HYBRID FABRICATION ROUTE - COST EFFICIENT CFRP PRIMARY AIRFRAME STRUCTURES

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Abstract

The following paper presents a novel manufacturing technology for the fabrication of structures from carbon fiber composite materials. Termed "hybrid fabrication", this technology is based on a combination of the prepreg and the injection technology both of which are already established in industrial production. Numerous experimental studies have been carried out to demonstrate the utility of this procedure for the manufacture of structural parts in aircraft construction. These investigations focussed mainly on the characterization of the contact zone generated through the use of two matrix systems as well as its mechanical properties. Flow experiments with a dye-containing injection resin system and subsequent tests of the mechanical properties of the joined samples have been used to demonstrate that the transition zone of the two matrix materials does not have detrimental effects on the composite in the case of the combination of materials tested.

In order to demonstrate the feasibility of manufacture and the expected properties of a durable, hybrid-fabricated structural component, two demonstrators supplementing the proof of suitability are presented.

1 Introduction

The range of feasible technical applications of fibrous composite materials, in particular of carbon fiber-reinforced plastics, has widened substantially since their first introduction into mechanical engineering and lightweight construction. Composite materials are in widespread use mainly in aeronautical and aerospace engineering, since their high degree of stiffness and mechanical stability at low specific weight makes a substantial contribution to improving the performance of technical systems that are relevant to aeronautics.

In order to reduce costs in the production of components, the development and provision of optimized fabrication procedures is of paramount significance. Just the handling and location of semi-finished fiber components accounts for approx. 30% of the cost of injection technologies and up to 45% of the cost of prepreg structures depending on their geometric complexity [1].

The use of CNC tape-laying machines can clearly simplify the lay-up of prepreg materials with simple geometric structures. However, this is usually not feasible in the case of complex and integral components, such as stringers and frames. If mechanical stability and weight requirements necessitate the fabrication of such components by means of prepreg technology, the costs increase significantly. A promising approach to counteract this trend presented in this paper is to combine the prepreg and injection technologies.

1.1 Prepreg technology

The manufacture of fiber composite materials by means of prepreg technology has become the most widespread of all procedures of aeronautics and aerospace of this type because of the high degree of process reliability and the quality of the components attainable with this procedure [2]. The characteristic feature of this manufacturing technology is the use of individual plies of fibers after soaking or pre-impregnating them in resin (PREimPREGnated). The fiber layers are usually supplied by unidirectional continuous bands. The substantial success of the prepreg technology in the aeronautics and aerospace industry is based on the excellent mechanical strength properties of the composite as compared to other manufacturing methods.

1.2 Infusion Technology

Liquid Resin Infusion (LRI) technology is a term used for a group of manufacturing procedures that are used to manufacture fiber composites from dry fiber preforms by injecting liquid matrix materials and subsequent hardening.

The particular advantage of the LRI procedures is that they provide for comparatively free (as compared to prepreg technology) combination of fiber and matrix materials which allows high flexibility in the fabrication process to be attained. Just as advantageous is the feasibility of the use of fabrics and Non-Crimp Fabrics (NCF). These two features effect a substantial reduction of the manual lay-up effort, while even the most complex geometries can be reproduced due to the excellent drapeability of the materials.

Notwithstanding these advantages, the application of the LRI technology is associated with some problems also. For example, only a small number of suitable and aeronautics-approved resin systems are available to date. Unlike prepreg resins, injection resins require lower viscosity in order to completely impregnate the dry fibrous material in the available process window. However, the lower viscosity comes at the price of increased brittleness of the resin matrix. Consequently, the mechanical strength values attainable in the components with the LRI procedure are, in some cases substantially, lower than the values attainable by prepreg technology. Another problem associated with the injection resins is related to the high volume shrinkage rates and ensuing internal stress of the components. In this context, the incorporation of nano-particles into the matrix promises to improve the shrinking properties and the impact strength, but this technology is not yet ready for use. Technological difficulties can also be due to inhomogeneous soaking of the fibers in large and dense structures. However, problems of this kind can usually be remedied by optimizing the respective fabrication process.

