

PROCESS INDUCED DEFORMATIONS OF THE BOEING 777 AFT STRUT TRAILING EDGE FAIRING

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ABSTRACT

During processing of polymer composite materials, residual stresses build up which affect the in-service performance of the component as well as dimensional control. Good dimensional fidelity is important for cost effective assembly of large composite structures, and is essential for concepts such as shim-less assembly. This paper presents a study of process-induced deformations of the Boeing 777 Aft Strut Trailing Edge Fairing. Deformations were measured for a number of parts and compared to predicted deformations based on models developed using a finite element based composites processing software. A methodology for modelling a large complex part such as the aft strut fairing is presented and the agreement between measured and predicted deformations is presented and discussed.

KEY WORDS: Dimensional control, residual stress, processing, autoclave, deformations

1. INTRODUCTION

Residual stresses build up when thermoset polymer composite structures are processed in an autoclave. The sources of these stresses are differential thermal expansion between fibres and matrix, resin cure shrinkage, as well as system effects such as tool-part interaction and cure gradients. Residual stresses affect the structural performance as well as causing curved laminates to “spring-in”, and, in some cases, cause flat panels to warp. Aerospace structures are manufactured to a high degree of dimensional control for performance and assembly reasons. Any significant change in the geometry of a component due to residual stress build-up during processing needs to be compensated for in the design of the process tooling. There are simple equations that can predict spring-in of simple curved laminates due to material anisotropy [1], however, because of the complexity of most aerospace components and processes, tool compensation is generally performed based on past experience in industry.

This paper presents a procedure to predict the process-induced deformation of a typical aerospace part with a complex three-dimensional (3D) shape using a two-dimensional (2D) special-purpose finite element code in conjunction with a simple 3D elastic finite element model. The agreement between model predictions and experimental data is presented and discussed.

2. EXPERIMENTAL

The Boeing 777 Aft Strut Trailing Edge Fairing provides a closeout to the Aft Strut Fairing and faired to the underside of the lower wing skin. It is a honeycomb structure with carbon/epoxy skins (Hexcel F593 style 3K-70-PW fabric prepreg), cured with film adhesive (CyttecFiberite Metalbond 1515) between the prepreg and the over-expanded Nomex honeycomb core (3/16 cell, grade 4). The fairing is approximately 1.8 m long, 0.3 m high and wide, and is processed on a female tool (Figure 1).

The fairing is processed in typical fashion as follows: apply Frekote 710 release agent to female tool, prepreg lay-up of tool side plies by hand, alignment of core detail, prepreg lay-up of bagside plies, final bagging for cure followed by an autoclave cure for 120 minutes at 310 kPa (45psi), 177C (350F). Following cure the fairing is NC trimmed, including forward and upper flanges, and at all hole locations.

The fairing is attached to the lower wing skin by four discrete pickups along the upper flange and to the Aft Strut Fairing via fasteners at the forward (wide) end joggle. Experience has shown that the process-induced deformation of this structure is significant enough that the process tool needs to be compensated for the deformation to avoid problems in assembly.

To determine the appropriate tool compensation, a total of six production parts and parts made in the development laboratory were measured for process induced deformations. Measurements were taken using a Romer portable coordinate measurement machine (CMM) to determine both the tool profile and the matching tool-side part profile at the upper flange locations. The difference between the two data sets gives the total process-induced deformation at each location.

3. FINITE ELEMENT ANALYSIS

There are many models in the literature for the simulation of processing of composite materials and autoclave processing in particular, e.g. [2-8]. In this study the 2D finite element (FE) code "COMPRO" was used. COMPRO simulates heat transfer from the autoclave gas to the tool and part, cure kinetics, resin flow, residual stress build-up during processing, and the resulting deformations when the part is removed from the tool. For details of the code, see [9,10]. The code was developed with input from The Boeing Company to ensure that it includes industrially relevant effects such as tool-part interaction. COMPRO has been used to simulate processes on the Boeing 747, 767, and 777 aircraft, e.g. [11,12].

