A design methodology using bi-angle ply laminates made from NCF carbon fiber materials

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1 - General vision of NCF

Non crimp fabric (NCF) is a class of composite materials made with layers of unidirectional plies at different angle combined together by a transverse stitching which holds the plies together allowing some light degrees of freedom between adjacent plies. In contrast with fabrics, NCF are fiber layers without crimp providing higher mechanical properties due to fiber alignment and higher volume fraction of fibers.
A new type of NCF has been proposed by S.W. Tsai and al. [1] and designed by Cognet and al. from Chomarat (France). It consists of unidirectional carbon fiber tapes and +25° tapes. The NCF is a composite in the form : [0/25] each ply is 80 g/m^2. The thin ply is obtained by spreading the initial tow. This NCF can be transformed by RTM, VARTM or simple infusion and compression. Prepegs can be made with the basic NCF. One built ply of NCF is about 0.125 mm twice as thin as conventional UD.
The material used in this study are a T700 Toray fibers and a RTM epoxy base resin. An intensive characterization program is underway but for the present work the data used are those given in Table 1.

Our notation N stands for a ply of NCF [0/25], Ñ stands for the flipped NCF [0/-25]. In actual design the N or Ñ plies can be associated with UD plies to obtain laminates in the general form [0 x/Nx / Ñy] where x, y, z are the number of plies of each type.
In this paper we have studied the optimum design of composite materials using the Chomarat NCF in the particular case of slender structures, i.e. having a high length to width aspect ratio as shown in figure1.

2 – Optimization of composite materials

Weight and thickness of materials issues for application with high energy performance specifications is often critical. In this paper we investigate a new design concept based on bidirectional laminates far from the conventional [0/90/45/-45] so-called “Pi by four” laminates. Main achievements in this study include:
i – Optimum bases laminates are designed by selecting an optimum ratio selection between ply orientations and not necessarily by angle selection.
ii – We show that lower number of ply orientation leads to thinner laminates compared to conventional “Pi by four” laminates. Such design often requires that a minimum of 5% to 10% of each orientation is included in the laminate which penalizes the total weight of the laminates without real benefit for the safety margin.
iii – The minimum being bi-angle laminates, we

investigate how an elementary construction of [0/θ] laminates can be used as a building block for optimum sized lamination for minimum weight composites for strength criteria. The angle θ = 25° appears to be an attractive choice in the case of slender structures.

iv – The building block being of [0/θ], we show that it can be manufactured using the NCF –Non Crimp Fabric - technology (Figure 2). The building block of [0/θ] can be used as of [0/-θ] by flipping the base block. It can also be laminated together with pure [0] NCF material. We show that the defined building blocks can be assembled in laminates in order to meet all the requirements of complex design such as wing-spar, wind blades, automobile parts, etc… [Figure1]

3 - Optimization of lamination

Criteria for minimum weight composite design can have many forms depending on the practical way composites are used in a structure. In this case we shall concentrate on the design of composites materials for strength. The same methodology would apply for composites materials design for stiffness (for instance minimum deflection or critical vibration frequency. In this case we also assume that the laminate is made with a single material (no hybrid solution is considered). The design variables in our study are therefore reduced to :

- the orientation of each ply (θ_i i=1 to n_{or} where nor is the number of maximum orientations)

- the number of plies in each orientation (n_j , j=1 to np)

The constraints are given by the failure criteria used to describe the failure mechanism. In this present study we used the Tsai-Wu failure criteria to determine the first-ply-level (FPF) of each ply of the laminate. The design requirement is that in all the value of the criteria should remain lower than one

$$G_{ij} . \varepsilon_i . \varepsilon_j + G_i . \varepsilon_i < 1$$

We also use the strength ratio R which is the ratio of margin to failure for the laminate

R solution of :

$$G_{ij} . R^2 . \varepsilon_i . \varepsilon_j + G_i . R. \varepsilon i =1$$

The optimization tools developed for conventional laminates optimization scheme are used [1] and compared to conventional design using “PI by four” laminates and normalized by reference to quasi-isotropic solution (so called black-aluminum design).

