COMPOSITES IN HIGH-END INDUSTRIAL APPLICATIONS

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ABSTRACT: Many high-end industrial applications feature moving parts, which need to be positioned very accurately or need to be transported very fast. Examples are parts in large milling machines, camera cranes, optical instruments in satellites and medical applications. Traditionally, these parts are constructed in metals like steel, or in some cases aluminium. Most high-end industrial applications are designed for high natural frequencies to avoid problems with vibrations. Composites can offer a further step in achieving a higher accuracy or higher speeds. This paper describes the design and production process development of an example of a high-end composite industrial application.

KEYWORDS: Industrial applications, vacuum infusion, flexible tooling, process control, preforming, fibre bridging, degassing

INTRODUCTION

The aim of this study is to demonstrate the technical and economical feasibility of the use of high-end composites, composite design solutions and composite production processes in industrial applications. In some high-end industrial applications, many similarities can be seen with the traditional composite applications from the space or aeronautical industry. Not just specific strength and stiffness requirements are important, but also specific subjects like tolerances, load introductions and joints. Composite materials can offer advantages over metals with respect to a higher internal vibration damping and no risk of Eddy currents in magnetic fields. If designed properly, composite structures do not suffer from fatigue damage which might allow for higher loads or longer design life. For structures performing under temperature gradients, composites can be applied in such a way that for a certain temperature range zero thermal expansion can be achieved which further enhances the accuracy of the application. This paper describes the design and production process development of an example of a high-end composite industrial application. The structure is a highly integrated carbon-epoxy carrier structure. A redesign from the original milled metal structure was made and analysed. It will be demonstrated that composites can offer great advantages and do not have any mayor drawbacks, which would prevent the application in most high-end industrial applications.

DESIGN OF DEMONSTRATOR

The original demonstrator is a milled metal carrier platform. It is a fast moving part which needs to be positioned very fast and very accurately. Several sensors are mounted on the structure, which needs to stay in place within nanometres. Therefore, the structure needs to be very stiff, very light weight and show very high natural frequencies to minimize the risk of vibrations and to ensure the required accuracy of positioning. During the service life, occasional crash loads can be introduced by surrounding structures by attachments on the four corners of the box. After such a collision, the sensors still need to be positioned accurately within nanometres. A redesign in composite will have to meet all these structural and geometrical requirements.

Conceptual design

A conceptual design of the carrier structure consists of a highly integrated carbon epoxy box.

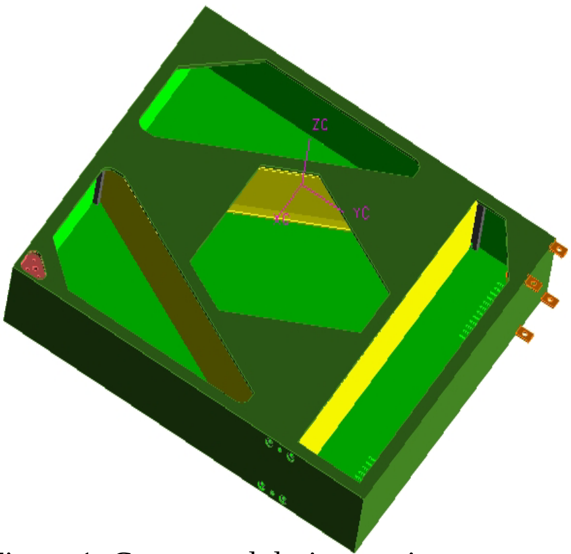

Figure 1: Conceptual design carrier structure

During a brainstorm session, various manufacturing concepts were considered. Since sensors need to be mounted on the outside and the structure was to operate within a limited geometrical volume, it was obvious rigid outer tooling was required. For the ease of manufacturing and to limit the costs of producing the first prototypes, the structure was subdivided in to two separate structures which will have to be assembled afterwards. These to structures are the outer rectangular box, including top flanges and a triangular box which fits in the outer box. A clever geometrical lay-out will ensure an easy assembly by bonding and a proper load transfer after assembly. The substructures will be produced by vacuum infusion in single-sided stiff outer tooling under flexible inner tooling. Any design changes like thickness changes would then still be possible without the need for new tooling. For future series production, pressure infusion in double-sided stiff tooling would be the best option, although the inner tooling would have to be divided in several smaller blocks to allow demoulding.

