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THINK COMPOSITE

"THINK outside the box" design practices for optimal, more competitive and durable structural COMPOSITEs

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"THINKCOMPOSITE"

1) PUBLISHABLE SUMMARY:

Scientific and engineering insights in materials research are crucial for being at the cutting edge that has not only scientific value, but also immediate applicability and added value for the society. This requires scientists and practitioners to communicate well and ideally tune their efforts from basic science to engineering ends. Making composites more competitive is no exception, and calls attention for advances and innovation in materials, and "thinking outside the box" design practices. THINKCOMPOSITE project aims to contribute bridging the basic scientific research to the more applied and engineering oriented research and focuses the skills for composites engineering and structural design end of this challenge.

Summary description of the project objectives

Two primary objectives of the THINKCOMPOSITE have been set

(1) to investigate innovative manufacturing/material alternative, namely thin-ply bi-angle non-crimp fabric (NCF) for optimal composite designs: New generation material, thin-ply multi-axial prepregs (in the sprit of non-crimp fabric- NCF composites) can substitute unidirectional tapes provided that their drawbacks versus gains are well understood, characterized and taken into consideration in a multi-objective design settings.

(2) to address the design practices within structural optimization framework and implementing micromechanics of failure (MMF): The design rules and practices have certainly reasons, some dominantly intuitive, but often the motivation is for being protective and conservative. For example, the fact that composite structures have many complex failure modes that are not captured by standard macro scale modeling, may lead composite designers to follow rules such as the use of symmetrical laminates, and fiber orientations imitating the isotropy. In contrast, unconventional fiber orientations and stacks in optimization efforts shall lead to more competitive designs once the failure are well captured in modeling.

Description of the work performed and main results

The project tasks have contributed to the exploration of the innovative bi-angle thin-ply NCF composites. The concept of bi-angle or three-angle tapes, in the spirit of non-crimp fabric (NCF) composites, is based on the elimination of laying off-axis plies by having those plies pre-combined with the [0º] ply to form [0/ϕ] NCFs, for instance. This unconventional concept of bi-angle along with a novel tow-spreading technology has created the thin-ply NCFs, C-Ply^{TM} that has been made available by Chomarat. The main distinction from the traditional NCFs is the intrinsic anisotropy achieved within a [0/ϕ] building block as thin as a typical high performance UD tape. An evolving research program on the thin-ply NCF has been driven by the outgoing host Stanford Composite Design group. The group and its global team involve industrial partners and academic institutions and collaborative efforts including the THINKCOMPOSITE project have been shedding light on why bi-angle thin ply NCF is a novel competitor for the composite structures. The thin-ply NCF promises better mechanical performance, ease of lay-up process, reduced amount of scrap, and tailored building block for sublaminate based homogenized design strategies to design composite structures out-of-the box. With these multi-angle NCF tapes, the axis of tape laying can be limited to one only along the x-axis, or two equal tape axes along the x- and y-axis. Ply drop can also be done on a tape drop basis. Great time savings can be achieved through not having to drop off-axis plies. For panels where more than one axis layup is needed, multi-directional tapes may be designed to fulfill special structural and manufacturing needs. One disadvantage of multi-angle tape is that the seams between two adjacent off-axis plies may be needed. Given these characteristics of the thin-ply bi-angle NCF, relevant actions herein and the highlights have been the following:

- *Thin-ply NCF stiffness and strength data generation*: the difficulty of testing the anisotropic coupons of [0/ϕ] NCFs for mechanical characterization can be circumvented by testing an orthotropic coupon like [±ϕ]. Such a coupon can be cut along the bisector of [0/ϕ]. From the orthotropic test coupons test results, MicMac toolset implementing the laminated plate theory is then used to back calculate what the ply stiffness and strength of a [0] NCF would be. With the ply data, predictions for laminates such as of [0/ϕ] can be made. These predictions are essential for homogenized laminate design.
- *Understanding of the seams due to discontinuous off-axis plies of bi-angle NCF strips in Tape laying:* as opposed to UD fiber reinforcement, discontinuous plies of NCFs are inevitable when the lay-up dimensions are larger than the finite width of the reinforcement and butt-joints of the NCF layers are needed. Being thin-ply and bi-angle this issue is less critical than the traditional NCFs: thinner the discontinuous ply, easier to smear the effect of the seams and homogenize the laminate through the thickness, and less number of discontinuous plies as only one off-axis ply is accompanied with the 0 degree ply on the building block NCF. Six inches wide C-Ply NCF tape rolls were used to make (0/-45/90/-45) lay-up by MAG Cincinnati's automated tape laying machine. Staggering the seams were also implemented. Models predict the strength of

the laminate with seams without staggering may be as low as 40% of the seamless strength (coupon cut at 45 degree orientation, resulting the discontinuity of the fibers parallel to the load axis). Staggering improves the strength substantially, increases the lower end of relative strength to 75%. Test data also correlate well with the predictions of the effect of the seams on the strength.

