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Technical Paper

Virtual assembly and residual stress analysis for the composite fuselage assembly process

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ABSTRACT

A new shape control system has been developed to reduce the dimensional deviations between two composite fuselages. To evaluate the system, the virtual assembly and residual stress analysis are needed. Since actuators' forces are applied to each fuselage during the assembly, residual stresses may remain after the release of actuators. The residual stresses could lead to severe mechanical problems for the fuselage. Therefore, we propose a new finite element simulation and virtual assembly analysis method for evaluating the assembly process of two composite fuselages. Our method simulates the release of actuators directly instead of applying reverse forces, which mimics the assembly process and increases the simulation accuracy. The dimensional change and residual stresses during and after the assembly process are evaluated. The results show that the assembly process with new shape control system is feasible since the residual stresses resulting from the control system are much smaller than the failure threshold.

1. Introduction

Composite parts have been increasingly used in the aircraft industry due to their advantages such as high durability, strength-to-weight ratio, and stiffness-to-weight ratio [1]. A new commercial aircraft has major structural parts made from composite materials, which consists of more than 50% by weight [2]. Since the global suppliers have a diversity of manufacturing and fabrication process, dimensional variability of composite fuselages inevitably exists. According to a report [3], there was a gap of 0.3 in. when two fuselage bodies were lined up in a major aircraft assembly process.

To reduce the dimensional variability and residual stress of the composite fuselage assembly, a new shape control system with multiple actuators has been proposed to adjust the dimension of the composite fuselage before assembly [4,5]. As shown in Fig. 1(a) and (b), ten actuators are located uniformly at the lower semi-circle of the fuselage. These ten actuators, which are hydraulic systems, can provide push or pull forces to change the shape of the fuselage. The new shape control system is capable of (i) computing the optimal actuators' forces to minimize the dimensional deviations of current composite parts to the ideal shape; (ii) implementing the shape adjustment automatically; and (iii) reducing the large uncertainty and inconsistency from manual operations.

During the fuselages assembly, two fuselages will be adjusted individually to the ideal shape by the shape control system. Fig. 2 shows the schematic diagram of the two fuselages that are adjusted separately by the ten actuators. After the two fuselages are aligned to the ideal shape, they are assembled by the riveting process. Next, the actuators applied on the two fuselages will be released, which will cause the spring-back of the fuselages and the occurrence of residual stress. Residual stress may hurt the part as well as generate other severe side effects (e.g., fatigue, stress corrosion cracking and structural instability). Therefore, it is important to develop an effective platform and associated methods to evaluate the residual stress during and after the assembly process when the shape control system is implemented.

In the literature, Stewart [6] used piecewise-linear elastic analysis to evaluate the residual stress in assembly fixtures. Abdelal [7] developed a nonlinear explicit finite element model to simulate the riveting process of a small panel and evaluate the deformation as well as the residual stress. These papers focused on the assembly of isotropic metal parts, which could not be directly applied to the composite parts assembly due to their anisotropic and nonlinear properties. For the assembly process of composite parts, Dong and Kang [8] proposed a response surface model and analyzed the relationship between part variation and assembly stress by using a finite element model. Zhang and Shi built a stream of variation model for prediction and control of

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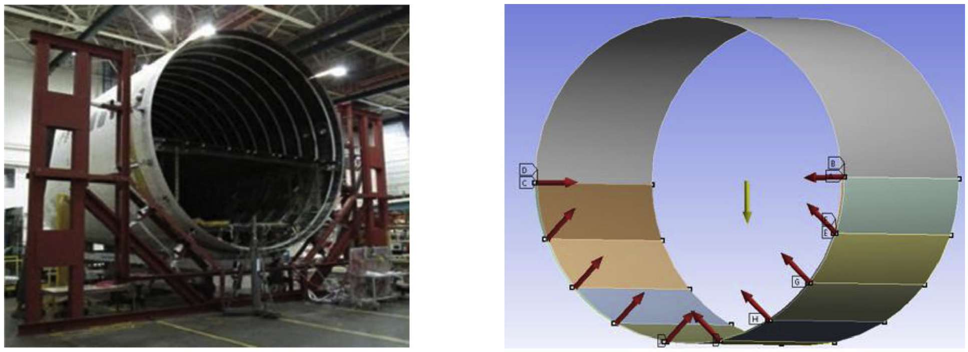


(a) The shape control system in the facility [4]

(b) Schematic diagram of the shape control system

Fig. 1. Illustration of fuselage and actuator positions.

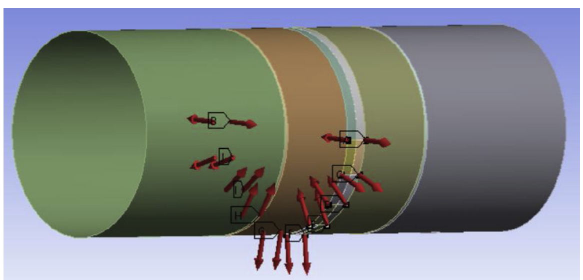


Fig. 2. Schematic diagram of the fuselages' adjustments before assembly.

dimensional variations of composite part assembly in single-station [9] and multi-station processes [10]. In their model, different sources of variabilities such as composite part manufacturing errors, fixture position errors, and relocation-induced errors were considered for analyzing dimensional variation and its propagation. Yue and Shi developed a surrogate model – based optimal feed-forward control strategy for dimensional variation reduction and defect prevention in the assembly of composite parts [11]. Gómez et al. proposed a supporting model and ad-hoc software for the decision-making process during the conceptual design of aircraft final assembly lines [12]. The literature gave a general framework of dimensional variation modeling of the composite parts assembly process and conceptual design of aircraft assembly line. However, these methods cannot be applied to our proposed shape control system due to the complexity of the fuselage structure, actuator design, as well as support structure placement.