The components presented in this paper are manufactured by a variant of the LRI procedure called Single Line Injection (SLI). This method belongs to the group of Differential Pressure Resin Transfer Moulding (DP-RTM) technologies. Unlike the unmodified RTM technology, these are characterized by the use of tools that are rigid on one side on which the components to be manufactured are evacuated under a sealing foil. Injection and hardening proceed optionally in a furnace or at elevated pressure in the autoclave. In the SLI procedure developed at the DLR Institute of Composite Structures and Adaptive Systems (Braunschweig, Germany), a single line is used to both evacuate the component and then (after actuating a switch) impregnate it with resin.

1.3 Combined Technologies

The idea to combine established fabrication processes in order to reduce the manufacturing costs of fiber composite components has been around for a while. Aside from pasting together already hardened composite structures, Airbus Industries has been applying the so-called co-bonding procedure in the fabrication of rudder units based on fiber composites for years [3]. In this process, individual assemblies manufactured earlier by different fabrication technologies, are pasted together by means of sequential hardening. However, the matrix systems of the assemblies do not cross-link to each other in this process.

A specific procedure using combined semi-finished parts is described in [8]. In this procedure, prepreg-made structures are placed on wet-wound carbon fiber components and then these are sealed and hardened jointly. This can be used, for example, for a wet-wound

fuselage tube with prepreg-made stringer reinforcements. Procedures of this type are called co-bonding procedures.
Another procedure using the co-bonding technology is described in [4]. In this procedure, complex and dry fiber preforms are placed on large shell structures and then impregnated with resin. In the case described therein, resin film infusion (RFI) is used for impregnation. The resin film fractions are introduced into the sealing jointly with the dry fiber pre-forms and liquefy jointly with the prepreg resin during the heating phase. The resin film preferably consists of the same resin as the prepreg resin used for the part rendering the two resins optimally compatible. However, the flow range in dry woven fabric of the resin reservoir generated by the resin film is limited such that only components with a small volume can be injected or the resin must be applied in several places of the dry preform. This problem is particularly evident when the viscosity of the resin system employed far exceeds that of a pure injection resin (e.g. prepreg resin 6376). Especially in the case of complex structures, this property makes the lay-up more difficult. It also increases the risk of creating defects since the wetting of the fibers by the resin is difficult to control. It is significantly better for a process of this type to supply the injection resin from outside with a pure injection resin.

2 Hybrid Fabrication

The term of "hybrid technology" is used in this paper to denote a fabrication procedure for the manufacture of fiber composite components that is based on a combination of proven prepreg and LRI technologies. Accordingly, a component manufactured by hybrid technology consists of a preimpregnated area and an injected area, whereby the injection resin is supplied from outside through the sealing of the component.
Thus, the application of this manufacturing procedure allows elements of the structure with a simple geometry, but exposure to high stress to be assembled solely from prepreg materials. The reinforcement or force-guiding elements with challenging geometries can be applied without much technical effort in the form of dry preforms for injection.

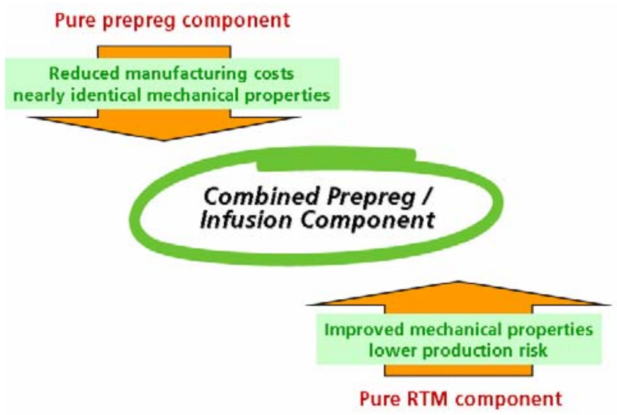

Fig. 1: Comparison of the „Hybrid Fabrication Route“ and the Prepreg and Infusion Technology [5]

