Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Summary

In the framework of a national technology program an one shot manufacturing process for closed composite box structures with accurate dimensions was developed. The goals of the program were the development of a manufacturing process which leads to net shaped box structures with a dimensional tolerance of ± 0.05 mm and the development of a reliable stringer/skin attachment without rivets. An RTM manufacturing concept with matched Invar tooling and a prepreg preform with stitched spars and stringers was developed. Three generic box structures were manufactured successfully. The dimensional tolerances of the boxes were within ± 0.05 mm and within ± 0.3º.

Contents

(14 pages in total)

1 Introduction

In the framework of a national technology program, Fokker Aerostructures and NLR conducted research in the field of composite manufacturing techniques. Within this program a method had to be developed for the manufacture of net-shaped closed box structures with dimensional tolerances within ± 0.05 mm and within ± 0.5º. For this purpose a generic box structure with dimensions 600 x 600 x 54.1 mm was designed. The closed box structure consisted of two I-spars, two C-stringers and a top- and bottom skin, see figure 1.

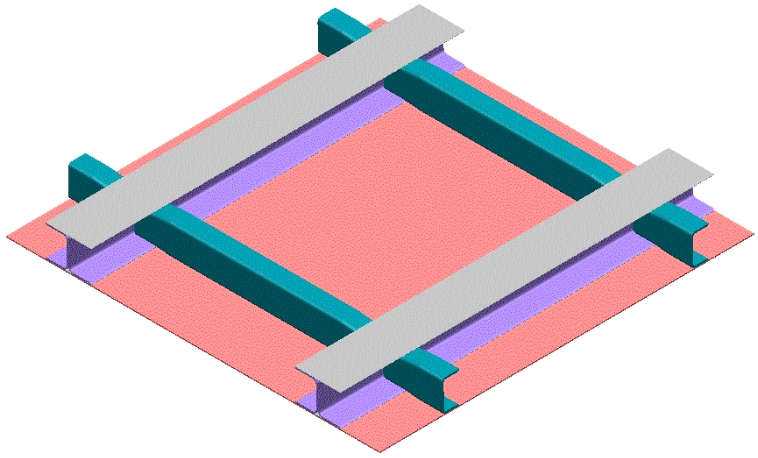

Fig. 1 Generic box structure (top skin not shown)

Because of mechanical and temperature requirements for the applications intended, the resin system Cytec Cycom 5250-4 and IM7 fibers were selected. With this material, the box was designed with skins with a quasi-isotropic lay-up of 12 plies UD-tape (145 gsm), fabric I-spars with a web-laminate of 18 plies (203 gsm) and C-stringers of 12 plies fabric. As a back-up design, the skins were designed with a quasi-isotropic lay-up of 8 plies fabric.

For this type of box structures acoustic fatigue can be a design driver, so the spar- and stringer/skin attachment is critical. To prevent debonding or stringer pop-off, rivets are often used, but currently Z-pinning and stitching are considered to be interesting alternatives, see reference 1. In the design of the generic box the I-spars and C-stringers are stitched to the lower skin with a Kevlar thread (K49, 2x40 Tex). The flanges of C-stringers are also stitched near the radius of the web. Rivets are used for the connection of the spars and stiffeners to the top skin.

In this paper the manufacturing concept developed for net-shaped closed box structures is presented. Furthermore the results are evaluated and conclusions concerning the use of prepreg preforms in combination with RTM processing are drawn.

2 Process and material selection

The main goal of the box development program was the development of a manufacturing process, which leads to net shaped products with accurate dimensions. Ideally, the manufacturing process is robust and cheap, and suitable for all types of composite doors, box structures and related types of products. The fact that the resin system Cycom 5250-4 is available both as prepreg and as an RTM resin implies that several process solutions are possible.

At this moment, autoclave processing still is the standard method used in the aerospace industry to manufacture structural composite components. However, the use of Resin Transfer Moulding (RTM) is increasing gradually, especially for complex shaped components with accurate dimensions. In this case autoclave processing is not feasible because of the dimensional tolerance requirement of ±0.05 mm, and RTM with matched metal moulds will have to be used. With Cycom 5250-4 however, parts that are difficult to preform with dry fabric or have to be made of UD-material for stiffness reasons, can be incorporated as a prepreg (B-stage) part in the preform. Furthermore, using prepreg for the preform can reduce the risk of dry spots and fiber misalignment, see reference 2. Also it is expected to have less resin shrinkage, because the B-stage prepreg already is polymerized to a certain degree. Because of this it is expected that the use of prepreg for the preform will lead to easier preforming for box type structures and a more robust process.