Residual stress test based on physical experiments is not practical for the preliminary step of new technology development due to the high cost and time-consuming. Thus, we develop a finite element model to mimic the assembly process of two composite fuselages. In order to realize the dimensional uncertainties, fuselages with different initial shapes are simulated. After that, the stresses during and after the adjustment process are evaluated, and failure tests are conducted via simulation.

The remainder of this paper is organized as follows. Section 2 introduces the detailed procedure of the finite element modeling of the composite fuselage assembly process, which includes generation of initial deformed fuselages, automatic shape adjustment, joining process, and release of the actuators. Section 3 shows the dimensional deformation analysis and residual stress analysis for the composite fuselage assembly process. Section 4 provides a summary of the work.

2. Simulate composite fuselage assembly process via finite element analysis

This section provides a detailed finite element modeling procedure for the composite fuselage assembly process. The finite element analysis

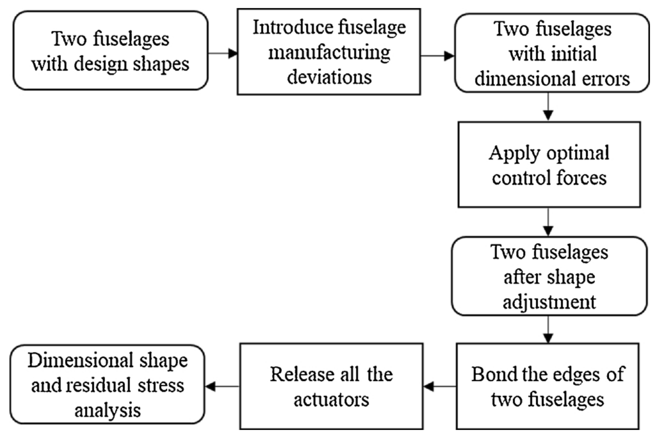
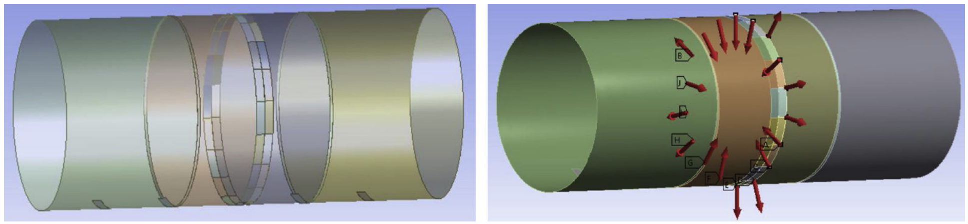


Fig. 3. The flowchart for the fuselages assembly process.

(FEA) model is developed by using the ANSYS composite PrepPost workbench [13]. The detailed procedure for FEA development and validation can be found in [4]. Fig. 3 shows the flowchart of the assembly process, which has five major steps: (i) generate two fuselages with the design shape (ideal shape); (ii) introduce the manufacturing deviations to the design shape and use the new shapes as their initial shapes; (iii) calculate and apply the actuators' forces needed to adjust the two fuselages to the target shape by using the Automatic Optimal Shape Control (AOSC) system [5]; (iv) add contact structure to bond the edge of the two fuselages; and (v) release the actuators' forces and the two fuselages will spring back to the final shape simultaneously.

2.1. Generation of initial deformation of fuselages

Before conducting the shape control and fuselage assembly, the incoming fuselages should have some inherent dimensional deviations, or initial deformations. Thus, we need to use simulation tools to generate initial shapes of the fuselages, which realize the fuselage deformations that are close to the real manufactured fuselage in the plant. Because a fuselage has its inherent design structure and stress, it is not reasonable to randomly generate the shape of the fuselage. In our simulation, we use the actuators to push and pull an ideal shape of the fuselage to get different dimensions of fuselages. The magnitude and direction of the actuators' forces are assigned according to the engineering domain knowledge. Fig. 4(a) shows the geometry of the two fuselages assembly. The colored blocks in the middle represent the locations where the actuators are applied. The circle straps and the bottom blocks on the left and right fuselages are the supporting structure that hold the fuselages in place. For the simulation in [5], only ten actuators are applied to generate the initial deformation of the fuselage. In this paper, we increase the number of actuators to generate the initial



(a) The geometry of fuselage assembly (b) Force allocation for initial deformation generation

Fig. 4. Eighteen actuators and their locations for initial deformation generation.

deformation of the fuselage to eighteen, which is illustrated in Fig. 4(b). The eighteen actuators setup increases the complexity of the deformation of the fuselage so that the deformed fuselage is more similar to real fuselage shape. Besides, the new setup makes the adjustment of fuselage more challenging and the results more convincing if the control error is within the engineering threshold.