The subsequent autoclave-based fabrication process includes the necessary injection of the dry fibers and joint hardening of the entire structure. The result of this procedure is a component that possesses not only the favorable mechanical properties of prepreg structures, but can also be manufactured much more cost-efficiently than a pure prepreg component because of the use of injection technology (Fig. 1).
Since the two selected procedures have opposite requirements with regard to the viscosity of the matrix material employed therein, the use of two different resin systems in hybrid manufacturing is indispensable. The assembly of a component of this type leads to the formation of a structurally critical area at the zone of contact of the various resins. Consequently, a comprehensive test of the transition zone of the composite material is required for the optimization of process control and the acceptance of the procedure in industrial-scale fabrication; this has been carried out by means of a selected pair of materials.

2.1 Physical effects in the transition zone

Prepreg materials are characterized by the non-hardened semi-finished components possessing a certain fraction of excess matrix material considering the desired fiber volume content in the fully cross-linked finished component. In regular fabrication, the excess resin material is taken up by the bleeder ply or peel ply [10]. In the semi-finished prepreg components that are customary to date, the excess of resin is very low. As a result, the dry fiber layers of the hybrid assembly may take up a certain amount of prepreg resin driven by the pressure difference between the vacuum applied to the dry fibers and the excess of prepreg resin and the capillary forces generated in the dry fiber bundles by the time of injection. This can be expected to shift the resin transition zone towards the area of dry fibers. The bleeding capacity of the prepreg material has therefore a fundamental effect in the manufacture of a component by means of the hybrid technology considered herein.

Mild bleeding into the dry fibers can even have a positive effect on the properties of the component thus generated in that it prevents an abrupt transition between the two matrix systems to form. Moreover, this effect can be used to prevent a mechanically critical border of the component from coinciding with the transition zone of the two matrix systems.

2.1.1 Transition zone between prepreg and injection resin

For assessment of the capacity of the prepreg resin to impregnate the dry fiber material, the first tests involved impregnating processes of a hybrid type without a subsequent injection step. After a certain holding time at injection temperature, the process was terminated and, after cooling, the penetration of the prepreg resin into the dry fiber material was assessed.

From the rising level and distribution of the prepreg resin, one can conclude that a capillary effect is a main drive aside from the pressure of the resin front versus the vacuum in the dry fiber material. The fact that the penetration depth is largely independent of gravity leads to the same conclusion.

2.1.2 Fluorescence microscopy of the transition zone

For assessment of the fiber layers and distribution of the matrix systems in the sample material after completion of the hybrid manufacturing process, it is customary to use polished specimen of a sample and analyze them under a microscope. The left side of Fig. 2 shows a photomicrograph of a sample manufactured by hybrid fabrication. The fibers are all oriented in the same direction and cut transverse to the direction of the fibers. The upper part shows the area manufactured by wet technology with clear distribution of the rovings. The individual prepreg layers can still be resolved in the lower part. It is not possible, though, to recognize the distribution of the matrix systems.

This can be remedied by a method that is commonly in microbiology. After treatment of the injection resin with a fluorescent dye, the dye converts the UV light of the illumination source into visible light.

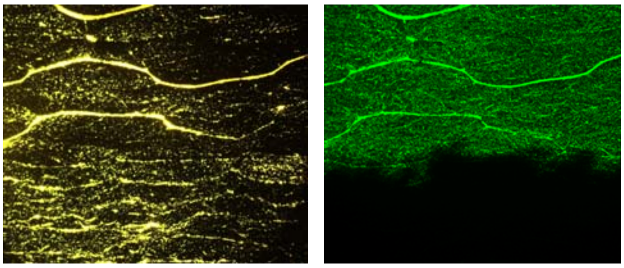

Fig. 2: Photomicrograph of a hybrid sample under visible light (left) or ultraviolet light (right) in a fluorescence microscope

A suitable filter can then be placed between sample and observer to completely blank the illumination source. The weak residual fluorescence of the dyed resin can be electronically enhanced to reveal the distribution of resin (Fig. 2, right). The prepreg resin shows up dark since it has no or little inherent fluorescence.

