INVESTIGATION ON HYBRID OUT-OF-AUTOCLAVE PREPREG/LCM PROCESS FOR INTEGRATED STRUCTURAL APPLICATIONS

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Abstract

Hybrid processes combining characteristics of prepreg and Liquid Composite Molding (LCM) techniques are interesting and advantageous solutions for manufacturing of highly integrated structures. The possibility, given by traditional prepreg technology, to manufacture elevated FVC parts with a good reproducibility and as well to introduce additives like flame retardants or tougheners, can be successfully combined with LCM characteristics. In this work, the research involved furthermore out-of-autoclave (OoA) prepreg materials, which provide additional cost-savings and environmental advantages compared with standard autoclave techniques. Goal of the investigation is to analyze the feasibility of this hybrid technology and study its sensitivity to the main parameters, with special characterization of the prepreg bleeding mechanism. A simple demonstrator has been also realized.

1 Introduction

Final costs and performances of composite structures depend on the manufacturing technique employed, which can bear specific economical burdens or technical restrictions for part design and ultimate application. As an example, traditional prepreg technology, which is commonly chosen for high-end applications, has main disadvantages in elevated production costs and quite laborious manufacturing of complex shape; while Liquid Composite Molding (LCM) offers higher process flexibility, but typically lower FVC are achievable.

Combination of different manufacturing techniques (e.g. hybrid processing) would ideally allow to overcome the limitations of single processes, reducing costs and integrating diverse functions (i.e. improved damping, toughening behavior, flame resistance, etc.) in the same structure. The co-bonding technique [1] is a usual example of procedure for combining processes; here individual assemblies (manufactured through different technologies) are consolidated together by sequential hardening. Another common procedure, known in literature as co-curing technique [2], implies a real cross-linking of different structures' resins by a simultaneous cure; in this case compatibility requirements are essential for a correct integration and good quality of the final product. Actual hybrid processing that combines prepreg and LCM technologies has been recently investigated by various industries and institutes. For instance, Eurocopter GmbH and DLR in Germany employed [3, 4] a Combined Prepreg and Infusion (CPI) process to fabricate several demonstrators, like spars, stringer-reinforced panels and helicopter floor covers with improved flame resistant properties. Researchers of Japan Aerospace Exploration Agency reported [5] the production of a quadrant section of fuselage using a VaRTM and prepreg hybrid (VPH) technology. A hybrid prepreg/RTM process named Same Qualified Resin Transfer Molding (SQRTM) has been additionally proposed [6] by the Sikorsky Aircraft Corporation and Aviation Applied Technology Directorate in USA for rotorcraft roof component. A scientific insight into hybrid processing is provided by the work of R. Kaps [2, 4], which pointed out that a possible drawback in the application of this technology can be ascribed to the formation of a critical area at the interface area between prepreg-side and LCM-side, due to usage of different resin systems. However, Kaps showed that, with a right selection of materials, no weakening effects are attributable to this transition zone.

In the framework of the EU-project CleanSky – Eco-Design ITD, the present research investigates a hybrid OoA prepreg/LCM process, which combines advantages of both technologies and allows integrate production of composite structures without autoclave; thus with evident energy, cost and environmental benefits. The investigations have initially addressed the issues of process feasibility through an analysis of obtained material properties in comparison with the ones resulting from pure processing. Then a sensitivity study has been carried out to examine the process robustness with regard to the main parameters controlling the transition zone between prepreg-side and LCM-side. Special attention has been here given to the characterization of prepreg resin bleeding into dry LCM fibers with numerical and experimental tests. Hence, optimized manufacturing routes have been used to fabricate a simple demonstrator, consisting in a prepreg plate stiffened with a LCM-made J-C profile rib, which showed the effectiveness of this hybrid process for manufacturing integrated structures.