The solver LAMRANK is a software for laminate optimization developed by T. Massard and G. Flanagan at the Air Force Materials Lab. in the mid 80’s.[2] and [3]. A significant improvement on weight and thickness is found without compromising other critical material properties such as CAI, open hole compression strength and delamination threshold. [4]

The LAMRANK method is based on the systematic generation of solutions using the sub-laminate concept developed by S.W. Tsai [4]. For n possible orientations (n=1 to 6 for practical means) we define a composite as a combination of a sub laminate composed of any of the orientations with a repetition value (r) and a possible symmetry (s). The general form could be written:

$$[\theta_1(n_1)/\theta_2(n_2)/.../\theta_6(n_6)]\ r\ .s$$

as an example a quasi isotropic laminate of 32 plies would be [0 /90/45/-45]4s with a repeating index of 4 and S for symmetry.

LAMRANK will generate all the possible laminates in the general form above with the following data :
between 2 and 6 orientations
between 2 to 10 plies in a sub-laminate
For each possible laminate the design criteria is calculated for each load (strength value R for strength design). All the solutions are ranked

following the desired criteria. The optimum solution is taken as the first of the ranking. This systematic solution has proven to be very efficient [3] and less computing time consuming than a pure Monte Carlo solution or a Ralph-Newton based-solution.

4 - Optimum design for slender construction

We have defined slender construction as an architecture where one main load is applied in one direction of the structure but other minor loads such as torsion, shear, transverse tension or compression are also applied to the structure. Typical slender structures are windmills blade, wings, stringers, ship mast, etc... We show that for slender construction bi-axial [0/25] or [0/-25] sub-laminate construction can be the most efficient solution. Industrialization of [0/25] as a whole product has lead to imagine a new NCF (non crimp fabric) with the two directions on top of each and stitched together by a very light polyester fiber. The NCF has been prototyped by Chomarat and is described thereafter. The NCF product can be laid with unidirectional tape in order to achieve a variety of laminates in the general form of:

$$[0_{\alpha}/25_{\beta}/-25_{\gamma}]r$$

where α, β, γ are the number of plies for each orientation and r is the repeating element.

S.W. TSai and al. have show that symmetry is not required if the number of plies is higher than 16 ?plies. The coupling matrix induced by the non-symmetry tends to zero as the square of 1/r.

5 - Study cases

We have generated two series of cases for slender construction in order to have some statistical vision of the capabilities of the NCF product. We have calculated the optimal solution using LAMRANK for each case using the NCF and unidirectional combination, using the four orientations 0, 90, 45, -45 with the requirements of each orientation used at least 5%, and the quasi-isotropic (QI) solution (black-aluminum). This can be considered as state of the art in conventional composite design. The performance of each solution has been normalized to the Quasi-Isotropic solution. QI can be considered as the bottom line design achievable with composites. So QI solution has a performance of 1. Any better solution has a performance higher than 1.

5.1 – Single inplane loads

Series A is a family of 7 cases of a single loads applied to the structure. The single load can be complex with all component of tension, compression in the longitudinal and transverse direction, and shear.

Table 2 shows the series A loading cases and figure 3 shows the performance of NCF compared to FP (fully populated quadridirectional composites). In averaging the 7 cases (figure xx) we show that optimum design for quadridirectional composites fully populated is 80% lighter or thinner than quasi isotropic solution, and we show that optimum design using NCF and UD has around 3.5 times a higher performance (lighter or thinner) than QI. Biaxial NCF and UD have a tremendous potential for slender constructions.

5.2 – Multiple inplane loads and bending moments

Series B is a family of 6 multi loads cases applies to the structure. Each load is applied individually but the structure has to sustain all the loads at a certain time of its life. It is a very common situation for structures having different loading profile, and the most complex case to solve in optimum design of composites. In the case of isotropic material the solution is trivial since each load can be replaced by an equivalent stress and the higher equivalent stress drives the critical load. In the case of composites there is no critical load *a priori*. The critical load depends on the composite lamination. The optimum design is found using a multiple criteria taking into account each load.

Table 3 shows the series B loading cases and Figure 4 shows the performance of NCF versus FP (fully populated quadridirectional composites). In averaging the 6 cases, we show that NCF and UD can be 2.7 times better than QI and conventional design is still 80% better than QI.
All these results are based on a low number of cases but the tendency is clear. From the results of series A and series B, we show that composites made with biaxial NCF and UD have a tremendous potential for slender constructions. An optimum use of this new product could lead to a reduction in weight by 2.5 to 3 where the conventional design is limited to 1.8 compared to quasi-isotropic (black aluminum) design.