This method can be used to analyze the impact of various selected process parameters on the spatial distribution of the matrix resins.

The selection of a suitable fluorescence dye must take into consideration certain limiting factors. Pigmented dyes must not be used since they contain particles with diameters of the same order of magnitude as the carbon fibers. For this reason, the dyes must be fully soluble in the injection resin, or they would be washed out and the brightness of the photomicrograph taken later would no longer coincide with the distribution of the injection resin. Moreover, the dye must be thermally stable up to 180°C and must not loose its fluorescence properties after mixing with the injection resin through quenching or disintegration of the dye.
The accurate representation of the location of the injection resin by the fluorescent dye was proved by analysing a suitable sample both with the fluorescent microscope and a technique called energy dispersive x-ray analysis (EDX). The EDX enables the analysis of the element distribution on a surface of a specimen and is used in conjunction with a scanning electron microscope (SEM). By moving the electron beam across the prepared sample each element of the sample material can be detected by its characteristic x-radiation.
Sulfur, which can only be found in the hardener compound of the prepreg resin, can be used to separate the location of the two matrix resins in hybrid fabricated samples.

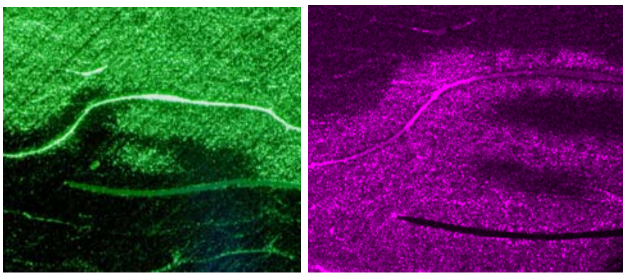

Fig. 3: Hybrid sample with green coloured injection resin (left) and purple coloured prepreg resin by EDX (right) [11]

In Fig. 3 both pictures show an overall accordance in the distribution of prepreg and injection resin in the transition zone so the generation of these structures by apotential diffusion of the dye can be excluded.

The temperature and duration of the holding step just before the injection of RTM6 emerge as the major process parameters in the hybrid fabrication process. The temperature has an impact on the viscosity of the prepreg resin and therefore on the distance the resin can migrate by flowing within the holding time. Prolonging the holding time therefore increases the extent of the distribution of the prepreg resin in the dry fiber material.
Fig. 4 (left) shows a sample manufactured by hybrid fabrication, in which a holding step of 90 minutes at 120°C was implemented prior to the injection of the dye-containing resin.

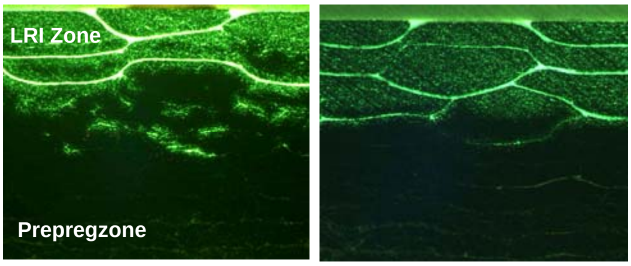

Fig. 4: Hybrid sample manufactured at a holding temperature of 120°C (left) and 90°C (right)

Compared to Fig. 4 (right), in which the duration was 30 minutes and the temperature was only 90°C, a clearly more extensive distribution of the prepreg resin and overall larger rising height into the fiber material of the wet-manufactured area are evident.
Inspecting the transition area in Fig. 4 (left) with regard to the mixing of the two matrix systems, especially the colored areas completely surrounded by the prepreg resin system are notable. These "injection resin islands" are generated mainly by capillary forces within the rovings of the UD band, whereby the areas surrounding the rovings remain rather dry. During the subsequent injection, these presumably become filled with RTM6 via channels that may also extend longitudinal to the cross-section, and thus form the visible inclusions of prepreg resin. Moreover, the exemplary analysis of hybrid-fabricated and dyed photomicrography samples by means of the energy dispersive X-ray (EDX) technique demonstrates wide-ranging consistency of the

actual matrix distribution and the distribution determined from dye distribution.