After obtaining two fuselages with different initial dimensions, they will be used in the shape control during the fuselage assembly process, shown in Fig. 2. Ten actuators will be applied uniformly at the lower semi-circle on the edge of each fuselage. The control step will be discussed in Section 2.2. The largest gap between two fuselages ranges from 0.1 in. to 1 in. depending on how large the actuators' forces are, which covers the 0.3-inch gap reported from the literature [3]. The generation of initial deformation of the fuselages is illustrated in Fig. 5.

2.2. Adjustment of fuselages to target shape via AOSC system

In an AOSC system, a set of actuators are uniformly located at the bottom half of the fuselage. The optimal forces for the actuators are calculated to change the two fuselages shapes to the target nominal shape. A surrogate model is developed with the consideration of uncertainties [5], which has the format as

$$Y_{ij}(\boldsymbol{F}_t) = \boldsymbol{F}_t \boldsymbol{S}_j + \boldsymbol{F}_t \tilde{\boldsymbol{S}}_j + \tilde{\boldsymbol{F}}_t \boldsymbol{S}_j + z_j(\boldsymbol{F}_t) + \varepsilon_{ij}(\boldsymbol{F}_t),$$

where $i = 1,2, \ldots, n_t$; $j = 1,2, \ldots, p$; n_t is the number of simulation replications; p is the number of nodes at the edge of fuselage. $\boldsymbol{F}_t$ is the actuators' forces; $\tilde{\boldsymbol{F}}_t$ is the additional random deviation vector of actuators' forces, that is relevant to the tolerance of the actuator; $\boldsymbol{S}_j$ is the sensitivity matrix and $\tilde{\boldsymbol{S}}_j$ represents the sensitivity variability from the part uncertainty. $z_j(\boldsymbol{F}_t)$ is a zero mean Gaussian process and $\varepsilon_{ij}(\boldsymbol{F}_t)$ is assumed to follow an independent normal distribution $\varepsilon_{ij}(\boldsymbol{F}_t) \sim \mathbb{N}(0, \sigma^2_{\varepsilon j}(\boldsymbol{F}_t))$.

The training datasets and testing datasets are generated according to the same material property, dimensions of the fuselage and support structures used in the real assembly process; we use the obtained surrogate model in [5] with the feed-forward control algorithm. The objective function of the feed-forward control is

$$\min_{\boldsymbol{F}} \boldsymbol{J} = (\boldsymbol{Y_c} + \hat{\boldsymbol{Y}}(\boldsymbol{F}) - \boldsymbol{Y}^*)^T \boldsymbol{W} (\boldsymbol{Y_c} + \hat{\boldsymbol{Y}}(\boldsymbol{F}) - \boldsymbol{Y}^*)$$
$$s.\ t.\ \ \boldsymbol{F_L} \leqslant \boldsymbol{F} \leqslant \boldsymbol{F_U}$$

where $\boldsymbol{Y_c}$ is a dimensional vector of the current fuselage; $\hat{\boldsymbol{Y}}(\boldsymbol{F})$ is the predicted dimensional deviation vector; $\boldsymbol{Y}^*$ is the designed target dimensional vector; $\boldsymbol{W}$ is the weighting coefficients; $\boldsymbol{F_L}$ and $\boldsymbol{F_U}$ are the lower and upper bound of actuators' forces. The optimal actuators' forces $\boldsymbol{F}$ will be used to adjust the fuselage to the nominal shape.

2.3. Joining of two fuselages

After the adjustment step, the two fuselages will have the same shape on the edge with different actuator forces applied. The next step is to assemble the two fuselages via riveting joins. Riveting is a forging process that can be applied to assemble different parts together by a part named rivet. The rivet is able to join the two parts through adjacent surfaces. In order to mimic the riveting joining process with two composite fuselages, we used bonded structures from ANSYS composite workbench to limit the deformation of the edges of two fuselages, which is shown in Fig. 6. Since the fuselage is virtually divided into several segments at the edge, we bonded each pair of edges for both fuselages, as shown in Fig. 6. The bonded structures restrict the two fuselages to deform simultaneously on the edge after we release the applied actuators' forces.

2.4. Release of the actuators

When the two fuselages are joined, the actuators' forces applied on the two fuselages still remain. Hence the last step of the simulation is to release the actuators, which means that the actuators' forces are reduced from the target values to zero during this period. In literature, the common method to simulate the release of the actuators is to apply the reverse force at the positions where the actuators are applied [9,15]. In this paper, a new method is proposed to simulate the application and release of fuselage actuator forces by using the dynamic force curve.

In literature [9,15], a three-step method is used to simulate the assembly process. The first step is to apply the static actuator forces to adjust the two parts to achieve the same shape; the second step is to join these parts via riveting process; and the last step is to apply the reverse forces in step one, which is considered as the releasing forces of the spring-back effect. An example to illustrate the reverse force method is shown in Fig. 7. In Fig. 7(a), one actuator is used to pull the right fuselage at +500 pounds. Then a -500 pounds force is applied to push the right fuselage back to the nominal. Next, the two fuselages are bonded and +500 pounds force is applied as reverse force, which results in the

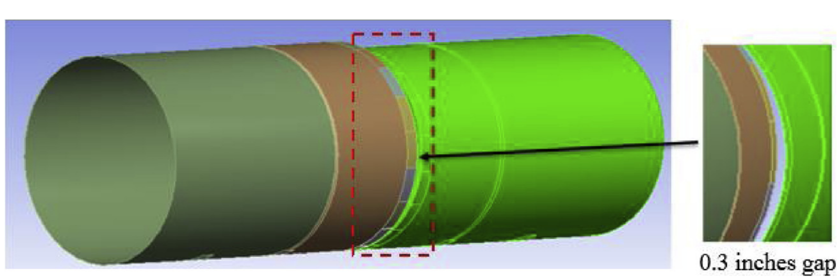


Fig. 5. Fuselages with different initial shapes.

