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Procedia CIRP 23 (2014) 235 – 240

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Conference on Assembly Technologies and Systems

Variation simulation for composite parts and assemblies including variation in fiber orientation and thickness

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Abstract

All manufacturing processes are afflicted by geometrical variation, which can lead to defect products. A simulation tool for geometry assurance analysis is therefore important in the design process. The use of composites has recently increased drastically, but there is still a lack of understanding about the effects of variation in such parts. A method for predicting variation in subassemblies, including variation in fiber orientation and ply thickness for composites is presented. The approach is demonstrated on an industrial case and finite element analysis is used to calculate the deformation. In particular, contribution from variation in material properties to the variation in critical points is analyzed. The results indicate that material uncertainties have a small impact on the geometric variation for the test case.

Selection and peer-review under responsibility of the International Scientific Committee of 5th CATS 2014 in the person of the Conference Chair Prof. Dr. Matthias Putz matthias.putz@iwu.fraunhofer.de

Keywords: Geometry assurance; FEM; Contribution analysis; DOE; Composites

1. Introduction

Composites and other high technology lightweight materials are becoming more common in many areas of production and manufacturing such as e.g. the aviation and automotive industries. This is due to the many beneficial properties of composites over traditional materials, e.g. weight reduction with retained strength and stiffness, corrosion resistance, thermal properties, fatigue life and wear resistance. The lower weight leads in turn to reduced fuel cost and carbon dioxide emissions. Almost all vehicles benefit from switching to composite materials. For example half of the Airbus A350 and the Boeing 787 aircrafts consist of composite materials. However knowledge about detailed behaviour of lightweight materials is still insufficient.

For composites, there might be variation in material and process related parameters, such as thickness and fiber orientation. In this paper, the influence of those on the level of geometrical variation in a subassembly is investigated. To do this, methods for variation simulation are used. An overview of variation simulation is given in Section 1.1 and an introduction to composite materials and manufacturing is given in Section 1.2. In Section 1.3 the finite element (FEM) model used for the composites is described. The industrial test case is described in Section 3 and the method used in Section 4. In Section 5 the results are discussed and Section 6 contains the conclusions.

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doi:10.1016/j.procir.2014.10.069

Background

1.1. Geometry assurance and variation simulation

Geometry assurance is a term used to gather a lot of activities aimed at securing the geometrical quality of the final assembled product. Sources of geometrical variation in a subassembly are mainly variation in shape and size of single parts and variation in the assembly process. The level of geometrical variation in the assembly is also dependent on the robustness of the design concept. A robust design concept is insensitive to variation and can suppress the effects of the sources of variation [1]. The main key to making a physical assembly geometrically robust is to find robust locating schemes. A locating scheme fixates the part in space during manufacturing and joining operations and control how variation propagates in the assembly. An overview of different locating schemes is given in [2].

In order to predict the level of geometrical variation in a subassembly or a final product, Monte Carlo based software for variation simulation is often used. The parts in a variation simulation can be modeled as rigid or non-rigid parts. Direct Monte Carlo simulation, combined with finite element analysis (FEA), is a standard technique for variation simulation of non-rigid parts. However, since a large number of runs are required to achieve satisfactory accuracy, the method is very time-consuming if a new FEA calculation is executed in each run. Liu and Hu [3] presented a technique called Method of Influence Coefficients (MIC) to overcome this drawback. The main idea of their method is to find a linear relationship between part deviations and assembly spring-back deviations. A sensitivity matrix, constructed using FEA, describes that linear relationship. This sensitivity matrix is then used in the simulations, and a large number of FEA calculations can be spared. The validity of the method was shown by Camelio et al. [4], who applied it to a multi-station system. MIC can also be combined with contact modelling [5]. Contact modelling is a way to hinder parts to penetrate each other virtually. Wärmefjord et al. [6] developed contact modelling for variation simulations further and showed its importance on an industrial case study.

There are several commercial software for variation simulation, such as 3DCS [7], VSA [8] and RD&T [9]. In the work described in this paper RD&T is used. RD&T is a commercial software but is also used as a workbench for research within the area of geometry assurance and non-rigid variation simulation. In RD&T, a Monte Carlo-based statistical variation simulation is conducted in order to analyze the tolerance stack up and to predict the geometrical variation in the final assembly. A total sensitivity matrix is implicitly defined in a FEA-based simulation model describing all mating conditions, kinematic relations and non-rigid behaviour.