2.2 Mechanical stability tests

The successful introduction of the hybrid fabrication technology combining prepreg and wet technology will ultimately depend on whether the mechanical stabilities of the joined components are sufficient not to weaken the overall composite structure. The following test programs were carried out in order to demonstrate this feature.

2.2.1 Interlaminar shear strength

In order to determine the apparent interlaminar shear strength according to DIN ISO 14130, test bodies 30 mm in length and 15 mm in width were sampled from the respective fiber composite panels.
The thickness of the samples was 3 mm for the desired fiber volume content of 60 percent which is within the range given by the DIN standard.

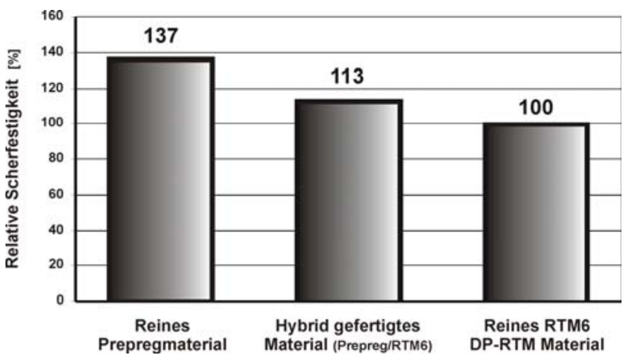

Fig. 4: Standardized interlaminar shear strengths (ILS)

Analysis of the standardized interlaminar shear strengths determined on the short bending bar Fig. 5 reveals that the shear strength of hybrid-fabricated fiber composite samples is higher than that of the pure injected materials, but lower than that of pure prepreg laminates.
Therefore, the contact zone that inevitably results from the use of different matrix materials is not a "weak mechanical link" within the detection limits. Although important for process parameter optimization, the influences of temperature and duration of the holding step were not reflected in the series of ILS samples. For this analysis, we had to resort to testing with other fracturing modes.

2.2.2 Peel strength

The experiments described in the following were used to investigate the mechanical strength properties of the transition zone by means of a more sensitive measuring procedure. For this purpose, the fracture toughness of the transition zone was tested. It is shown that this type of fracture-mechanical test is capable of reflecting process parameter-related changes in the mechanical strength properties in the transition zone [6].

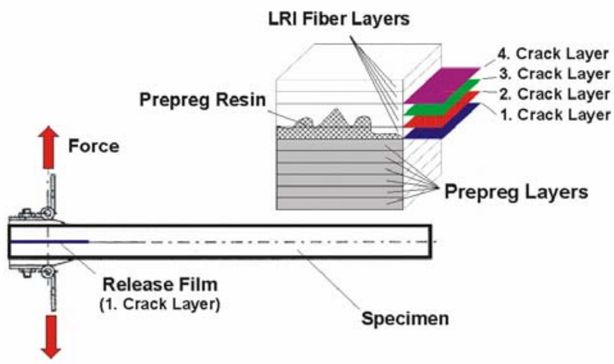

Fig. 6: Description of samples and crack positions

Peel test samples for use in the tests of fracture toughness were prepared and tested in accordance with DIN 6033. Since a crack in the form of an inserted halogen film was required for this type of sample, as shown in Fig. 6 , it had to be ensured that this crack coincided with a relevant interlaminar separation plane containing the corresponding matrix transition. Since it was impossible to exactly determine the actual position of the prepreg resin in the transition zone, the number of samples for each parameter variant was increased to reflect four different crack levels.
A series of samples made from pure prepreg vs. pure injected fiber material was prepared in order to demonstrate the independence of the fracture toughness values thus measured from the crack level. The results obtained with this

series of samples demonstrate the independence from the actual layer, since all samples yielded the sample fracture toughness values with a standard deviation of less than 2.5%.