2 Materials and hybrid processing methods

Raw materials used for the investigation are OoA prepreg with epoxy matrix system MTM®44-1 and single component epoxy resin for infusion MVR444, both supplied by Umeco. They have been suggested for hybrid out-of-autoclave processing within the CleanSky project, since their formulations are compatible and co-cure is possible by a common heat treatment for 4 hours at 130 °C, therefore no heavy weakening effect is expected at the interface between the two resins. The used fibrous reinforcements are woven 2x2 twill carbon fabrics: MTM44-1/CF5804A (40% resin weight) OoA prepreg plies, with fiber type HTA40 (6K) and area weight 284 gsm, by Toho Tenax, have been employed for the prepreg-side of the structures and identical textiles used as dry fabric for the LCM-side.

The hybrid fabrication method consists of a number of steps. First the prepreg plies are stacked up on the mold, operating a vacuum debulking during the lay-up to reduce final porosity [7]; afterwards the lay-up can be completed placing the dry fabrics for the LCM-side and eventual ancillary materials. At this stage, two options are possible: covering the mold with a vacuum bag, like in a typical VARI technique, in case of hybrid OoA prepreg/VARI process; or closing everything in a whole rigid mold, in order to perform a RTM-like injection, in case of hybrid OoA prepreg/RTM process. After the closure, the mold can be heated up to the processing *temperature* and kept for a certain time (*holding time*) before infusing/injecting inside the degassed MVR444 resin system. After wet-out completion, the structure is cured in an oven under vacuum using the above mentioned common heat treatment, followed by a free-standing post-cure at 180 °C for 2 hours. Another suitable co-curing cycle can be operated heating the part at 130 °C for 2 hours and at 180 °C for additional 2 hours.

3 Feasibility study and comparison with pure processing

The feasibility study has been carried out manufacturing 2-mm thick plates by means of the above described hybrid processes (where half thickness of the plates were occupied by prepreg plies and the other half by fabrics impregnated through a VARI-like or a RTM-like process). Standard 3-point bending and interlaminar shear strength tests have been performed to evaluate the performances of the hybrid plates and compare them with the ones achieved by similar plates manufactured through pure processing. The results are summarized in Figure 1 and 2, where it is noticeable that hybrid plates' properties fall in the range of pure plates' ones, being typically closer to the pure prepreg plates. For combined OoA prepreg/VARI process, a comparison with the co-bonding technique shows that the results are mostly overlapping, although the averages of hybrid co-curing are usually higher than co-bonding.

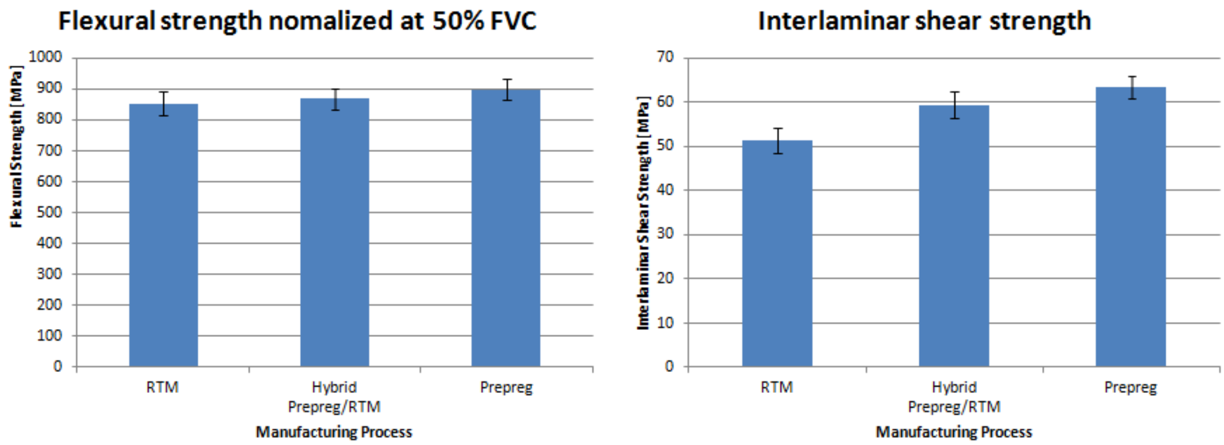

Figure 1. Feasibility test results for hybrid OoA prepreg/RTM process.