- *Homogenized FPF and LPF envelopes for the thin-ply NCF building block:* Homogenization of laminates through the thickness is enabled by the thin-ply NCF building block, and failure envelopes can also be treated as of homogenized material in addition to common ply-by-ply laminate prediction of strength (in terms of strength ratio R). Given the stiffness and strength data predicted for a sublaminate configuration, Tsai-Wu first ply failure envelopes (FPF) were computed. Envelopes in strain space are also readily available indicating a fixed strain allowable of 0.4 percent, a typical design criterion for most common loading conditions, is not consistent with the quadratic failure envelope based on FPF. This fixed strain can be either grossly under-utilizing a laminate or also unsafe depending on the applied combined strain components. The last ply failure (LPF) prediction is also essential information in design cycle of laminated composites. Here the use of homogenized equivalent strength parameters in LPF as well as FPF predictions was also investigated, as the thin ply NCF material can make homogenized laminate concept much more practical and attractive in design. Homogenized FPF and LPF envelopes matching very well with the ply-by-ply analyses are ellipsoids and well behaved functions. They can easily be incorporated parametrically in the design tools.
- *Designing for deformation by Anisotropy*: The bending-twisting coupling due to anisotropy has been long recognized for its potential of controlling or designing the deformation counter effects on each other loading types, usually referred as passive aeroelastic tailoring. The deformations are coupled even in case of an isolated single loading mode. Bi-angle thin-ply NCF is intrinsically anisotropic. As it enables homogenized laminates, designer can get rid of inplane-bending coupling, but allowing the bending shear coupling for deflection control.
- *Assessment of Hybrid carbon/glass bi-angle NCFs:* One way to reduce the material cost and seek potential competitor composites is to hybrid use of carbon fibers and glass fibers within the NCF building block. Back-calculated ply data of C-ply of carbon fibers (thin-ply T700/epoxy) along with the ADVANTEX glass fiber/epoxy ply data were exercised in order to assess the potential from hybrid bi-angle NCFs. Stiffness and strength predictions of the bi-angle NCF of 0 degree carbon ply with glass fiber off-axis ply and similarly, use of carbon at the off-axis ply were considered. Stiffness matrix plots were generated as a function of the off-axis angle and both configurations, carbon/glass and glass/carbon NCFs. Hybrid use of carbon and glass outperforms all glass NCF as expected, and may provide reasonable alternatives for all carbon NCF if the cost criteria is dominant. Such predictions can help composite engineers to determine what to ask from the material providers.
- *Homogenized laminate design optimization by thin-ply bi-angle NCFs building block*: Homogenized laminates with simple building-block of thin-ply bi-angle NCFs can potentially be tapered with much simpler ply drop strategy than heterogeneous ones. Laminate sizing is also made simpler as the off-axis ply angle is a much better, and continuous variable along with the homogenized laminate thickness than the discrete ply change of p, q, r in somewhat more traditional $[0_p/\pm45_q/90_r]_S$ scheme. The wing optimization problem was solved using MSC.NASTRAN modules (Aeroelasticity and optimization) where equivalent/homogenized stiffness and strength data were incorporated. Traditional quasi-isotropic ($\pi/4$) sublaminate based design was found to be over weight compared to the bi-and three-angle counterparts $[0/\phi]$ and $[0/\pm\phi/0]$, respectively.
- *Additional "ThinkComposite" concept: nano-augmented composites - Integration of nanofibers as interlayers in conventional laminated composites*: As the project aims and calls for "thinking outside the box" practices, another "ThinkComposite" concept has also been pursued. Epoxy matrix compatible polymeric nanofibers are being integrated into the fiber reinforced composites to serve as interlayers and enhance the mechanical performance of the laminates. Substantial increase in fracture toughness, flexural strength and stiffness were reported although the weight penalty is merely negligible. Their benefit against free-edge stresses and stress concentrations are also intriguing and show great potential as a ThinkComposite concept.

Expected final results and their potential impact and use

Competitiveness of the composites will be better recognized by thorough understanding of the novel material concepts such as thin-ply bi-angle NCF composites and nano-augmented or nano-integrated composites. The THINKCOMPOSITE serve for the purpose of making such composites more competitive and design strategies/guides more efficient so that their effective use and impact will be elevated to the benefit of the society via safer, more reliable and cheaper composite applications.