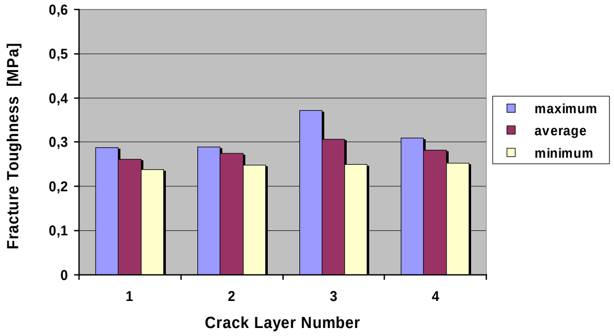

Fig. 7: Distribution of fracture toughness in hybrid-fabricated samples manufactured with a holding time of 90 minutes at 120°C

Some preliminary rheological tests on prepreg resin system 6376 were carried out in order to determine the sensible ranges of temperature and holding time to be varied in the experiments. This resulted in the use of two temperatures and two holding in the investigations of the influence of process parameters on the fracture toughness: 120°C at a holding time of 1.5 h and 90°C at a holding time of 0.5 h. The comparison of the respective samples evidenced that these parameters do indeed have an impact on the sample. The fracture toughness values of the samples with a holding temperature of 90°C and 30 minutes holding time are approx. 30% higher than those of the samples manufactured with a holding time of 1.5 h and 120°C holding temperature.
The distribution of fracture toughness within the different layers of the hybrid-fabricated samples shown in Fig. 7 reveals a peak of fracture toughness at exactly the crack level at which the matrix transition zone is expected to be. The relatively low values in the direction of the prepreg at crack 1 were confirmed in tests on pure prepreg material. The fiber volume content determined in these tests by analysis of photomicrographs was approx. 60%.
The influence of the process parameters on the distribution of fracture toughness is shown in Fig. 8. In this test, both the temperature and the holding time were reduced to 90°C and 30 minutes, respectively, before injection of the resin. Considering these parameters, the rising height of the prepreg resin into the dry fiber material and therefore the shift of the transition zone of the matrix systems from its original position can be expected to be reduced.

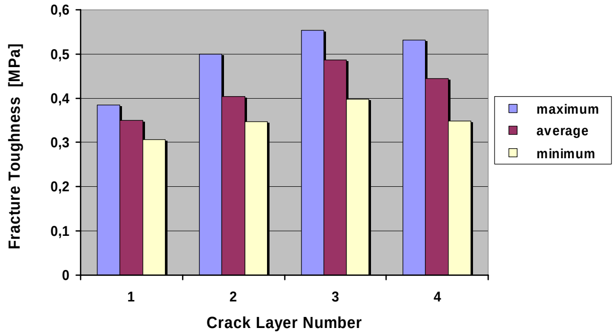

Fig. 8: Distribution of fracture toughness in hybrid-fabricated samples manufactured with a holding time of 30 minutes at 90°C

Fig. 8 indeed shows a peak of fracture toughness at the level of the third crack. The overall magnitude of the toughness values is higher in this series of samples than with the process parameters for higher rising heights. One possible explanation is the ratio of the relative gelling times of the two matrix systems. At a holding temperature of 120°C and 90 minutes holding time, the cross-linking of the prepreg resin proceeds significantly beyond the level at lower temperatures and shorter holding times. One possible consequence might be lesser bonding to the subsequently injected resin and therefore slightly lower fracture toughness.
Whether or not the peaks of fracture toughness thus determined truly reflect the position of the transition zone between prepreg resin and injection resin remains to be investigated, for instance with the EDX technique. However, it can be concluded that the peel samples again show that the resin transition zone is not a weak point in a component, but may even tend to improve the properties of the transition zone.

3 COMPONENT DEMONSTRATORS

So-called demonstrators are used not only to demonstrate the feasibility of manufacture and the testing of fabrication methods, but also to provide proof of the successful implementation of mechanical concepts. Components for each of these purposes were prepared.

3.1 Stringer-reinforced panel

One possible and promising application of hybrid fabrication is the utilization of components to be injected that are made from dry and easily draped fibrous semi-finished parts as reinforcing elements on prepreg shells.