Conceptual process development

It was decided to use a resin infusion process. This would allow for the use of a room temperature curing epoxy resin systems which would minimize the risk of geometrical inaccuracies due to thermal expansion of the mould. Furthermore, infused laminates based on fabrics allow for better milling with less risk of delamination. Since a high degree of integration is aimed for, conventional tooling can not be used. A dedicated preform method based on folding flat cut-outs was developed to be able to produce accurate performs. The injection strategy for the structure was validated by infusion simulations and simple infusion experiments on flat specimens. The infusion tooling, including the basis infusion strategy is shown in Figure 2. The preform is placed in the rigid outer tooling. A flat metal ring is placed on top of the preform and mould top ensure a good surface definition of the top side of the flange. A preshaped reusable rubber mould is placed in the preform and sealed on the top of the rigid outer mould. Resin is introduced along a channel around the top flange. From there, the resin flows to a central located vacuum outlet. By infusion at a low absolute pressure and curing at a high absolute pressure, in combination with proper degassing of the resin [1], airtight tooling and a very accurate fibre preform, a void free laminate can be produced.

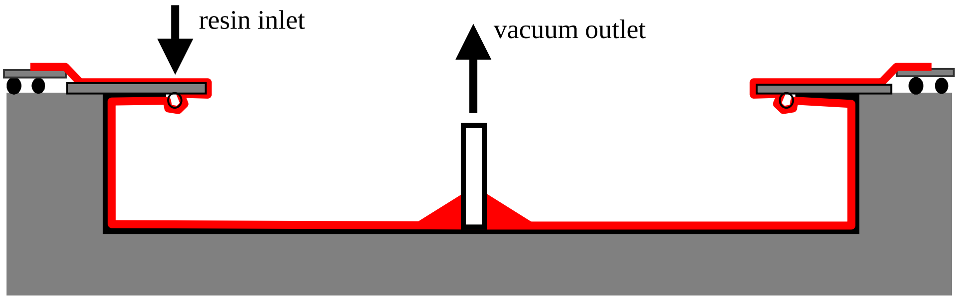

Figure 2: Typical cross-section of infusion tooling

The final mould system, for the triangular box is shown in Figure 3.

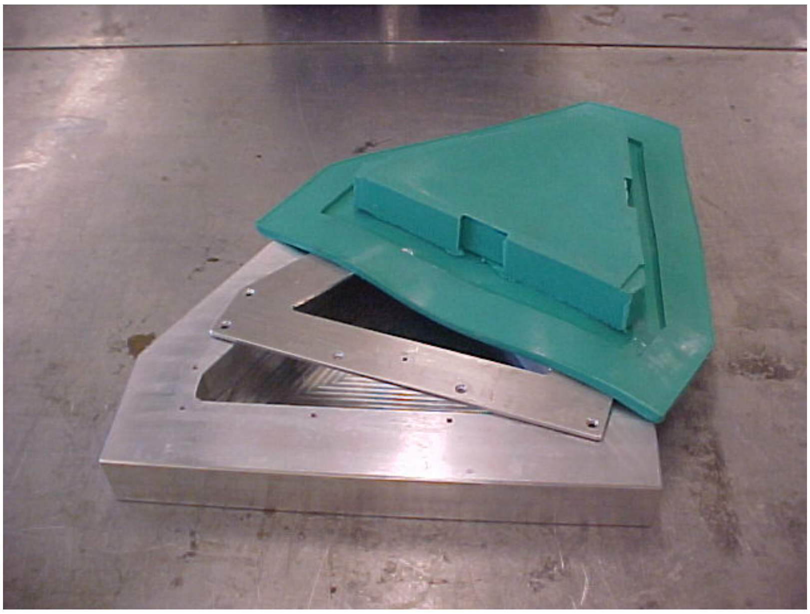

Figure 3: Mould system for triangular box

MATERIAL PROPERTIES

The properties which can be achieved with carbon composites depend on:

- Carbon type:
  - T300 or AS4: E_{f1} = 230 GPa
  - IM7 or T800H : E_{f1} = 276 – 294 GPa
  - M40J : E_{f1} = 377 GPa
- Fibre orientation:
  - Quasi-isotropic: 25 % 0°, 25 % 45°, 25 % 90°, 25 % -45°
  - Ortho-pref 0/90: 37.5 % 0°, 12.5 % 45°, 37.5 % 90°, 12.5 % -45°
- Fibre volume ratio, depending on:
  - Production method (RTM, Vacuum infusion, prepreg)
  - Fabrics or UD
  - Process parameters