1.2. Composites

Generally composites are materials consisting of a composition of two or more different components. The most common are made of two materials, a matrix material and some kind of reinforcement to increase strength and stiffness. Basically there are three kinds of composites, fibrous, particulate and laminated. Fibrous composites consist of fibers in one material inside a matrix in another material. Particulate composites are macro sized particles inside a matrix material. Finally laminated composites are made of plies of different materials. The plies can be either of the two first kinds of composites as well as any other material.

Common to all composites with continuous fiber reinforcement is that they will have highly anisotropic behavior being much stronger along the direction of the fibers. This enables a precise design of laminated composites with fibrous composite plies having different orientations according to where the strength is needed. More detailed information on composites can e.g. be found in [10] and [11].

There are several composite manufacturing processes, hand lay-up, resin transfer moulding (RTM), automated tape laying (ATL) and automated fiber placement (AFP) to mention some of the most common ones. In the hand lay-up process, the composite plies or the fiber mats that will constitute the laminate are placed as a dry stack in a mould, then the resin that will constitute the matrix are impregnated into the fibers using rollers or brushes. Then the laminate is left to cure in room temperature or in an oven. The RTM process is similar to the hand lay-up with the difference that another mould tool is placed on top of the dry stack of fibers forming a cavity where the resin is then injected. There can also be vacuum in the cavity to help the resin being drawn into the fabrics. Hand lay-up and RTM are methods typically used for smaller more complex components and the quality of the finished product is dependent on the skills of the laminators.

ATL and AFP are both, as the name suggests, highly automated processes. In ATL a preimpregnated tape with fibers are placed by a robot in rows next to and across each other in specific directions over a large surface. AFP works in the same way, but single fiber tows are placed instead of a tape. These two methods can handle parts with holes as well as parts with varying thickness and number of plies in different areas. Further ATL and AFP are widely used in production of large aircraft structures such as wings skins, spars and stringers. More about composite manufacturing can be found in e.g. [10] or [12].

In the finished composite part there are several structural uncertainties and defects. For example resin-rich (i.e. fiber-poor) regions, voids, microcracks, delamination, variation in fiber alignment and thickness [10]. Several studies have been done about the effects of one or more of these defects, see e.g. [13], [14], [15], and [16]. The purpose of this work is to investigate whether uncertainties in fiber orientation and ply thicknesses affect the level of geometrical variation in a final subassembly.

1.3. Finite element method for composite shells

For the variation simulations of non-rigid parts, a finite element shell model is used. The formulation is based on the theory developed by Simo & Fox in [17], for smooth structures, and extended by Ibrahimbegovic in [18] to nonsmooth structures. The formulation is suitable for thin structures undergoing small or large strains, i.e., large displacements and rotations. A thorough description of the shell formulation is beyond the scope of this paper. Interested readers are referred to [17] and [18] and references therein.

The shell model is formulated with six degrees of freedom in each node; three translations and three rotations. The constitutive equations are formulated with stress resultants, which mean that the stress is integrated through the thickness. This has the benefit of creating a very fast and memory efficient implementation for elastic material models. For laminate composite materials we consider each ply to be modeled by an orthotropic elastic model. The material properties are expressed with the Young's moduli E_i along material axis i, the shear moduli G_{ii} and the Poisson's ratios ν_{ii}. The material axes may be variable over the structure and may not be aligned with the local orientation of the shell elements, in which case the stiffness tensor needs to be transformed.

Plane stress is assumed, which means that the stress component in the shell normal direction is zero. A further assumption is that the fibers along the shell normal remain straight after deformation. This is known as first-order shear deformation theory. The assumption is applied to all plies in a laminated composite which enables an analytical integration over the thickness, see Reddy [11].

Discretizing the shell variation formulation over finite elements, considering small deformations, we obtain a linear system for the displacements $\mathbf{u}$,

$$\mathbf{K}\mathbf{u} = \mathbf{f},$$

where $\mathbf{K}$ is the stiffness matrix and $\mathbf{f}$ is the external force vector. Any nonzero prescribed boundary condition is put into the force vector, and the stiffness matrix is reduced in size.

2. Industrial test case

As test case we will use a subassembly from automotive industry, see Fig. 1. The subassembly consists of two parts referred to as lower and upper part as shown in the figure. Both parts are assumed to be Graphite-Epoxy and the lower part is 1.6mm thick and consists of eight equally thick plies while the upper part is 1.2mm thick and consists of six equally thick plies. The fiber orientations of the composition of all plies are shown in Fig. 2.