The structure of the generic box is not heavily double-curved but on the other hand rather complex in some areas like the C-spar/I-spar intersection. Because of the complex shape of the preform in this area, difficulties with fiber alignment and three-dimensional flow paths during injection can be expected. This makes the generic box structure ideally suited to evaluate the application of prepreg preforms in combination with RTM processing. Based on these considerations it was decided to develop a single shot manufacturing concept with a (stitched) prepreg preform in combination with RTM processing.

If prepreg is used for the preform, it is important to keep in mind that the cured ply thickness of a prepreg is based on sufficient resin flow under autoclave pressure. The ply thickness of a prepreg ply before curing usually is about 10 % higher than after curing. This means that compared to autoclave laminates of the same material, the effective thickness of a ply has to be increased to be able to close the mould. To prevent this problem, the cured ply thicknesses of both the UD-tape and fabric were increased with 10 %. In general the concept with prepreg preforms implicates that a prepreg with a fiber volume of more than 62 % has to be used if a fiber volume content above 55 % is desired.

3 Design of the tooling

3.1 Simulation of the injection process

In order to achieve accurate dimensions without shimming during assembly the complete box has to be manufactured with accurate metal tooling in one shot. Because the top skin will be riveted afterwards, a concept with removable tooling inside the box is feasible if the top skin can be replaced to its exact position after tooling removal. This can be realized by using a perforated separation film between the spars/stringers and the top skin. However, manufacturing the whole box in one shot with such a perforated film included gives a more complex injection process that might influence the tooling design. Therefore flow simulations have been carried out with the software tool RTM Worx.

First a model of the generic box structure is built. Next, the permeability of the materials used has to be incorporated. Usually the permeability of materials can be measured, see reference 3. However, in this case prepreg will be used. Because the fibers of a prepreg are more or less impregnated with a B-stage resin, the material does not have a permeability that is comparable to any dry preform. With a prepreg preform, the amount of resin transfer through the preform will depend largely on the viscosity of the B-stage prepreg resin. To determine the relation between temperature, time and viscosity, rheology measurements are carried out on the prepreg, see figure 2. Based on the rheology measurements an injection temperature of 130 ºC was selected.

Fig. 2 Rheology measurement equipment

After determination of the parameters flow simulations were carried out. Simulations with a single point or single line injection strategy did not produce useful results because many air inclusions were predicted. Therefore, simulations with central injection simultaneously at both skins were carried out. With this injection strategy the flow simulations showed that the resin arrives at the edges of the skins and the edges of the webs of the stringers and spars simultaneously, see figure 3. This means that ventilation ports at the edges of the skins and edges of the webs of the spars and stringers will be necessary.