Fig. 9: Dry stringer preforms (left) and prepreg shell (right)

Such structures are always needed where thin-walled shells have to bear large torsional and flexural loads.

Fig. 10: Assembly of the stringers on the prepreg shell with pressure plates

Their membrane-like structure makes components of this type quite sensitive to denting and therefore requires suitable reinforcement. Stringers and frames, e.g., are used for reinforcement in fuselage tubes and wing boxes. Planar or slightly curved prepreg shells with sufficiently large radii can be layed-up automatically with CNC-controlled machines. This leads to a significant reduction of the cost of lay-up of the shell material. In the shell demonstrator presented in this paper, the stringers are provided in the form of so-called omega-stringers with a Rohacel foam core.

One layer of woven fabric each on top and on bottom was taped by means of a binding agent as a final layer in order to stabilize the stringer cells (Fig. 9, left). Stringers with this design are largely inherently stabile and do not require tools for their assembly other than covering plates. Layers of fabric hoses are used as the main layers of the stringer.

Fig. 11: Finished stringer-reinforced prepreg shell made by hybrid fabrication technology

The prepreg shell with a wall thickness of 2 mm was built-up with the layers at angles of 0°/90° (Fig. 10 right). After lay-up of the prepreg, the stringers were positioned on the shell without any difficulties, then provided with covering plates, connected to the resin lines, and sealed under a vacuum foil and evacuated. Fig. 10 shows the stringers in final position on the prepreg shell shortly before the installation of the resin lines. The finished shell demonstrator is shown in Fig. 12 . Ultrasound scans taken subsequently revealed that the points of attachment of the stringer foot to the prepreg shell are free of defects and largely free of pores.

3.2 Fracture experiments on spars (subjected to bending)

The hybrid fabrication concept will be successful only if not only the feasibility of the manufacture of components from the combined semi-finished parts, but also the preservation of the favorable properties of the materials in the combination can be shown. For this purpose, a three-cell experimental spar was designed to allow for a direct comparison in fracture tests to be made between a spar made solely by injection and a spar made with prepreg fractions[7].

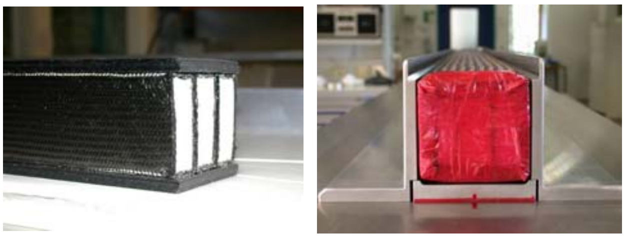

Fig. 12: Manufacture of the spar with prepreg belts (left); spar with final wrapping in the tool (right)

The concept of the three-cell spar allows the load from the thrust of the web to be introduced into the spar caps in multiple places rather than focussed in just one point of web-cap attachment. Tensile and compressive forces are taken up mainly by the cap bands in a spar.

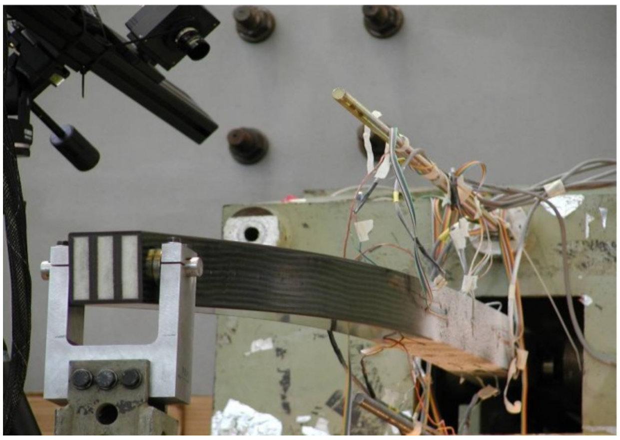

Fig. 13: Fracture testing of a spar with prepreg belts

High-stiffness and high-strength materials are preferably used as materials in this test. These areas are particularly well suited to accentuate the favorable properties of UD carbon fiber prepregs. For this reason, an experimental spar each with injected and prepreg caps was constructed and then exposed to load until fracture occurred. The four spar webs are identical in the two spars and take the form of wet preforms. The structure of the spar with prepreg cap bands and web cells made of dry fabric tubes is shown clearly in Fig. 13 (left). The right part of Fig. 13 shows the finished preform with its final layer of fabric tube in the tool (no lid yet) ready to be sealed.