The two parts are fixed in space using a 6-direction locating scheme. Read more about locating schemes in e.g. [2]. They are then joined together at seven points. Further there are tolerances defined for each locating point and each joining point.

3. Method

We will do variation simulation both for the geometric parameters (i.e. including part variation, assembly fixture variation and also taking contact modeling into consideration) and the material parameters and then analyze the resulting geometric variation in the subassembly. As material parameters we will include fiber orientation and thickness of each ply. For the industrial test case we have one part with eight plies and one with six, i.e. in total fourteen plies. Further we have two parameters for each ply, one describing the fiber orientation and one the ply thickness. This gives in total 28 material parameters. The fiber orientation parameters are given the tolerance ±13º, as used in [13], while the ply thickness parameters will have the tolerance ±20% of the nominal thickness, used by [19]. The subassembly parts will be modeled as non-rigid in the software RD&T that is used for the variation simulations. That is, both parts are allowed to bend during assembly and are described by finite element (FE) meshes. For each setting of the material parameters M Monte Carlo iterations are done for the geometric parameters. The result of a variation simulation is a prediction of the level of the variation or, more frequently used, the level of 6σ, where σ is the standard deviation for each FE node in the assembly. This result can be illustrated using color coding, as shown in Fig. 3. To get one measure of the level of variation for all nodes, the root mean square (RMS) of 6σ is often used. To see how this is computed we start by looking at the variance of each node, i, which is computed as

$$\sigma_i^2 = \sigma_{ix}^2 + \sigma_{iy}^2 + \sigma_{iz}^2, \tag{1}$$

where

$$\sigma_{i\alpha}^2 \approx \frac{1}{M-1}\sum_{k=1}^{M}(t_{i\alpha k} - \overline{t_{i\alpha}})^2,$$

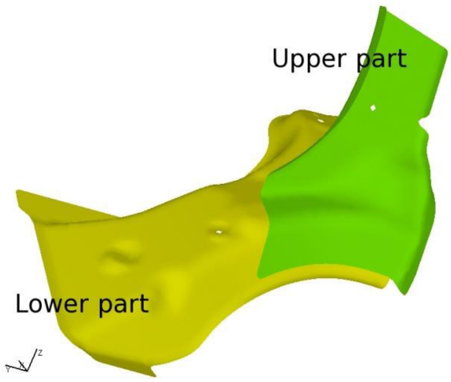

Fig. 1. The subassembly used as test case.

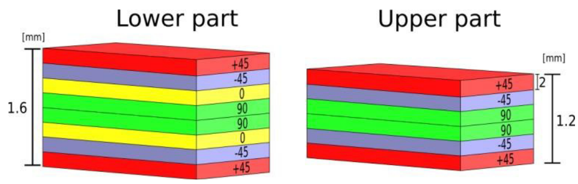

Fig. 2. The composition of plies for the two composite parts in the test case showing the fiber orientation of the respective plies.

where $t_{i\alpha k}$ is the deviation in the direction $\alpha = x, y, z$ in iteration k for node i, and $t_{i\alpha}$ is the mean deviation in the direction α over all M iterations for node i. Then we get

$$6\sigma_{\mathrm{RMS}} = 6\sqrt{\frac{1}{N}(\sigma_1^2 + \ldots + \sigma_N^2)}, \tag{2}$$

where N is the number of nodes. The level of variation is usually described by 6σ, which in the case of normal distribution corresponds to 99.73% of the population. Therefore $6\sigma_{\mathrm{RMS}}$ is used here. By including only the nodes for the lower (or upper) part we get a measure of the total geometric variation in the lower (or upper) part. Including all nodes gives a measure of the total geometric variation for the complete subassembly.

We have done two studies on the industrial case, first we want to study what happens with the geometrical variation when the material parameters are at their extreme values. This is described in Section 3.1. Then we do variation simulation over the material parameters, further described in Section 3.2.

3.1. Material parameters at extreme values

The material parameters are not likely to be at their extreme values all at the same time. However it is interesting to see how large changes we get in the geometrical variation if this would be the case. To try all combinations of the 28 parameters being at their lower and upper limit would require 2^{28}=268 435 456 runs, which is not possible to do. Therefore we use design of experiment (DOE) to find a suitable fractional factorial test. Then we can cope with 2^6=64 tests and still get the desired result, see [20] for further reading.