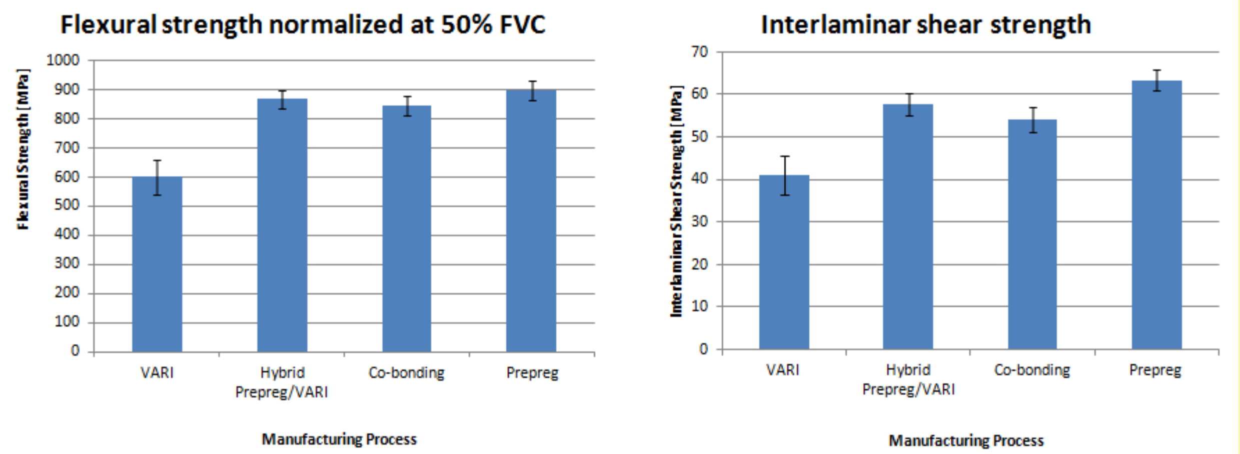

Figure 2. Feasibility test results for hybrid OoA prepreg/VARI process.

4 Sensitivity analysis and bleeding characterization

As far as the sensitivity study is concerned, two process parameters have been investigated: mold temperature and holding time. According to [2], they have a major influence on the interaction between prepreg and LCM matrixes at their interface. The reason hereof is ascribable to the fact that prepreg resin bleeds into the dry fabric prior the effective LCM-side impregnation, because of a pressure gradient due to vacuum application, capillarity forces and also fabric compaction. In a combined prepreg/LCM process, the bleeding mechanism could be positively exploited, by tuning holding time and temperature, to obtain a gradual transition zone and improve resin merging, and thus to achieve increased mechanical properties. For this purpose, the sensitivity analysis has been carried out by manufacturing different hybrid plates, changing the mentioned process parameters. The various fabrication routes have been set by combining extreme values for mold temperature – 80 °C (recommended for MVR444 injection) and 130 °C (curing temperature) – and holding time – 0 min (immediate impregnation) and 150 min (gel point). Results for hybrid OoA prepreg/RTM technology (Figure 3) show a substantial robustness of the process in respect to the changed parameters, with a trend of increasing interlaminar shear strength at higher temperature and time (i.e. higher bleeding).