Although COMPRO is a 2D code and real structures are 3D, the effect of the third dimension is often mainly geometric and does not have a significant effect on the residual stress build-up in the other dimensions [13]. This means that the residual stress build-up during processing and the effect of these stresses on the final shape of a 3D structure can be separated using a sub-structure methodology [13]. The approach is to divide the structure of interest into substructures (2D sections) that are modeled using high mesh density 2D process models to capture the detailed phenomena causing residual stress build-up. The resulting deformations of the 2D process models are then transferred to a simple 3D shell model where the equivalent forces, giving the same overall deformations as the 2D models, are calculated. Shell models of different representative substructures are then assembled to calculate the resulting deformations and reaction forces of the entire structure. The methodology is best described using a concrete example and is applied below to the Boeing 777 Aft Strut Trailing Edge Fairing.

Step 1. Select appropriate 2D sections of the 3D structure. Four cross-sections perpendicular to the length axis of the fairing were chosen as measurements revealed that the primary deformation was in this plane, see Figure 1A.

Step 2. Create and run 2D models of the selected sections. One FE model was created for each section. Each model consists of a FE mesh, initial and boundary conditions, material properties, and cure cycle. The FE meshes were created using the PATRAN pre-processor, based on a CAD description of the part. The rest of the model was set-up in the COMPRO software. The FE mesh created for section 2 is shown in Figure 1B. Only one half of the part and tool is modeled due to symmetry.

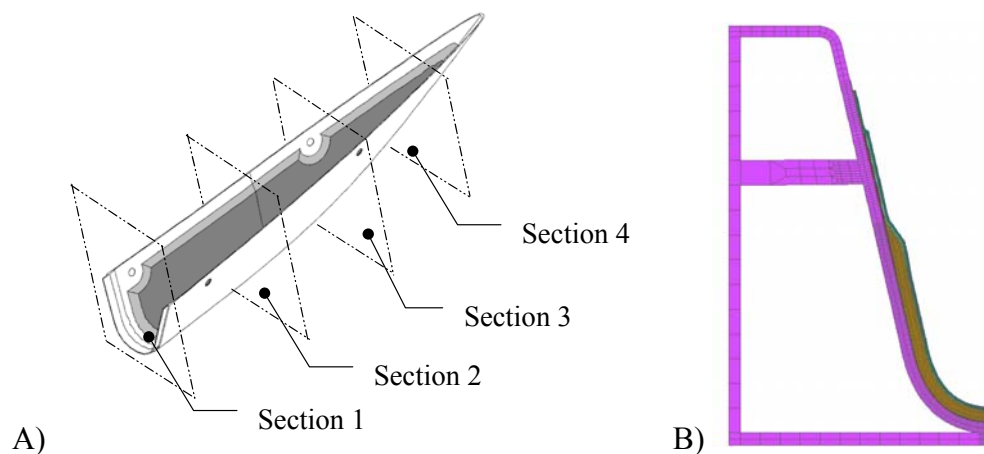


Figure 1. A) Boeing 777 Aft Strut Trailing Edge Fairing with four select 2D sections; B) Finite element mesh of one half of section 2, including process tooling.

Step 3. Study the predicted deformations of 2D models. After the models were executed in COMPRO (approximately 1 hour run time on Pentium III class PC), the deformed shape of the 2D process models were analyzed, see Figure 2. All four models showed that the principal mode of deformation is “spring-in” of the flanges. In the present case we are particularly interested in spring-in at the end of the flanges where the fasteners are located.

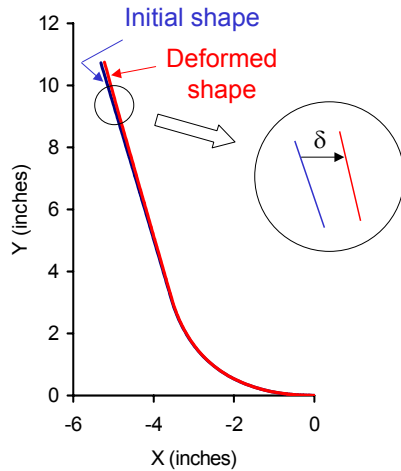


Figure 2. Initial and deformed shape of the tool-side surface of the part for the FE model shown in Figure 1B.

Step 4. Create 3D model of the part. A full 3D elastic model of the part was created using the FE package ABAQUS. The tooling was not modeled, and shell elements were used, see Figure 3 and Figure 4. The purpose of the 3D model is to study how the deformations of the individual sections interact when the part is fully cured, cooled down, and removed from the process tooling.