Preliminary parameter selection

For the first estimates and calculations, a satin weave material is selected since the drapeability properties of such a fabric are very good which will be advantageous for the production of a box-like structure. The fabric layers are lay-up under 0/90 and +/-45 degree orientations to guarantee a quasi-isotropic laminate. For each layer (200gsm) a thickness of 0.2 mm is assumed. A fibre orientation of ortho-pref 0/90 would be preferable to increase the E-modulus. A minimum amount of 12.5% of +/-45 degree is required to guarantee adequate shear properties. By doing so, it will also be possible to allow holes in the laminate without the need for local thickening of the laminate. To end up with a 2.4 mm ortho-pref laminate, three layers of +/-45 and nine layers of 0/90 degree fabric are needed. For other thicknesses, other fabric arial weights need to be selected. A fibre volume content of 50% is assumed since this can be achieved quite well with infusion processes. By tuning process parameters and selecting optimized fabrics, higher fibre volume contents are also possible. For fibre type, the common T300 from Torayca (supplier Pechiney) or AS4 from Magnamite (supplier Hexcel) are selected. In two steps, fibres with higher moduli are considered. The first step consists of IM7 from Magnamite or the T800H from Torayca. The next step consists of M40J from Torayca. Higher modulus fibres are also available but the processing characteristic diminishes considerably due to increasing brittleness and the prices increases. In the table below, the stiffness properties of quasi-isotropic and orthotropic 0/90 laminates are given for a fibre volume content of 50%. The properties are calculated by using the classical laminate theory.

Table 1: Laminate properties

Carbon type	T300 of AS4		IM7-5000		T800H		M40J	
Fibre orientation	QI	OR 0/90	QI	OR 0/90	QI	OR 0/90	QI	OR 0/90
E_1 [GPa]	44.1	53.8	51.6	63.4	54.5	67.2	68.1	84.7
E_2 [GPa]	44.1	53.8	51.6	63.4	54.5	67.2	68.1	84.7
G_{12} [GPa]	16.8	10.4	19.6	11.8	20.7	12.4	25.8	14.9
ν_{12}	0.31	0.16	0.31	0.16	0.32	0.16	0.32	0.15

Joints

Not only the two substructures need to be joined together, but there will also need to be external parts like sensors attached. These sensors will need to be positioned very accurately. The surface of the composite structure will not guarantee this accuracy, not even when this surface is determined by hard tooling. Therefore, it was decided to use metal inserts in the composite. The position of the holes for the inserts can be determined very accurately by a CNC milling machine. In this way, the high geometrical tolerances can be met in a rather conventional way by metal pick-up points. Several options for joining the composite parts and the metal inserts are considered. Basically, four options for joints in composites are available:

- Form closure
- Pre-stressed bolts
- Bonding
- Close tolerance bolts

Form closure joints are not suitable since this type of joint requires two fitting shapes (for instance a cone in a conical hole) which are pre-stressed together. This requires solid elements which are not available. Pre-stressed bolt are not suitable since the carbon laminate will creep due to the pre-stress. A limited pre-stress up to 15 MPa can be allowed though. This pre-stress should then be applied in two steps to allow creeping of the material prior to the final pre-stressing of the bolts. It requires a rather large number of bolts to pre-stress a reasonable area. The strength of close tolerance bolts can be predicted quite well with existing models. However, the geometrical tolerances, especially after peak loads, are not as good as required. But in combination with glue, better tolerances and stability can be achieved. Pure bonded joints are a good option if the peak loads are limited. The bond line should be thinner than 0.2 mm to avoid tolerance problems. The bonding material is relatively weak material which good cause deformations of the structure in case of thick bond lines. The close tolerance bolts and bonded joints are considered below in more detail.

Close tolerance bolts

In case of a collision of the structure, loads of 3000N are introduced on the joint. For 2 mm laminate thickness, a maximum bolt diameter of 6 mm (D/t=3) can be used for carbon laminates [2]. The nominal stress of 3000 N / 2 mm / 6 mm = 250 MPa will be increased by a factor 2 due to the single lap condition and by a factor of 1,5 due to the stress concentration. The maximum tensile stress is then 250 * 2 * 1,5 = 750 MPa. The design strain under tension is 0.9% for carbon T300. This implies that only 484 MPa is allowed. Therefore, the carbon needs to be thickened locally to 3 mm: 3000 N / 3 mm / 9 mm * 2 * 1.5 = 333 MPa. This still leaves a reserve factor of 1.5 which can be used as material factor.