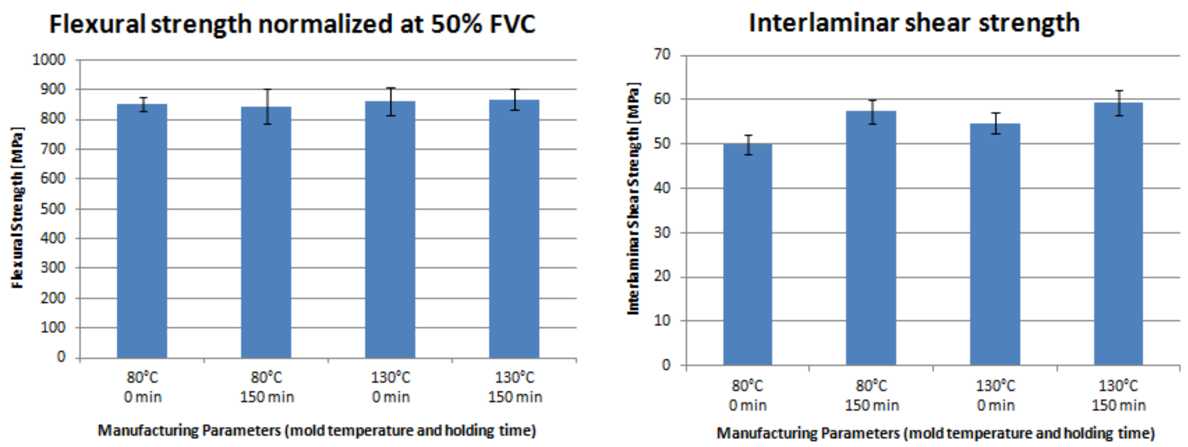

Figure 3. Sensitivity test results for hybrid OoA prepreg/RTM process.

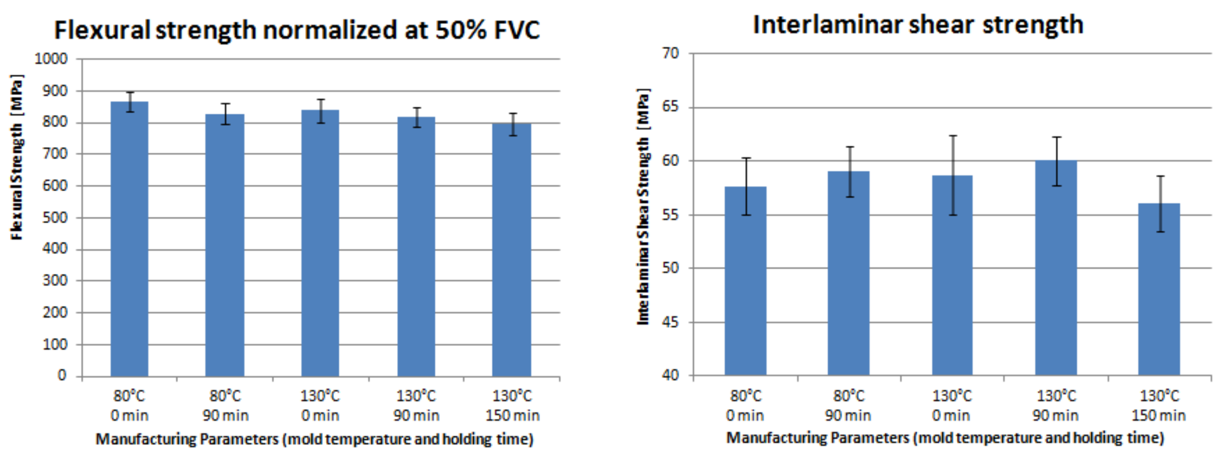

Figure 4. Sensitivity test results for hybrid OoA prepreg/VARI process.

Also for combined OoA prepreg/VARI process (Figure 4), no huge differences in achieved properties are noticeable among the different manufacturing routes. However it has to be stated that the interlaminar shear strength, which is particularly dependent on resins' interaction, is higher if an intermediate holding time (i.e. 90 min) is considered rather than the gel limit of 150 min. This result could be explained considering that a capillarity-driven bleeding is occurring before the LCM resin infusion, and it leads to a rough interface of prepreg resin having already a certain degree of cure. Therefore, if the prepreg resin is completely gelled (as in case of 150 min holding time), its mobility is reduced to the minimum, so the integration with LCM resin is compromised and possible micro-voids at the transition zone have limited chances to be compacted or filled by the matrix. On the contrary,