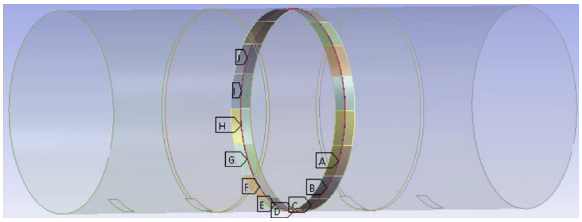


Fig. 6. Bonded structure of the riveting joins.

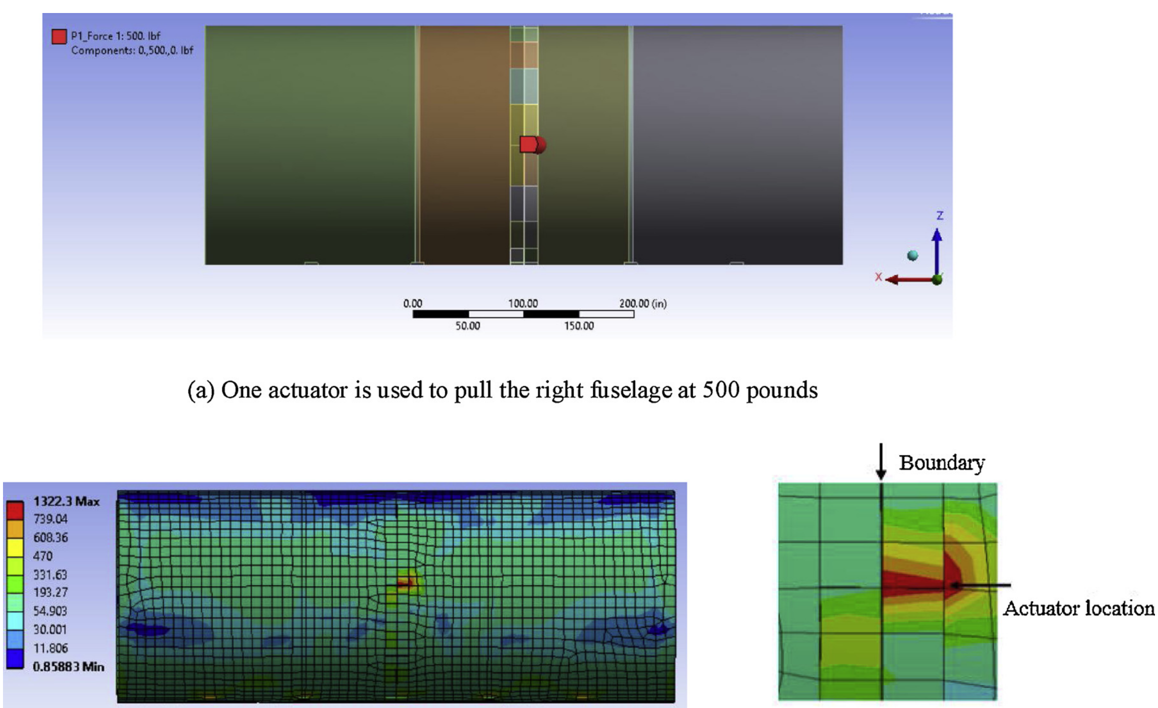
spring-back of two fuselages. The residual stresses after the spring-back are shown in Fig. 7(b). The maximum stress is near the actuator location, and the residual stresses around the actuator are very large, which is shown in Fig. 7(c). The results show that the residual stresses are mainly caused by the reverse force, which does not make sense. the residual stresses should result from the mixed effects of the releasing forces, bonded structures as well as support structures.

To improve the simulation accuracy, we propose an improved approach which is named the dynamic force curve method. In ANSYS, the force can be constant, tabular, or functional. Hence the application of actuator’s force is equivalent to the increase of force from zero to target value. The release of actuators force can be considered as the decrease of the force from the target value to zero. As shown in Fig. 8(a), the x-axis is the time stamp, and the y-axis is the force in pound. From time stamp 0 to 1, the actuator’ force decreases from zero to -500 pounds, which is the adjustment step discussed in subsection 2.2. At time stamp 1, the bond structures are added, which is the joining step discussed in subsection 2.3. From time stamp 1 to 2, the actuator’s force increases from -500 pounds to zero, which is the release step discussed in subsection 2.4. The use of dynamic force curve integrates the three steps into one simulation via element birth and death for contact elements. The residual stress by using the dynamic force curve method is shown in Fig. 8(b) and (c). The major difference between Figs. 7(c) and 8 (c) is the location of high stresses. In Fig. 7(c), the high residual stresses can be found around the actuator location. In Fig. 8(c), however, the high residual stresses occur around the boundary of two fuselages. The dynamic force curve method is more accurate because the right fuselage will spring back after the actuator is released in reality. However, the left fuselage is bonded with the right fuselage, and as a result, residual stresses occur at the boundary area of both fuselages in reality.