Bonded joints

The inserts for the structure need to transfer a load of 2500 N. In case of bonded joints, the loads will always have to be transferred by shear forces, rather than perpendicular to the plane. For the inserts under review, the dimensions are 45 mm x 45 mm x 5 mm. The average shear force is: 2500 N / (45 mm x 45 mm) = 1.23 MPa. This seems low at first sight, but one should consider the peak loads at the end of the bond line. These can be estimated by using the method of Volkersen [3]. For an aluminium insert of 5 mm bonded to 2 mm carbon laminate (T300 OR 0/90) with a bond line thickness of 0.2 mm, peak loads of 10.3 MPa are found. By increasing the thickness of the carbon laminates to 6.5 mm, the peak loads decreases to 4.6 MPa. The Volkersen calculation method gives a reasonable estimate in

trends, but the absolute values are not reliable, as practical validation tests have shown. This is caused preliminary by the fact that the not only shear stresses are present in a single lap, but also peel stresses due to the excentricity of the joint. These peel stresses can be of the same order of magnitude as the shear stresses. FE analyses are better suited to study these effects. However, even a FE analysis will not give a complete description of the problem. A singularity at the location of the end of the bond line will cause infinite stresses in the model. In reality, the details of the geometry of the joint (fillets, radii) and plasticity will determine the actual strength. Until now, this can only be determined by practical experiments. The measured tensile strength of epoxy bonding systems like Araldite 2015 or 3M 9323 is around 25 MPa and 42 MPa respectively. Due to a scatter on the strength values, a lower value is used as design value. The 3M 9323 showed a scatter of 1.4 MPa; therefore a design strength of 39 MPa is used. Based on the Volkersen method, a strength reserve of 3.8 MPa is present. The material factor to be used for carbon composites (and joints in carbon composites) is at least 1.5. The conversion factor can be assumed to be 1 since temperature, moisture and creep do not have an influence in these conditions. If we assume that the load factor is already in the loads, we can show that the joint meets the requirements.
The only remaining failure mode can be fatigue. If the load can occur several times in the live of the joint, say a 1000 times, then fatigue should also be considered. To be able to withstand this number of loadings, a bonding strength of 21 MPa is required according to a fatigue analysis based on $R = -1$ and $k = 10$. The materials factor of 1.5 should also be applied to this value leading to a minimum required strength of 31.5 MPa, which is still very reasonable.

It should be noted that this analysis is based on several assumptions and uncertainties. The Volkersen method it self has proven to be not very accurate in certain cases. It is also questionable whether the tensile strength can be used for determining shear strength failure. Therefore, the bonded joint should still be subjected to static and fatigue tests. The deformation of the joint is 2500 N / (45 mm x 45 mm) / 967 MPa x 0.2 mm = $2.55 * 10^{-4}$ mm. As long as these deformations are in the elastic region, no problems will occur. If the bond line thickness is smaller less deformation will occur. The outer collision structure will introduce a load of 300N on the joint. The stresses and strains are a factor 1,2 higher. Fatigue might become a load case, which requires a greater interface surface to be able to introduce all loads properly. It might also be advantages to taper the inserts near the ends to lower the stresses locally.

The close tolerance bolts result in a much lighter joint than the bonded joint, which requires a much heavier interface. The tolerance issue can be solved by using a “wet” installation of the bolts; a bonding system will then fill up the fitting tolerance. The bonding system does have a lower bearing strength than the carbon laminate. The bond compression strength will around 150 MPa. The bearing stresses can increase up to 3000N / 3 mm / 9 mm * 2 * 1,25 = 278 MPa. But this value assumes that all loads are taken up by one bolt, and the factor of 2 for a single lap is also very conservative. Based on strength considerations, close tolerance bolt offer a good solution. Whether the geometrical tolerance requirements can also be met has been tested with practical experiments. Several variants of close tolerance bolts with wet installation have been tested on coupon level. On a first set of coupons, the static strength of the joint was measured. On a second set of coupons, the geometrical stability after the occurrence of a peak load of 3000 N was measured. Measurements prior to testing and after testing showed no shift in position of the inserts larger than the required stability.