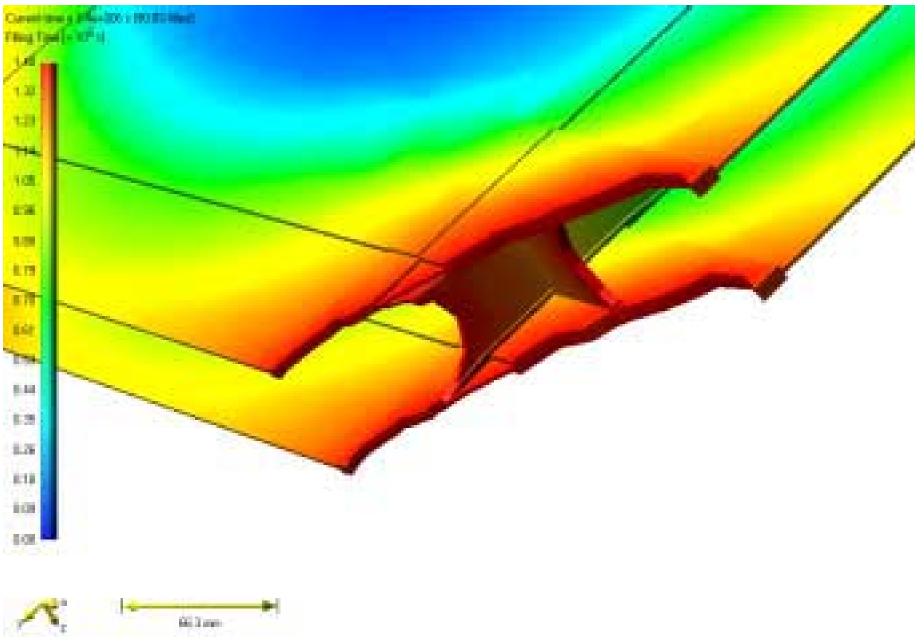

Fig. 3 Results of flow simulations for dual point injection

3.2 Design of mould parts

Because accurate dimensions of the cured product were very important and the tooling concept had to be suitable for larger structures also, it was decided to use Invar 36 as mould material. Invar 36 has an expansion coefficient of only $1.6e^{-6}$/°C, which is about the same as quasi-isotropic carbon/epoxy laminates ($\alpha = 2 - 3e^{-6}$/°C). This prevents all problems related to different expansion coefficients, and enables the use of a preform that fits in both a cold and a hot mould. Also, the cured product can be released from the mould at room temperature without difficulties due to thermal stresses. Disadvantages of Invar 36 are the low hardness, the poor machining properties and the fact that it is expensive.

Flow simulations have shown that the box can be injected in one shot, so now a tooling concept with removable metal blocks inside the box structure had to be designed. The mould concept developed can be seen in figure 4, and consists of a lower mould, a middle section with a ring, several blocks and a central section, and an upper mould.

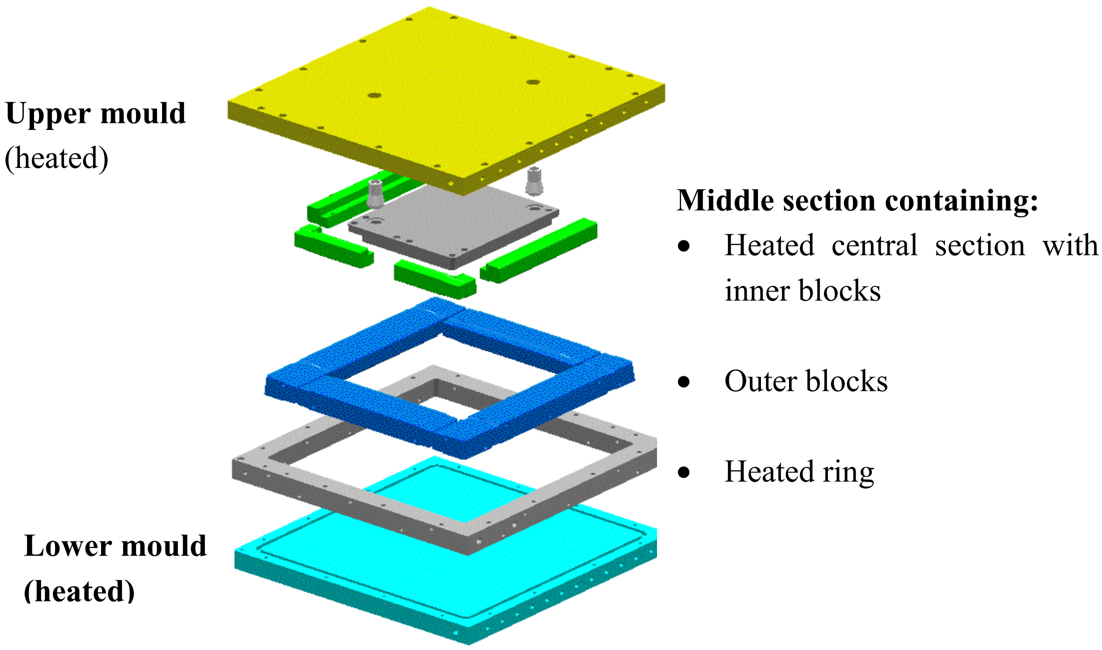

Fig. 4 Mould concept for the closed box structure

In the middle section of the mould several requirements have to be met. First of all, the middle section has to enable an airtight assembly of the mould and provide accurate dimensions of the spars and the skins. Furthermore all parts have to be heated and must be removed after curing without damaging the component. Because of the flanges of the I-spars and C-stringers, separately removable blocks have to be used inside each flange. The easiest way to heat the removable blocks is by means of conduction from the counter part. Therefore the blocks for the outer flanges of the spars and stringers are heated by mounting the blocks on an oil-heated ring. For the inner flanges of the spars and stringers four blocks are mounted on a central section with oil heating, see figure 4. In order to provide accurate dimensions of the spars, stringers and skins, all blocks are positioned with tight fitting bolts. To enable easy mounting and demoulding, all contact surfaces between the blocks, central section and ring do have a slope of 5º. The connectors for oil supply to the central section are pointing through the upper mould part. This implies that the upper skin op the composite box will have two holes, but for composite box structures this is required for in service inspection anyway. The holes in the upper mould part also provide the positioning of the central section with the four inner blocks.