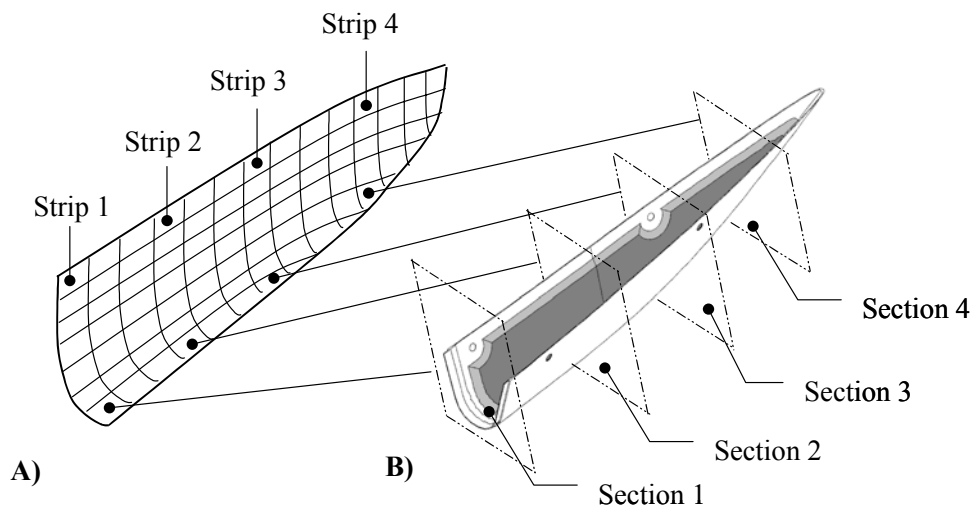


Figure 3. Schematic of 3D FE model of half the part showing 'strips' (A) corresponding to the four sections used for the 2D COMPRO models (B).

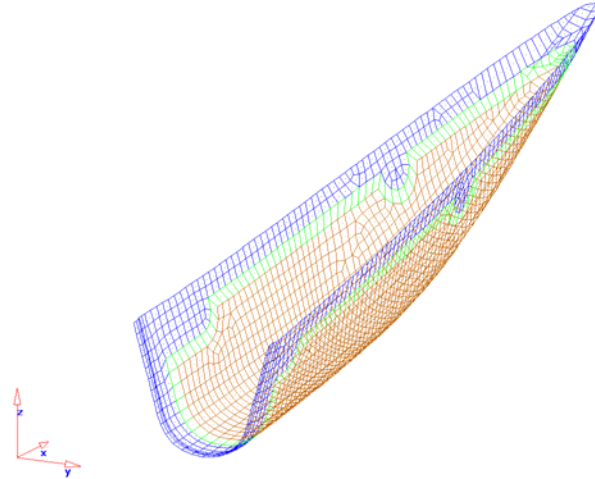


Figure 4. 3D FE mesh of 777 Aft Strut Trailing Edge Fairing.

Step 5. Isolate cross-sections in 3D model and match deformations. Strips of the 3D model, corresponding to the 2D sections created under Step 1 were isolated, see Figure 3 and Figure 5. The loads (moments) that need to be applied to the strip models so that the deformations agree with the 2D process models were determined using the principle of superposition: $\delta_1 = C_{11}M_1 + C_{12}M_2$; $\delta_2 = C_{21}M_1 + C_{22}M_2$, where δ_1 and δ_2 are the displacements from the 2D model, C_{ij} the compliance of the 3D strip model, and M_1 and M_2 the moments required to get the 3D strip model to give the same deformation as the 2D model.