3. Dimensional deformation and residual stress analysis

3.1. Simulation configurations

In this simulation study, two composite fuselages are assembled with actuator forces applied, which is illustrated in Fig. 2. Each fuselage has a length of 24 feet and a diameter of 18 feet. The thickness of each fuselage is 0.29 in.. The ply design follows the fabrication of composite fuselage, and the detailed information about the material properties can be found in [4]. The initial gap between two fuselages is about 0.3 in. according to the literature [3]. We use Maximin Latin Hypercube design to create 20 pairs of fuselages with different initial deformed shapes. The maximum force in the design is 500 pounds. For example, by using the actuators' forces shown in Fig. 4(b), the initial total deformation for the two fuselages is shown in Fig. 9(a) and the deformation at the edge is shown in Fig. 9(b) and (c) for those two fuselages respectively. The red lines in Fig. 9 are the deviation direction and proportional magnitude of each node. The length of the red line is exaggerated for illustration purpose. The deformation at the edge in Fig. 9(b) and (c) is viewed from negative X direction. At the right top corner of each fuselage, the left fuselage deforms toward left about 0.2 in. while the right one deforms toward right about 1 inch, which introduces a gap of more than 1 inch. The goal is to use the finite element model developed in section 2 to simulate the assembly process of those two fuselages and estimate the deformation and stress during the process. For illustration purpose, the following figures show the simulation results based on the initial shape design in Fig. 4(b).

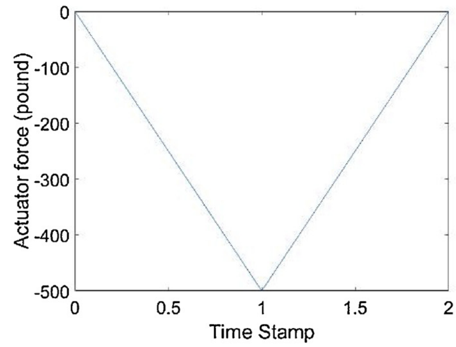


(a) One actuator is used to pull the right fuselage at 500 pounds

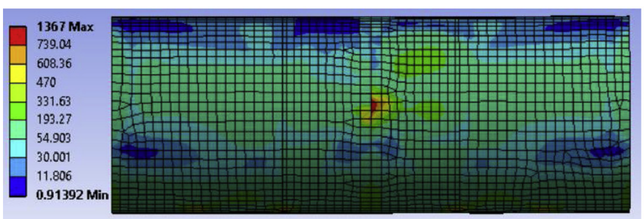
(b) -500 pound force is applied to push the right fuselage back

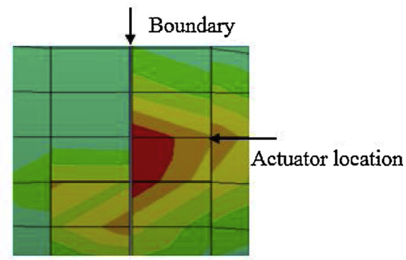
(c) Residual stress near the actuator

Fig. 7. Simulation of the assembly process via the three-step method.



(a) Dynamic force curve for the actuator

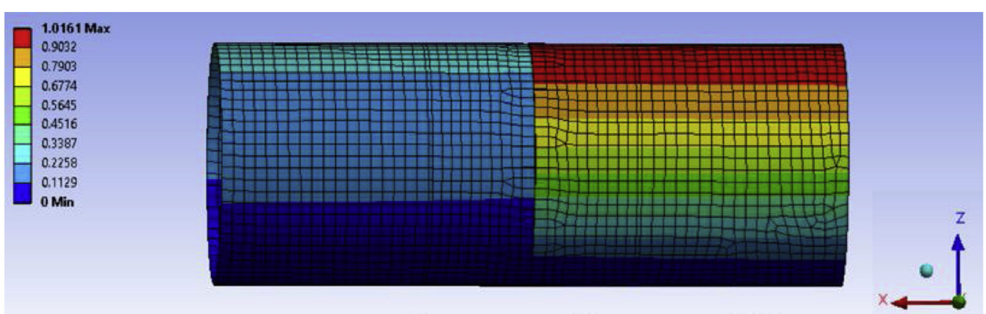




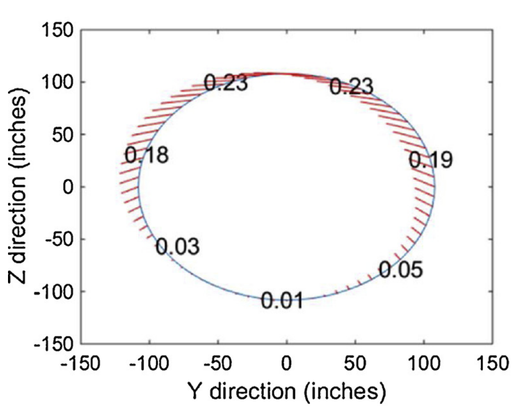
(b) Residual stress after the joining process