6 - The effective way to build NCF / UD laminates

A cost effective process for the laying of slender structures can be derived from this study. We show how to use the base building block concept with tape laying or fiber placement techniques where only unidirectional ply is laid without any off axis laying. Figure 5 shows the tape lying scheme for efficient use of Chomarat NCF C-Ply for a tapered beam. Although the fiber orientation are 0 , 25° and -25° the tape laying process only requires straight laying which speeds up the process by a factor 5 to 7.

7 – Technology development for C-Ply NCF

Figure 6 shows the NCF machine modified by Chomarat for this study, including a tow spray technique and a special arm for the off-axis plies up to 20°. Benefits are - i : more homogenous layers – ii : very thin and lightweight product - iii : possibility to use heavy tow – iv : higher quality aspect

We have investigated the efficiency of NCF for combined loads where the ratio N_6/N_1 and N_2/N_1 varies between 0 and 0,5. The figures 7 and 8 shows the results for NCF and UD compared to design using pure unidirectional, 0° and 900 and design using 0°, 90°, 45° and -45°. In both cases, NCF has a large zone of interest as a building block for efficient composites.

8 – Conclusions

Preliminary investigations of the potential of Chomarat C-ply NCF [0°/25°] have shown a great potential to design slender structures under main loads in tension and compression combined with lateral and/or shear minor loads. This loading situation is very common in many applications such as wind blades, wing spar, golf shaft. Further work will include a complete characterization of the NCF C-ply including CAI and open-hole tension and compression to investigate the damage tolerance of the concept.

9 - References

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Table 1 – Mechanical data for T700/RTM6

T700/RTM6			
Ex =	110 GPa	Ey =	7,4 Gpa
Es=	4,2 GPa	Vx =	0,3
X =	2300 MPa	X' =	1500 MPa
Y' =	220 MPa	S =	93 MPa
Y =	66 MPa	Vf =	50%
Ef =	210 GPa	Xf =	4900 MPa

Table 2 – Test cases : Single Inplane loads

A	N1 (MN/m)	N2 (MN/m)	N6 (MN/m)
A1	1	0	0,1
A2	-1	0	0,1
A3	1	0,1	0
A4	-1	0,1	0
A5	-1	-0,1	0
A6	1	0,1	0,1
A7	1	-0,1	0,1
A8	-1	0,1	0,1
A9	-1	-0,1	0,1

Table 3 – Test cases : Combined Inplane loads

B	N1 (MN/m)	N2 (MN/m)	N6 (MN/m)
B1,1	1	0	0
B1,2	0	0	0,1
B2.1	-1	0	0
B2.2	0	0	0,1
B3.1	1	0	0
B3.2	0	0	0,1
B3.3	0	0	-0,1
B3.4	0	0,1	0
B3.5	0	-0,1	0
B4.1	1	0	0
B4.2	0	0	0,1
B4.3	0	0	-0,1
B5.1	1	0	0
B5.2	0	0	0,1
B5.3	0	0,1	0