if the prepreg resin has not reached the gel point yet (as in case of 90 min of holding time), void reduction and better cross-linking with LCM resin are feasible.
Results of sensitivity analysis pointed out that a characterization of the bleeding mechanism is needed to select the best values for holding time and temperature, in order to set up an optimal processing route. Hence, bleeding kinetics has been studied by means of experiments and simulation tools. Experimentally, six samples have been prepared with the lay-up shown in Figure 5 (A), and cured under vacuum in an oven at 80 °C, without infusing LCM resin; the aim of the test was to analyze the time needed by the prepreg resin (from 3 or 6 prepreg plies) to bleed into 1, 2, and 3 dry fabrics. Figure 5 (B), (C), and (D) show bleeding status after 5, 15 and 45 min respectively; it is noticeable that the bleeding is a relatively fast phenomenon (the first layer of fabric is full impregnated after 45 min, using both 3 and 6 prepreg plies), thus the 90 min holding time may be comfortably halved.

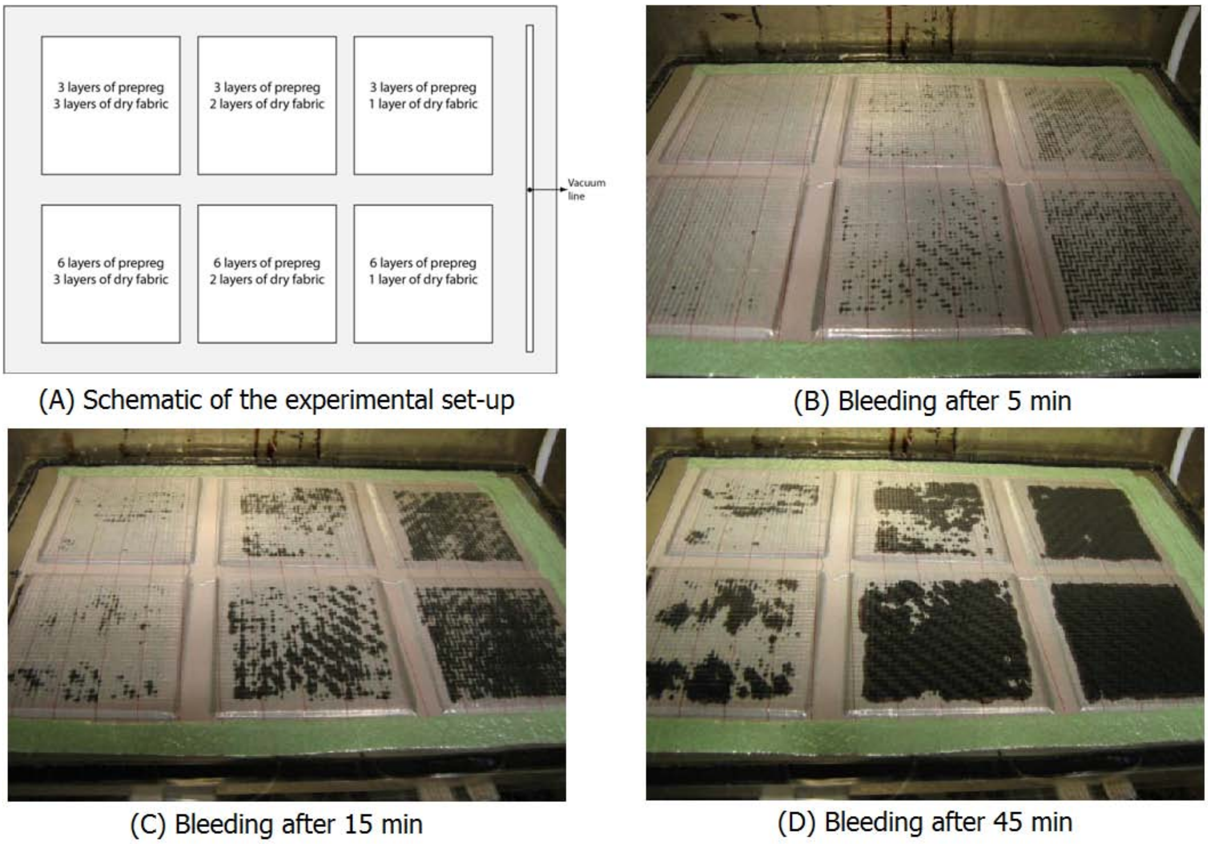

Figure 5. Prepreg resin bleeding characterization test.