4 Manufacturing of three box structures

4.1 Laminating of the preform and assembly of the mould

Because prepreg was used for the preform, the techniques applied were equal to the techniques used for autoclave products. This provides easy material handling and preforming, accurate fiber orientations and the possibility to use unidirectional plies.

The plies for the C-stringers were laminated directly on the RTM-tooling. The shape of the C-stringer has strongly double curved parts at the ends, which made it necessary to apply some cuts. Laminating each ply separately enabled a good distribution of the cuts and simplified the laminating. A separate laminating tool was used for laminating the I-spars. The fillers in the radii of the I-spars are stacked with UD-tape material with a 0º orientation. Next, all stiffeners were stitched to the two top plies of the lower skin, starting with the I-stiffeners. For stitching, a twisted Kevlar 49 thread of 2x40 Tex was used. For this thread a thickness of 13 layers of prepreg is the maximum thickness that can be stitched without regular failure of the thread. Therefore the stringers and spars were stitched only to the first two plies of the lower skin.

After stitching the sub-assembly of the two top plies of the lower skin and the spars and stringers, the subassembly was placed on the remaining plies of the lower skin. This preform then was positioned on the lower mould. Next the inner blocks and the central section were mounted in place. Next the outer blocks were placed. Although in the design the cured ply thickness of the prepreg was increased with 6 % to compensate for the higher thickness of an uncured prepreg ply, the thickness of the preform still was too high. Due to this, the outer blocks could not be placed exactly in the correct position. However, because of the slope of

5º, the ring could be mounted over the outer blocks, pushing the outer blocks to the right position.

Before placing the upper skin on top of the spars, first a perforated release film was applied on top of the spars, stringers, the central section and the blocks. On top of the release ply the upper skin was applied, followed by the upper mould. In order to prevent bending of the lower and upper mould, the assembled mould was clamped in a clamping frame. The total assembly is shown in figure 5.