Table 4 – Test cases : Combined Flexion load

	M1 (MN)	M2 (MN)	M6 (MN)
B6	1	0	0,1
	N1 (MN/m)	N2 (MN/m)	N6 (MN/m)
B6.1	1	0	0,1
B6.2	-1	0	-0,1

Figure 1 – Slender structures for NCF design

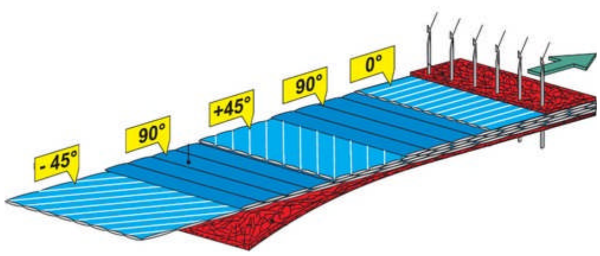

Figure 2 Non Crimp Fabric Technology

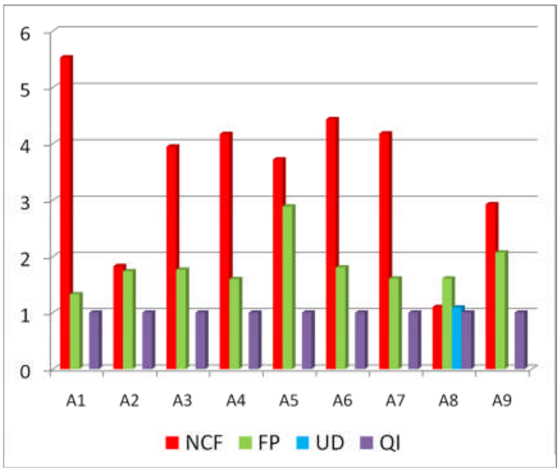

Figure 3 – Design results for test cases series A

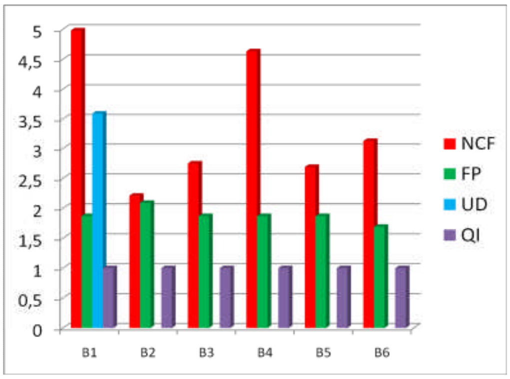

Figure 4 – Design results for test cases series B

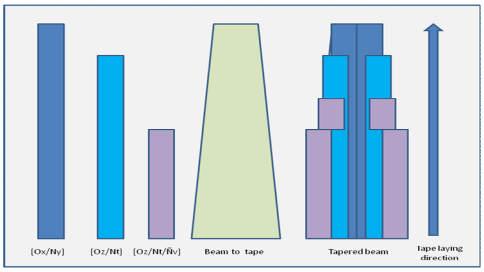

Figure 5 - Efficient tape lying using the NCF UD concept

Bi-angle tape laying on the NCF machine (Chomarat)

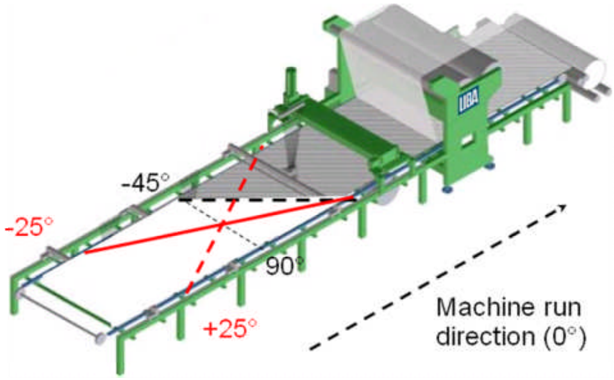

Figure 6 – NCF technology for HP composites

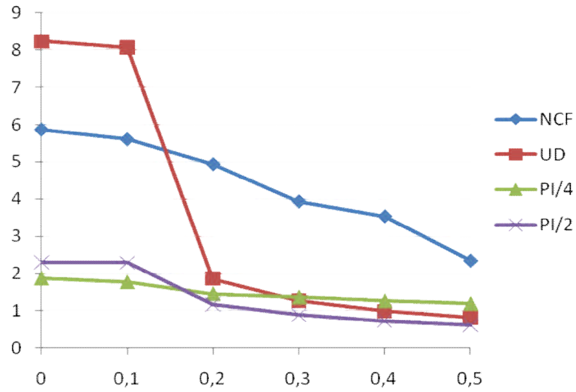

Figure 7 - Performance of NCF compared to PI/2 and PI/4 laminates normalized to Quasi-iso for various N_1/N_6 values In blue the interest zone for NDC design

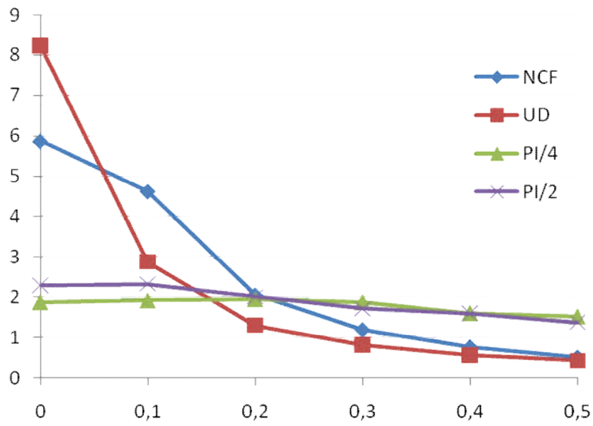

Figure 8 - Performance of NCF compared to PI/2 and PI/4 laminates normalized to Quasi-iso for various N_1/N_2 values