Fig. 14: Break point after fracture; top: wet spar with belt detached; bottom: hybrid spar

The fracture experiments were very successful with regard to the nominal loads (15 kN, wet spar and 16 kN, hybrid spar): 15.27 kN were achieved with the pure wet spar and 16.24 kN with the hybrid spar. In both spars, the pressure cap was shown to have failed due to pressure fracture. However, unlike the wet web (Fig. 14 , top), the prepreg cap remained attached to the web cells over the entire length of the component except for the fracture zone (Fig. 14 , bottom). This observation can be explained by the better shifting properties of the free prepreg filaments affording better contact in the chamfer of the web cells. However, the enlargement of the contact area of web cells and spar cap due to this effect is quite small compared to the plain width (< 8 %). For this reason, it is more likely that the improved mechanical properties of the tough-modified prepreg resin that penetrated into the contact zone during the heating phase of spar production is responsible for the better attachment of the spar cap to the web cells. With regard to the ability of a functional component to bear mechanical loads, these observations and the fact that the calculated fracture loads were actually attained demonstrate the successful applicability of the hybrid fabrication technique. The desired combination of the favorable properties of the semi-finished parts is indeed preserved in the finished component.

4 SUMMARY

The hybrid fabrication technology presented in this paper is an attractive alternative to established manufacturing methods. The suitability of this novel method for the manufacture of aeronautical components has been demonstrated by a large variety of methods. For this purpose, components and samples manufactured with this technology were systematically tested for their performance using technological and material parameters that can be measured in experiments as the criteria. The investigations focussed mainly on the compatibility of the matrix materials, characterization of the transition zone, determination of the mechanical properties, as well as the manufacture and testing of entire assemblies. The latter tests were designed to reveal the behavior of the material when exposed to complex loads and serve as the basis of a comparison with composite materials manufactured by other technologies.

The characterization of the transition zone allowed us to prove that the impregnation behavior of the prepreg resin is a function of the two process parameters, holding time and holding temperature. Experiments with dyed injection resin to investigate the flow behavior showed in all samples tested some "merging" of the matrix materials used therein. In contrast, the direction of action of gravity has only a negligible influence on the observed soaking properties and attainable rising heights.

Proof of the suitability of the pair of materials used in the work presented in this paper for fabrication purposes was provided by determining the interlaminar shear strength (ILS) in accordance with DIN 65 148. The values were found to be independent of the fabrication method selected in the individual case in that they showed only minor variation. Peel tests in accordance with DIN EN 6033 were carried out in order to assess the influence of the main process parameters. These tests confirm the insights gained in the ILS tests and show that the contact and transition zone, if anything, is even stronger, in terms of the fracture toughness measured, than pure prepreg or pure injected areas.

Demonstrators were then used to show the manufacture of complex components by means of hybrid fabrication. Fracture experiments with spars made by wet technology with and without a prepreg fraction allowed us to demonstrate that the combination of favorable mechanical and process engineering properties of the semi-finished parts is retained in a component made by hybrid technology.

It can be concluded that the fabrication procedure investigated in this work is, on principle, suitable for the manufacture of carbon fiber-reinforced composite materials. Negative effects on the properties of the components due to the combining of two different matrix materials and different types of semi-finished components were not detected. In fact, there are even some synergistic effects from the combination of fabrication methods in that the fracture toughness of the resin transition zone was found to have improved.

Since all tests presented herein have only used static loads, there still is the need to carry out tests under dynamic load conditions to demonstrate the applicability of the procedure in the future. Because of the large effort involved in investigations of this type, they are justified only when concrete applications with defined semi-finished parts are being planned.

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