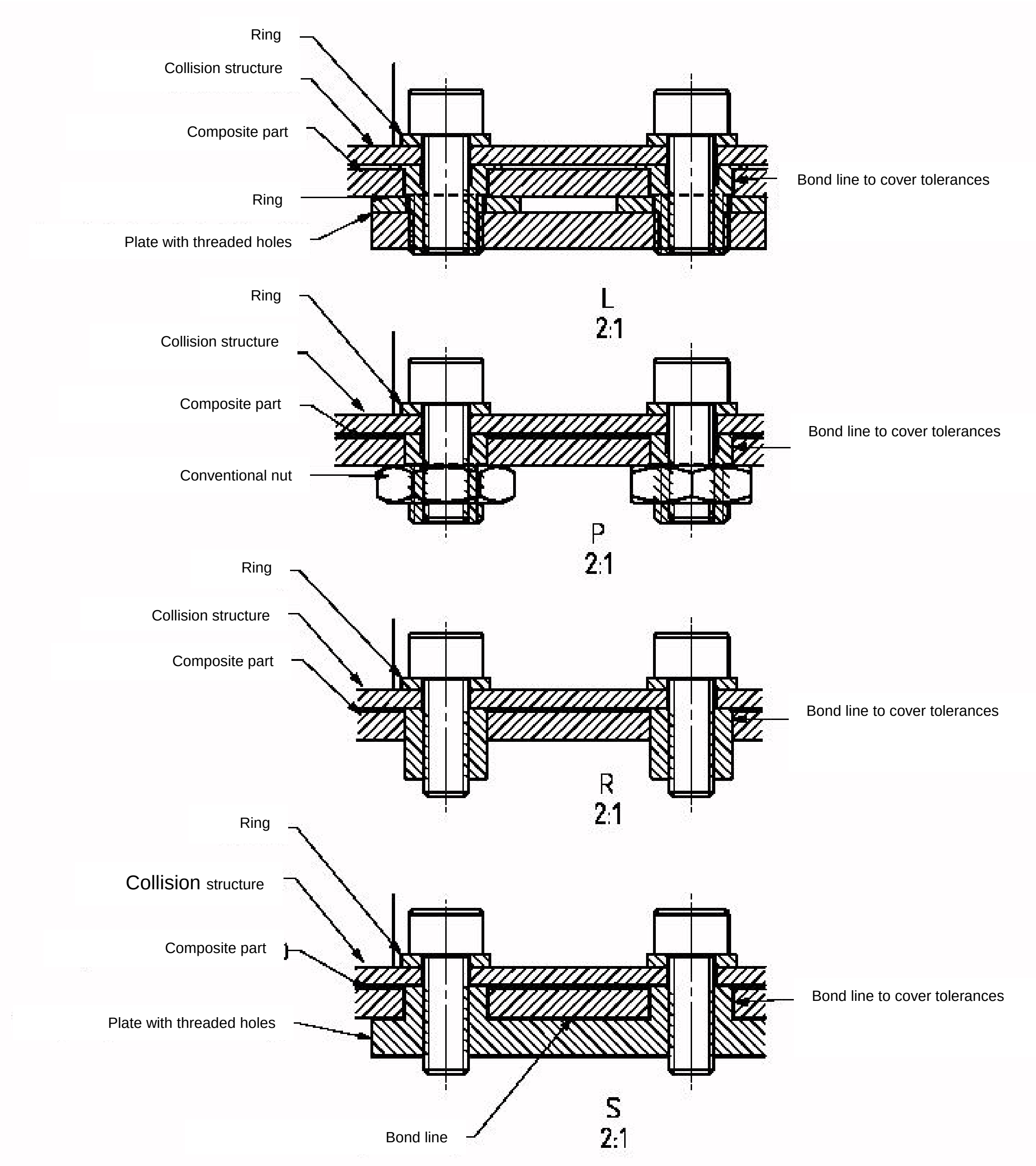

Figure 4: Four options for metal inserts in the composite laminate

PROTOTYPE PRODUCTION

A prototype of the carrier box is produced. The fabrics are preformed and placed inside the stiff outer mould. The metal ring for the definition of the top flanges is attached to the mould. Then, the flexible mould is placed inside the preform and sealed along the sides to the outer mould. Inlet and outlet tubes are fixed in the rubber mould and vacuum is applied. A vacuum of 20 mbar absolute pressure is applied. The air tightness of the mould is checked and the epoxy resin is mixed. The resin is degassed at 5 mbar [1]. Then, the infusion is started. As soon as the resin has reached the vacuum outlet, the pressure is increased to 600 mbar. After a few minutes, the resin inlet is closed and the product is left to cure at room temperature for 24 hours. A subsequent post-cure at elevated temperature is applied prior to demoulding. Both rectangular and triangular box are trimmed and assembled. The assembled structure is shown in Figure 5. The metal inserts still need to be positioned and bonded in.

Figure 5: The assembled carbon carrier structure

ACKNOWLEDGEMENTS

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