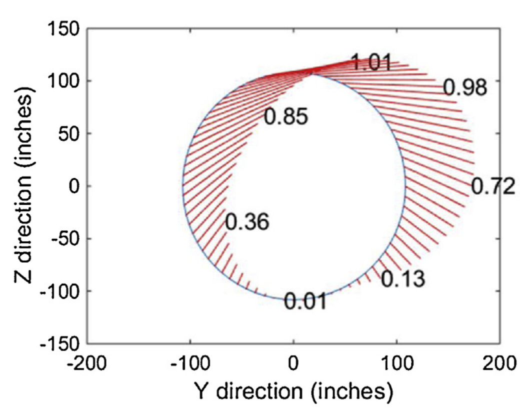
(c) Residual stress near the actuator location

Fig. 8. Simulation of the assembly process via the dynamic force curve method.



(a) Two fuselages to be assembled

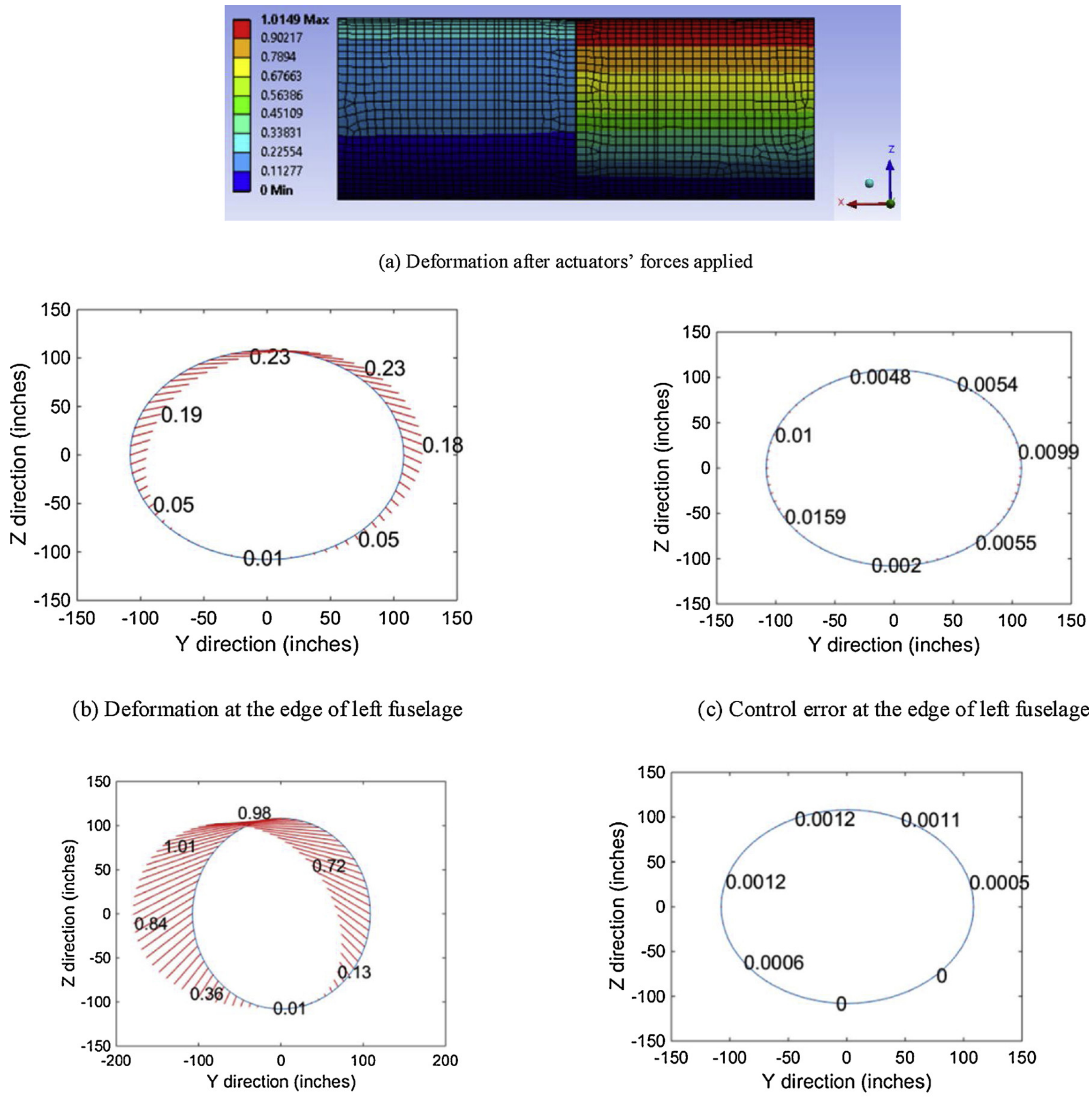




(b) Dimensional deviation of the left fuselage

(c) Dimensional deviation of the right fuselage

Fig. 9. Initial deformations of both fuselages.