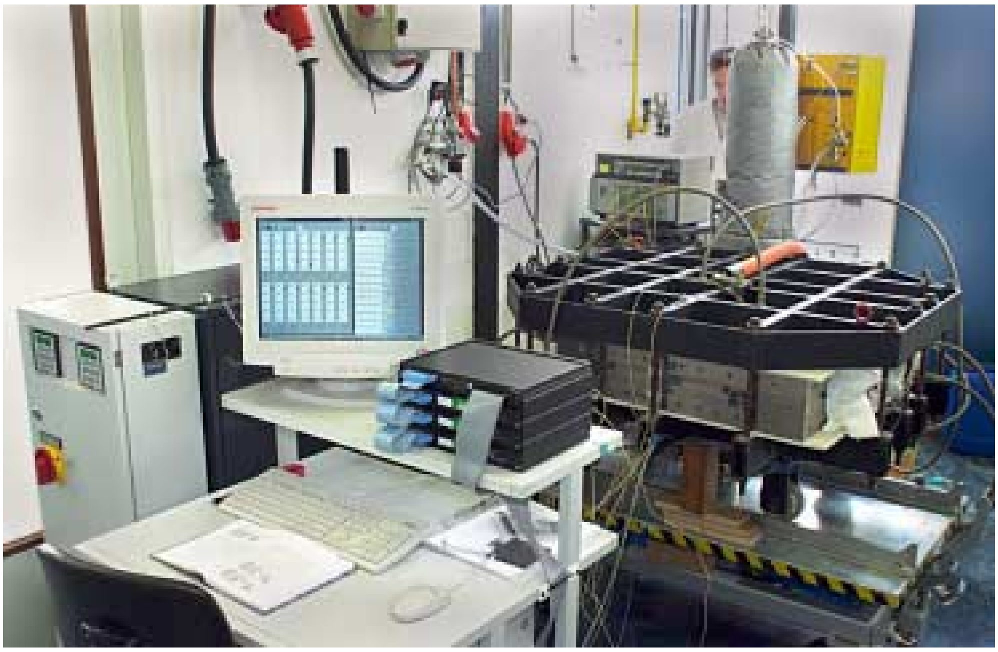

Fig. 5 Set-up of the mould, data-acquisition and RTM-machine

4.2 Injection of the box structures

Because of the risk for staging the B-stage prepreg resin, the process window is small and the possibilities to interrupt or change the process from the moment the mould is heated are very limited. Based on the rheology measurements an injection temperature of 130 ± 5 ºC was chosen, At this temperature a time of approximately 40 minutes was available to inject the component if the mould was heated rapidly from room temperature to injection temperature. The box structures were injected with a constant flow, and cured at 180 ºC with 8 bar pressure.

After curing the boxes were released from the tooling and postcured for 6 hours at 230 ± 5 ºC in an oven. The upper skin could be released easily due to the perforated film. The blocks inside the spars and stringers were hard to release, probably due to the fact that the expansion coefficient of Invar 36 (1.6 $^{e-6}$/ºC) is even lower than the expansion coefficient of the cured quasi-isotropic laminate, which is approximately 3 $^{e-6}$/ºC.

4.3 Results

The first generic box, made with skins of UD-tape, is shown in figure 6. The outer plies of the skins were slightly distorted due to the resin flow around the injection port. However no other visual defects could be seen.

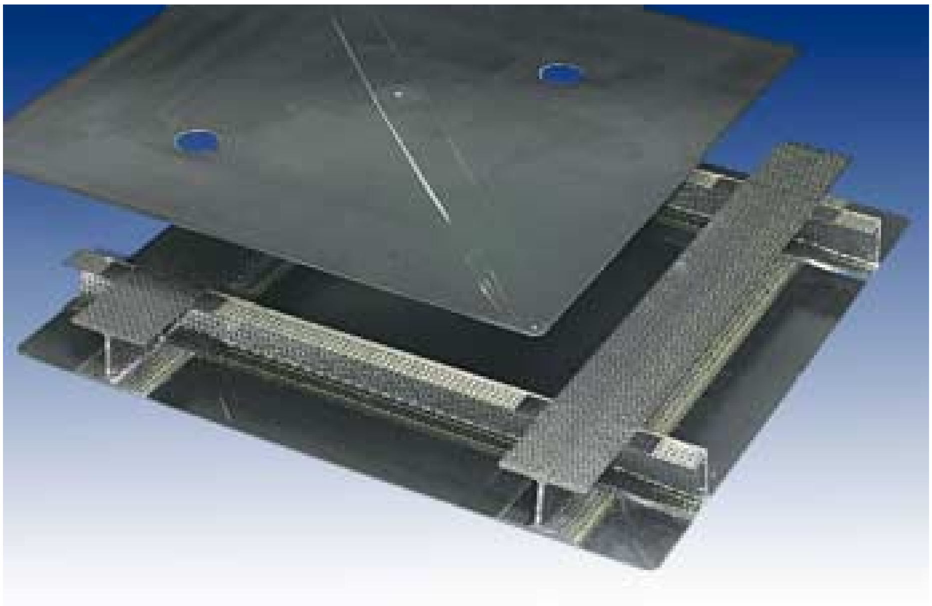

Fig. 6 Generic box structure with skins of UD-tape

The second and third box were made with skins of fabric. With fabric, the injection of fabric through the prepreg preform is easier because of the lower fiber volume contents and the “open” structure of the fabric. Furthermore, no fiber distortion occurs because the fiber bundles are locked within the fabric structure, see figure 7.

