is their ability to taper much more aggressively and efficiently than quad layups can. This is another positive concomitant of homogenized layups. It is hard to quantify the additional weight saving potential of tapering as it greatly depends on the loads, geometry and a set of other parameters, but double–double laminates are expected to significantly outperform quads in any case.

Numerous industrial segments could benefit from the weight savings achievable with double–double composites (e.g. transportation, wind energy and aerospace industries). The demonstrated 6% weight reduction with double–double composites compared to the current industry standard quad composites is a conservative estimate, as this is before taking the aggressive tapering of double–double composites into account, which is expected to lead to significant additional weight savings. The airframe of a modern commercial aircraft is using about 50% composites (53% for the Airbus A350 XWB aircraft [21]). Considering that usually about 10.000 commercial aircrafts are in flight at the same time, double–double laminates alone could reduce the weight we need to fly by tens of thousands of tons globally, at any given moment. The reduced fuel consumptions and emissions of aircrafts due to the weight savings achieved with double–double laminates would not only be economical but could be a step towards reducing our carbon footprint and protecting the environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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