Along with the experimental tests, a numerical tool has been established to simulate the bleeding advancement. The simulation results at different times are summarized in Figure 6, where, along the thickness, on the top the dry fabrics are represented in red, while on the bottom the plies wetted by prepreg resin are in blue, and the bleeding front location is the yellow line (a thin red line shows the initial separation between the prepreg-side and LCM-side as well). The simulation tool is able to estimate the evolution of the prepreg resin when a compression state is applied on the laminate. In order to optimize the process, the LCM resin should be injected before the prepreg one reaches the final position (so excessive bleeding and large void formation are avoided). However, only qualitative considerations can be drawn by the simulation results so far, since a precise out-of-plane unsaturated permeability function of the fiber volume content for the employed textile has still to be introduced in the code. Future experiments will address the problem to measure accurately this function.

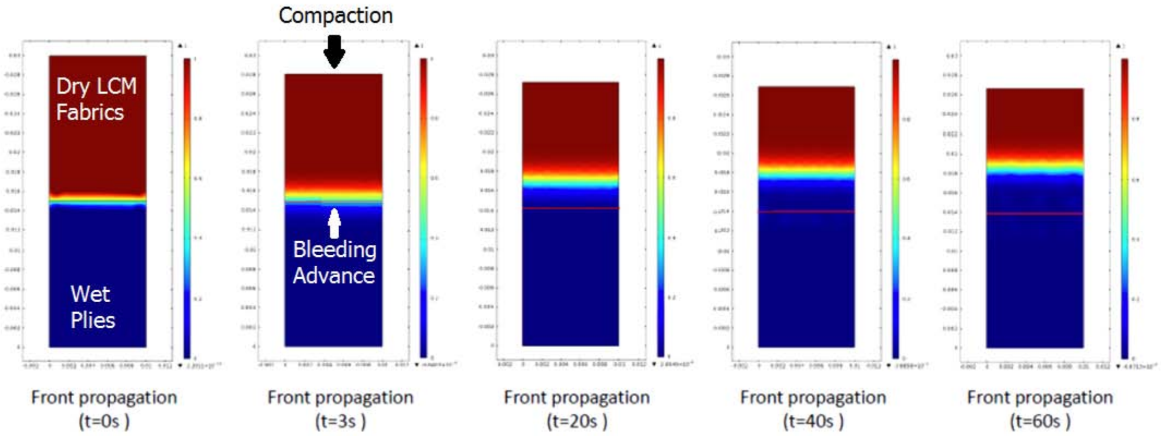

Figure 6. Prepreg resin bleeding simulation.

5 Conclusions

This paper summarizes the main results of investigations performed on hybrid OoA prepreg/LCM process in the framework of the CleanSky project – Eco-Design ITD. This hybrid technology seems to be suitable to manufacture integrated multifunctional structures, because it allows a natural combination of prepreg and LCM processing, without resorting to an autoclave, and so with technical and economical benefits.

A feasibility study has showed that the achieved mechanical properties are comparable with the ones from pure processing and typically closer to the prepreg technology. Furthermore, sensitivity tests have demonstrated that the hybrid techniques are substantially robust with regard to the main process parameters. Especially in the case of combined OoA prepreg/VARI processes, variations in the final material properties can be explained by taking into account the mechanism of the prepreg resin bleeding into dry fabrics before LCM resin infusion. In fact, mild bleeding turns to be beneficial for prepreg and LCM resins' integration and co-curing, therefore an optimal holding time to wait before introducing the second matrix in the cavity can be found (together with an optimal temperature). An experimental bleeding characterization has shown that its kinetics is rather fast and dry fabrics get impregnated already after relatively short holding times. Finally a simulation tool has been realized to predict the bleeding; it gives valuable qualitative estimations, but accurate material parameters have to be introduced to obtain reasonable quantitative results. Future work will tackle the issue to refine the simulation results, in order to figure out optimal values for holding time and temperature.

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