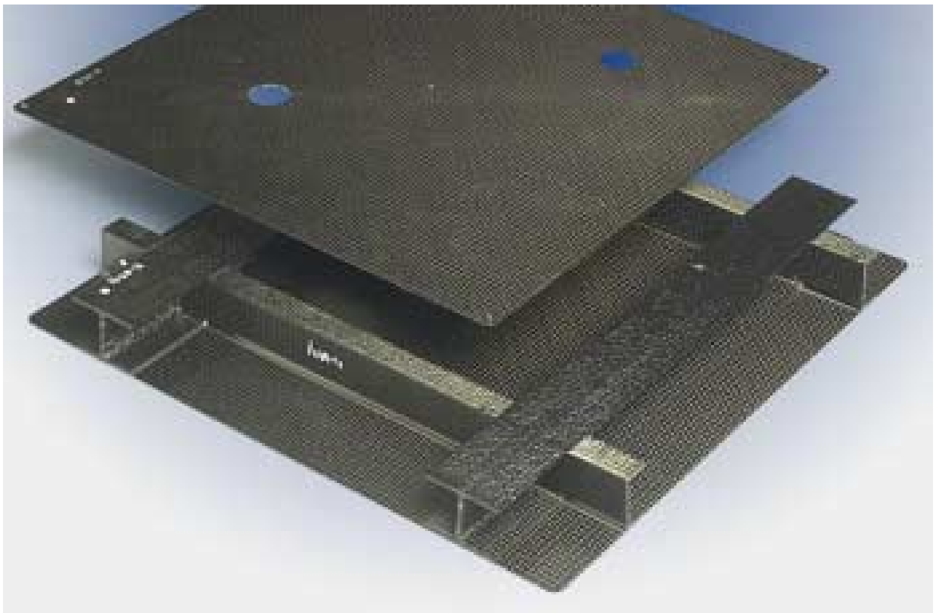

Fig. 7 Generic box structure with fabric spars, stringers and skins

The boxes were inspected with C-scan equipment using a 5 MHz probe. At a few spots underneath the fillers of radius of the C-stringers small delaminations were found. Furthermore the two boxes with fabric skins showed some porosity at two edges of both skins. This was due to cold spots in the mould. Except for these small defects no deviations were found. The small delaminations probably occurred due to a non-correct structure of the filler, which blocked the resin flow in this area. The mould temperature in the area with the local porosity in the fabric skins was approximately 10 ºC colder. This was caused by heat loss at the edges of the mould, and an insufficient number of oil channels.

The results with the three boxes show that the use of accurate preforms and an even mould temperature distribution is very important if prepreg preforms are used. An inaccurate preform or a scatter in mould temperatures will cause the origination of resin paths instead of a homogeneous flow front through the B-stage prepreg resin. Once a resin path to the vents exists, no RTM-resin will flow into the remaining part of the structure because of the differences in viscosity between the prepreg resin and the RTM-resin.

The dimensions of the first box with skins of UD-tape were measured with a digital DEA measuring machine. The deviation of the thickness compared to the mould cavity was within the target of ± 0.05 mm. The angles of the flanges were within a tolerance ±0.3º of the theoretical angle. This box was also mechanically tested. The tests were completed successfully and no damage was caused in the interfaces between the skins and the stringers and spars. Furthermore the small delaminations between the C-stringers and the lower skin did not grow.

5 Conclusions

Using a prepreg preform, Invar tooling and an one shot RTM manufacturing process, three generic boxes were made. The first generic box consisted of fabric spars and stringers and skins of UD-tape. To reinforce the stringer-skin attachment Kevlar stitching was applied for the attachment of the spars and stringers to the lower skin. For the second and third generic box structure, fabric was used for the spars, stringers and skins. In these box structures no stitching was applied.

In general the manufacturing concept developed works rather well. If the right processing parameters and fresh prepreg materials are used, complex products of good quality can be made easily. Advantages of the use of prepreg for the preform are easy material handling and preforming, accurate fiber orientations and the possibility to use unidirectional plies. Furthermore a really dry spot will not occur, but porosity and delaminations still can appear.

Disadvantages are the small processing window and the limited flexibility to interrupt or change the process from the moment the mould is heated. Also, stitching is more difficult with prepreg as with dry fabric. If prepreg is used for the preform, a high heating ramp rate from room temperature to injection temperature and an even mould temperature distribution is necessary to prevent partial curing of the prepreg during heating. This limits the application of prepreg preforms to rather thin walled structures without unheated inserts. Furthermore, prepreg with a fiber volume of more than 62 % has to be used if a fiber volume content above 55 % is desired in the final product.

In the case of the generic box structure, the concept with prepreg preforms and RTM processing provides a net shaped product with accurate dimensions. The manufacturing concept with matched tooling of Invar 36 worked well and provided dimensional tolerances within the goal of ±0.05 mm. The angles of the flanges were within a tolerance ±0.3º of the theoretical angle. However, Invar 36 is soft which gives problems with fretting and surface damage. Invar alloys with about the same expansion coefficient but higher yield strength and more hardness will be a better material for this kind of matched tooling.

6 References

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