(a) Deformation after actuators' forces applied

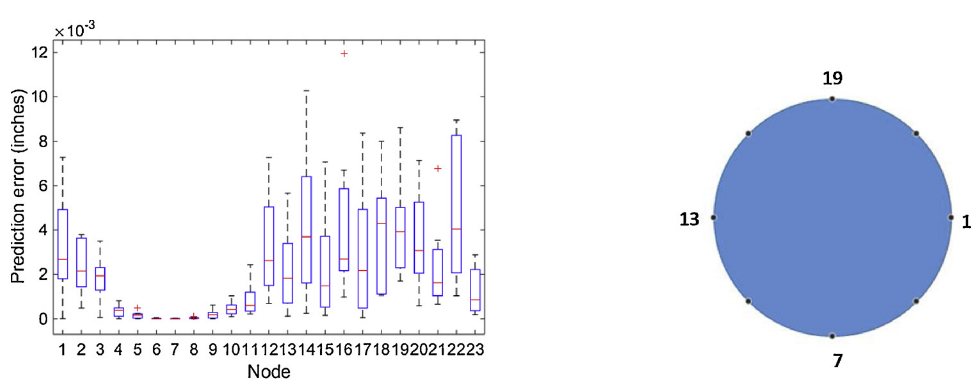
(b) Deformation at the edge of left fuselage

(c) Control error at the edge of left fuselage

(d) Deformation at the edge of the right fuselage

(e) Control error at the edge of the right fuselage

Fig. 10. Initial deformations and adjustment error after adjustments.



(a) Control errors box plot

(b) Location of node

Fig. 11. Performance of the shape adjustments.

3.2. Simulation result

3.2.1. Dimensional variation between adjusted shape and target shape

During the shape control of the fuselages, the ten actuators' forces are calculated using the model provided in Section 2.2. Fig. 10 shows the deformation of two fuselages after the actuators' forces are applied. The total deformation during shape adjustment in Fig. 10(a) is similar to the initial total deformation in Fig. 9(a), but in a negative direction. Fig. 10(b) shows the deformation at the edge of the left fuselage after the actuators' forces are applied. At each node, the deformation ought to have a similar number but in the opposite direction to the node in Fig. 9(b). Fig. 10(c) shows the control error of the left fuselage, which is the deviation between the adjusted shape ($\boldsymbol{Y_c} + \hat{\boldsymbol{Y}}(\boldsymbol{F})$) and the target shape ($\boldsymbol{Y}^*$). The average control error is the mean of the absolute control error of all the nodes, which is $\sum_{j=1}^{p} \|y_{cj} + \hat{y}_j - y_j^*\|/p$. Here the mean control error is 0.0056 in.. Fig. 10(d) and (e) illustrate the deformation and control error at the edge of the right fuselage. The average control error is 0.0009 in..

To ensure that the two fuselages are adjusted to the same target shape, the control errors between the 40 adjusted shapes and the target shape at each node are calculated. Fig. 11(a) shows the box plot of the control error at each node. 91 nodes are collected at the edge of each fuselage. One node is selected for illustration from every four adjacent nodes. Thus, the control errors of the 40 adjusted shapes at 23 selected nodes are shown in Fig. 11(a), and the locations of the nodes are shown in Fig. 11(b). Nodes located at the bottom of the semi-fuselage have better control accuracy compared with the top ones, which makes sense because the actuators are installed at the lower semi-fuselage and the support structure at the bottom constrains the deformation at the lower semi-fuselage area. Although the control error is higher for the upper semi-fuselage area, it is still below the engineering threshold. The average control error is 0.002 in., which is lower than the 1% of the 0.3-inch gap. Therefore, the shape control system is adequate to change the initial shape of two fuselages to the target shape.

3.2.2. Deformation during and after the assembly process

During the shape control of those two fuselages, the deformation after the actuators' forces applied is shown in Fig. 10(a). The maximum deformation is 1.015 in.. Then the two fuselages will have the same target shape and be bonded together at the edge. After that, the actuators' forces will be released and the deformation after the spring-back of two fuselages is shown in Fig. 12. Although the two fuselages have similar deformation in magnitude at adjacent locations, the directions of the deformation are not the same. As shown in Fig. 12(b), the left fuselage deforms towards –z direction in the middle while the right fuselage deforms towards + z direction. The maximum deformation after the two fuselages spring-back is 0.625 in., which is lower than the maximum deformation after the actuators' forces are applied.

3.2.3. Stress during and after the assembly process

The stresses during and after assembly are the key metric that engineers attach importance to since they reflect whether the composite fuselage will be hurt during the assembly process. For the shape control step, the stresses caused by actuators are shown in Fig. 13(a). The maximum stress is 1192.4 psi, which is located at the bottom support structure of the right fuselage. After the joining process, the two fuselages cannot spring back to their original shapes. Hence the residual stresses remain after the release of actuators, which is shown in Fig. 13(b). The maximum residual stress is 739.04 psi, and it is also located at the bottom support structure of the right fuselage.

3.2.4. Stress analysis and failure test

One practical concern is whether the implementation of the shape control system in the assembly process will introduce very large stress that damages the fuselage. Through the simulation of 20 pairs of fuselages assembly, the maximum stress during and after the assembly is less than 3000 psi; and the maximum stress mostly occurs in the support area of fixtures. The residual stress at the assembly edge is even smaller. The maximum residual stress from shape control and assembly process is much smaller than the failure threshold. Stress test under Tsai–Wu failure criteria is also conducted [14]. Among all the experiments, the largest inverse reserve factor, which calculates the inverse margin to failure, is 0.19. It is much lower than the threshold at 1.00. Therefore, it is safe to conduct the automatic shape control and assembly for the composite fuselages.