Using a two-level factorial test means to assume linear behavior between the material parameters and the resulting variation. This may not be the case but still factorial testing is a good starting point trying to understand the relation between changes in material parameters and the geometric variation and to find trends in this relation.

3.2. Variation simulation of the material parameters

To investigate a more realistic scenario we do a variation simulation of the material parameters. For each parameter we define a distribution. A normal distribution is assumed with mean value zero for both the thickness and the fiber orientation parameters. The standard deviation σ is chosen such that the assumed lower and upper tolerance limits are at $\pm 4\sigma$. So the standard deviation of the fiber orientation parameters becomes 13/4=3.25º and for the ply thickness parameters it is 20/4=5%. Then as already mentioned M Monte Carlo iterations for the geometric parameters are performed for each material-Monte Carlo iteration.

4. Results/Discussion

We have performed M=2000 Monte Carlo iterations for the geometric parameters for each material setting in all test cases. First Fig. 3 shows a color-coded plot for the variation in each node, $6\sigma_i$, where σ_i is the square root of (1), when the material parameters are at their nominal values. Then Fig. 4 shows the same result but zoomed to the area with the most variation. This is to be compared with Fig. 5 and Fig. 6 showing the variation in each node for the cases giving the smallest and largest $6\sigma_{\mathrm{RMS}}$ for the complete subassembly, respectively. The $6\sigma_{\mathrm{RMS}}$ values for both the complete subassembly and the two parts separately for these cases are presented in Table 1.

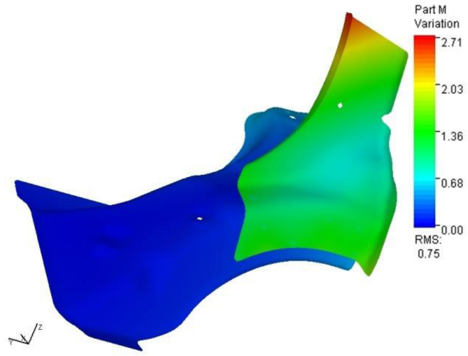

Fig. 3. Mean variation, $6\sigma_i$, in all nodes after 2000 geometrical Monte Carlo iterations. Material parameters are at nominal values and $6\sigma_{\mathrm{RMS}}$=0.75.

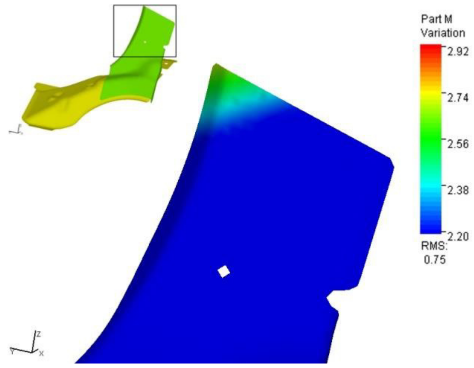

Fig. 4. Mean variation, $6\sigma_i$, in all nodes after 2000 geometrical Monte Carlo iterations. Material parameters are at nominal values and $6\sigma_{\mathrm{RMS}}$=0.75.

Further we look at the maximum node deviation in the nominal case, which is $6\sigma_i$=2.71, and compare that with the worst node in the two extreme cases which gives a value 2.92 of $6\sigma_i$. This means there is a relative difference of 7.7%.

For the variation simulation of the material parameters we have performed 2000 Monte Carlo iterations. Then the variation measure (2) is computed for the lower and upper parts as well as for the total subassembly. The result is presented in three histograms, see Fig. 7. The vertical line in each histogram marks the $6\sigma_{\mathrm{RMS}}$ value for the nominal material case.

Table 1. The $6\sigma_{\mathrm{RMS}}$ values for the total subassembly and the lower and upper parts for three cases from the factorial test results.

Variation measure, $6\sigma_{\mathrm{RMS}}$	Nominal	Min $6\sigma_{\mathrm{RMS}}$	Max $6\sigma_{\mathrm{RMS}}$
Complete subassembly	0.749	0.736	0.767
Lower part	0.198	0.234	0.125
Upper part	1.340	1.302	1.394

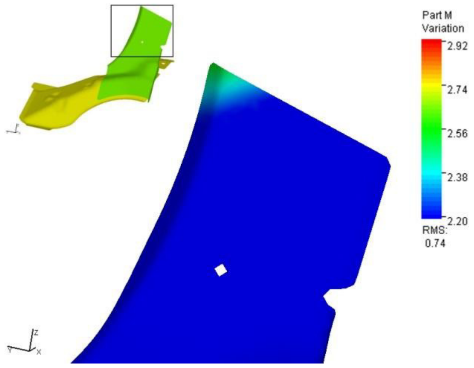

Fig. 5. Mean variation, $6\sigma_i$, in all nodes after 2000 geometrical Monte Carlo iterations. Material parameter setting giving the minimum total variation, $6\sigma_{\mathrm{RMS}}$=0.74.