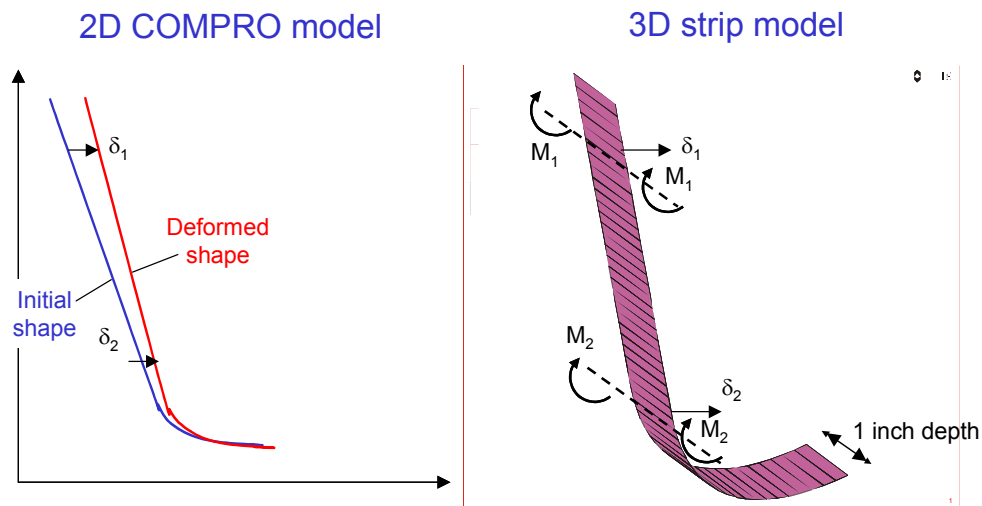


Figure 5. Schematic of the procedure of matching of displacements between 2D COMPRO model and corresponding 3D strip model.

Step 6. 3D-interaction analysis. The loads determined in the previous step were applied to the full 3D model shown in Figure 4. The loads were applied as line loads, varying linearly between the isolated cross-sections, see Figure 6.

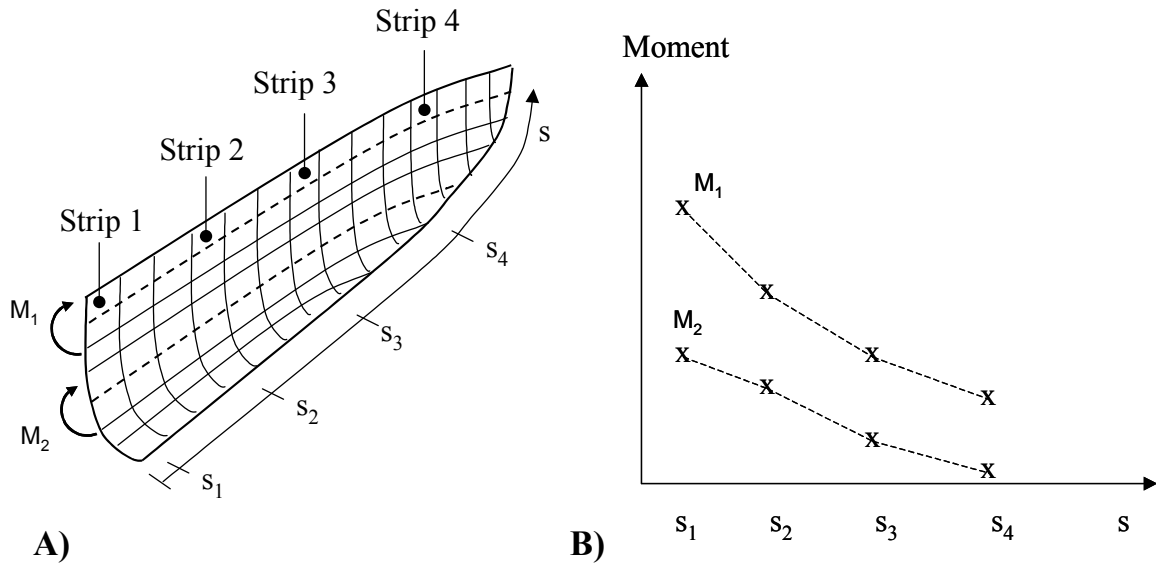


Figure 6. A) Schematic of 3D FE model showing the lines on which the moments are applied; B) Schematic showing the linear interpolation of the applied moments per unit width between the four strips.