3.3. Discussion

3.3.1. Location of maximum stress

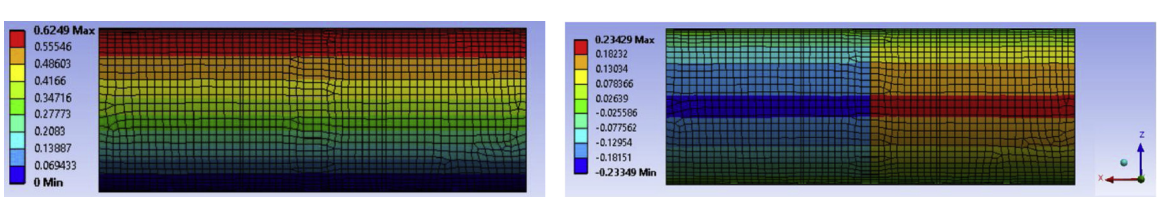
Among the 20 pairs of fuselages assembly simulations, 7 cases have the maximum stress located at the node where an actuator force is applied. The rest 13 have the maximum stress located at the support structure area. Residual stress for one pair of fuselages assembly is shown in Fig. 14. The fuselages are viewed from the bottom in the figure. Therefore, stress test in the factory should have higher priority at the edge of the fuselage where actuators are applied, as well as the support structure area during the assembly.

3.3.2. Relation between maximum deformation and maximum stress

Through the experiments, the pair of fuselages with larger maximum deformation is not always generating larger maximum stress. The residual stress is affected by mixtures of factors, including the release of actuators' forces, the bonded structures, and the support structures. Those factors and their combined effects will generate different fuselage deformations and stress patterns. For example, the maximum residual stress in Fig. 13 is 739.04 psi while the one in Fig. 14 is 596.23 psi. However, the maximum deformation for the pair of fuselages in Fig. 13 is 0.625 in. while the one for the pair of fuselages in Fig. 14 is 0.701 in..

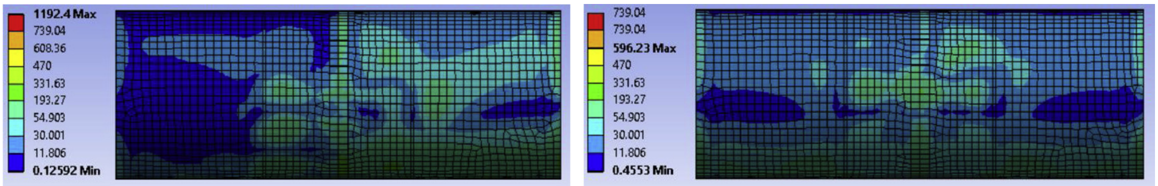
4. Summary

Composite parts have been increasingly used in the aircraft industry due to their superior properties. Dimensional variability of composite fuselage is an important problem due to the diverse sources of manufacturing suppliers and the complex fabrication process. A new shape control system with actuators has been developed to adjust the shape of fuselage during the assembly. In such a system, residual stress may exist in the fuselages after the release of actuators during the assembly. Thus, modeling and analysis of the residual stress are very important to avoid severe mechanical problems for the fuselage assembly and usage. In this



(a) Total deformation (b) Z directional deformation

Fig. 12. Deformation of both fuselages from initial the shapes to the shapes after spring-back.



(a) Stresses after the actuators' forces applied (b) Stress after the release of actuators

Fig. 13. Stresses distribution of both fuselages.

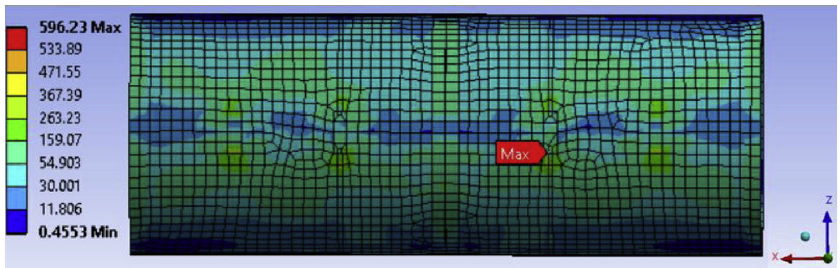


Fig. 14. Location of maximum stress after assembly.

paper, a new finite element simulation is developed to realize the virtual assembly of two composite fuselages with actuators' forces applied. We utilize the AOSC system [5] to conduct the shape adjustment. For the assembly process, a new dynamic force curve approach is proposed to simulate the spring-back effect after the assembly. The actuator's force during the assembly is dynamically applied, which means that it increases from zero to the target value during assembly and reduces from the target value to zero after the two fuselages are bonded. It is more accurate than the traditional three-step approach that is using reversed force to realize the spring-back. Our proposed simulation can estimate the deformations and stresses of the two fuselages during the entire assembly process, including the adjustments of two initial fuselages, the bond of the adjusted fuselages, and the release of actuators. The simulation result indicates that the new shape control system with multiple actuators is effective in the fuselage assembly, which achieves high assembly accuracy. Meanwhile, the residual stresses generated from the assembly process is much smaller than the safety threshold.

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