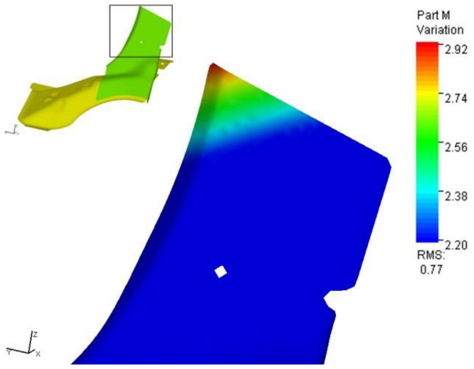

Fig. 6. Mean variation, $6\sigma_i$, in all nodes after 2000 geometrical Monte Carlo iterations. Material parameter setting giving the maximum total variation, $6\sigma_{\mathrm{RMS}}$=0.77.

From the histograms we see that the geometrical variation still has the mean value centred at the nominal $6\sigma_{\mathrm{RMS}}$ value. That is, in most cases of material variations the geometrical variation will not change very much. We see also from the histogram for the lower part that the geometric variation can in some cases be changed by approximately 10%. Since the mean variation is still the same this uncertainty can be added to the geometric variation and regular variation simulation for the geometric parameters would be enough even for composite parts.

5. Conclusions

In this paper we have studied the effects of material variation in composite components on the geometric variation. A subassembly from automotive industry was used as test case. The test results indicate that adding realistic variation in the fiber orientations and ply thicknesses of the composite parts to the already existing variation simulation of geometric parameters will not make a significant change to the geometric variation outcome.

Since this is the first study on these effects more studies and tests, based on different case studies, would be necessary to be sure about the conclusions. However the results from this paper indicate that material variation simulation could be excluded from the geometry assurance process on assemblies including composite parts and the results would still be accurate and reliable.

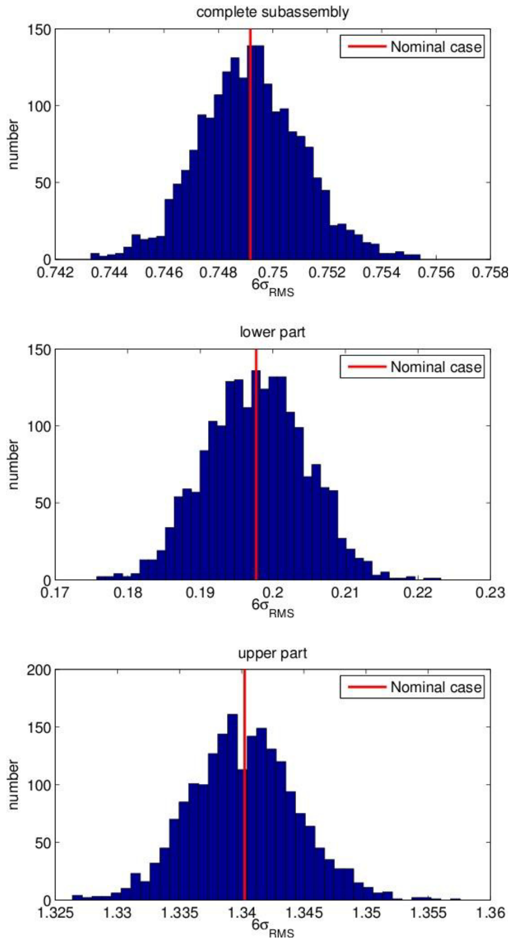

Fig. 7. The distribution of $6\sigma_{\mathrm{RMS}}$ after a variation simulation for the material parameters with 2000 Monte Carlo iterations (including 2000 Monte Carlo iterations for the geometrical parameters in each material iteration).

Acknowledgement

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°314003. The work was carried out in collaboration with Wingquist Laboratory VINN Excellence Centre within the Area of Advance – Production at Chalmers, financed by the Swedish Governmental Agency for Innovation Systems (VINNOVA). The support is gratefully acknowledged.

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