4. RESULTS

Both measurements and model results showed that the process-induced deformation of primary interest in assembly is the spring-in of the flanges, and in particular the resulting gap created at the fastener locations at the end of the flanges. Measurements of the gap for six fairings showed consistently that the flanges sprung-in, with a maximum spring-in at the wide end. Figure 7 shows the average measured gap at the end of the flanges. Error bars represent \pm one standard deviation. The decrease in the total gap towards the tip of the fairing is expected due to the reduction in flange length. The small decrease in the measured gap between approximately 5 and 15 inches from the wide end corresponds to the location where the honeycomb core is slightly thicker. Figure 7 also shows the COMPRO 2D predictions, which are the predictions of spring-in for the four individual sections disconnected from the surrounding structure. The agreement between the 2D predictions and measurements is good at sections 2 and 3, but poor at section 1. At section four there is no experimental data to compare the predictions against. The prediction for the total gap at section 1 is 0.59 inches and can't be seen in the figure. Section 1 is a solid laminate section, and the spring-in is much greater than the surrounding honeycomb structure if it was to be removed from the surrounding structure. Sectioning revealed experimentally that the solid laminate section at the wide end (section 1) of the fairing sprung-in significantly more than a honeycomb core section adjacent to it. The constraint of the surrounding structure on section 1 can be seen in Figure 7 (ABAQUS-COMPRO 3D prediction). When all four sections are connected in a 3D model the larger spring-in of the solid laminate section is significantly reduced and the

overall agreement between predictions and measurements is reasonably good. It should be mentioned that the predictions were initially poor due to a coarse finite element mesh in conjunction with using 4-noded isoparametric elements. When 8-noded isoparametric elements were used, the predictions improved significantly as seen in Figure 7. Some of the discrepancy between experimental data and “ABAQUS-COMPRO 3D prediction” shown in Figure 7 can be explained by simplifications done in the 3D model due to the geometric complexity of the actual part.

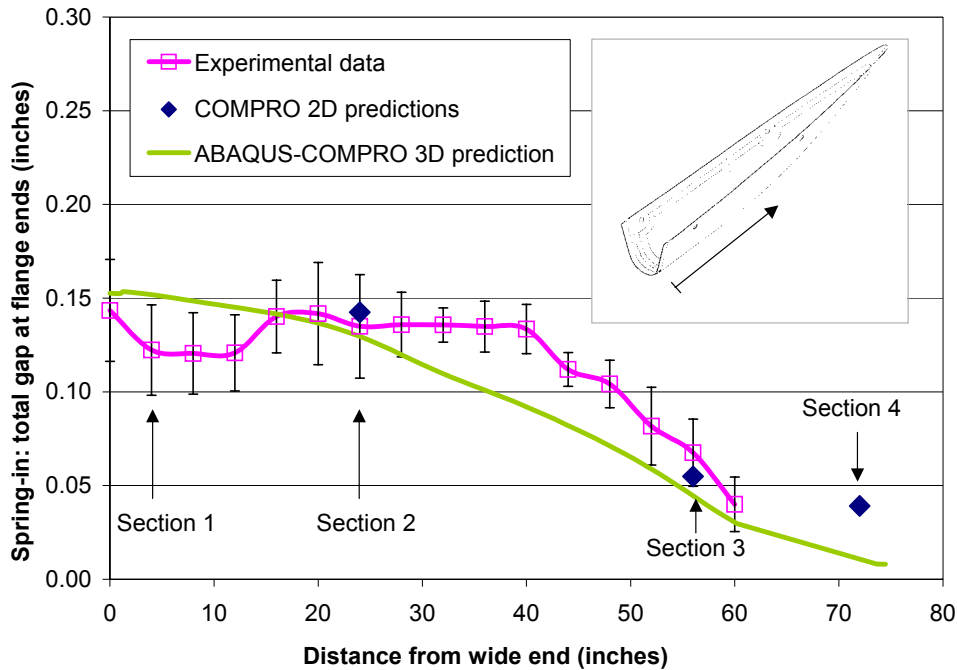


Figure 7. Comparison of experimental spring-in measurements (both flanges) and model predictions.

5. CONCLUSIONS

This study showed that 2D COMPRO process models in conjunction with a 3D elastic shell analysis gives reasonably good predictions of the process induced deformation of the Boeing 777 Aft Strut Trailing Edge Fairing provided that a sufficient mesh density or higher order finite elements are used. The methodology presented is believed to work for a large class of problems of practical interest in the aerospace industry. The approach has shown to give good results for a simpler geometry previously [13]. An advantage with the methodology is that it is very computationally efficient. The main drawback is that it is difficult to automate and requires some engineering judgment in its implementation.

6. ACKNOWLEDGEMENTS

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