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Feasibility analysis of composite fuselage shape control via finite element analysis

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ABSTRACT

Composite parts have been increasingly used in aircraft industry because of their high strength-to-weight ratio and stiffness-to-weight ratio. Due to the diversity of suppliers and fabrication process variation of composite parts, dimensional variability of composite fuselages inevitably exists. In order to improve the dimensional quality and increase the productivity, a new shape control system has been proposed to conduct dimensional shape adjustment before the assembly process. By using finite element analysis, we conduct the feasibility analysis of this new shape control system. Firstly, we develop a finite element model with detailed material property, ply design, fixture structure, and actuators installation considered. The finite element model is then validated and calibrated by physical experimental data. Feasibility analysis via FEA includes single-plane dimensional control capability analysis, double-plane scheme analysis, stress/strain analysis, and failure test. We conclude that the single-plane with ten actuators scheme is feasible for the shape control, and the actuators do not damage the fuselage.

1. Introduction

Composite materials have been increasingly used in aircraft industry due to their advantages like high strength-to-weight ratio, high stiffness-to-weight ratio, corrosion resistance, and high durability [1]. Aircraft parts made from composite materials, such as fairings, spoilers, floor beams, and flight controls have been developed. These composite structures realize better weight savings over aluminum parts [2]. A new generation of large aircraft is designed mostly with composite fuselage and wing structures. As an example, a commercial aircraft has major structural parts made from composite materials, and the composite parts represent more than 50% by weight [3]. Dimensional control of the assembly process for these advanced composite parts requires an in-depth knowledge of composite structures, materials and properties, which is very important for the quality management, high productivity of manufacturing process and running safety of assembled aircrafts. However, due to the diversity of suppliers and multiple manufacturing batches from each supplier, the dimensional variability of composite fuselages inevitably exists. For instance, a report showed that a gap of 0.3 in. occurred when the nose-and-cockpit section lined up with the fuselage section [4].

For the sake of reducing dimensional variability and residual stress of the composite fuselage assembly process, a shape control system with multiple actuators is proposed to adjust the dimension of the composite fuselage before assembly. In the current practice, a “pogo” shape control system is used to reduce the dimensional deviations between the real composite part and the ideal shape. The photo and schematic diagram of the current “pogo” system are shown in Fig. 1(a) and (b). The disadvantages of the current system include that (i) the capability of dimensional shape control is very limited, (ii) it takes a long time to adjust the actuators to get an acceptable dimensional shape, and (iii) highly skilled engineers are required to conduct the adjustment. Therefore, a new shape control system is designed to realize better dimensional quality control. As shown in Fig. 1(c) and (d), ten actuators are assigned cross the edge of the lower semi-circle of the fuselage. These ten actuators can provide push and pull forces to change the in-plane shape of the fuselage. An automatic shape control system will be developed that can effectively and efficiently adjust composite parts to an optimal configuration [5]. The new shape control system can (i) compute the optimal actuators’ forces to minimize the dimensional deviations of current composite parts and the ideal shape; (ii) implement the adjustment automatically; (iii) release the workloads of highly skilled engineers. Before the development of automatic shape con-

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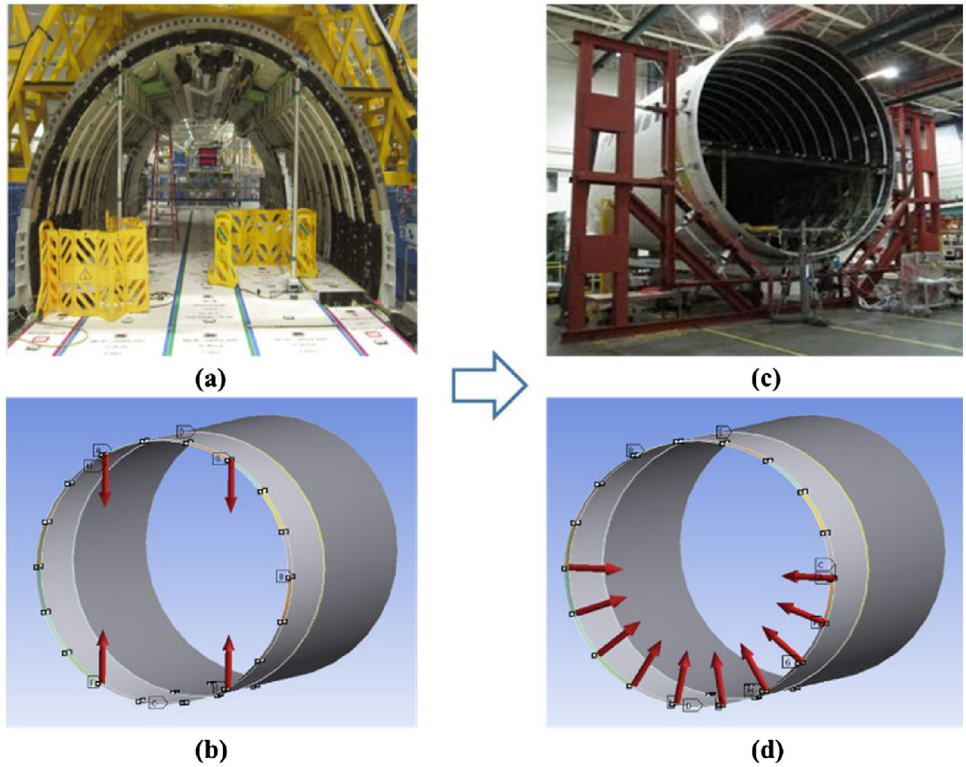

Fig. 1. (a) Current "pogo" system, (b) schematic diagram of current "pogo" system, (c) new shape control system, (d) schematic diagram of new shape control system.

trol system, a feasibility analysis of the new shape control system for the composite parts should be conducted systematically.

In the literature, Pinkerton and Moses assessed the capabilities of a new out-of-plane displacement piezoelectric actuator called thin-layer composite-unimorph ferroelectric driver and sensor (THUNDER) to alter the upper surface geometry of a subscale airfoil to enhance the performance under aerodynamic loading [6], and the assessment was based on physical experiments. Sofla et al. [7] reviewed the recent activity in conceptual design, prototype fabrication, and evaluation of shape morphing of an aircraft wing, especially for smart materials including shape memory alloys, piezoelectric actuators, and shape memory polymers. Sodano et al. [8] presented the feasibility of using macro-fiber composites for vibration suppression and structural health monitoring. The aforementioned literature focused on the feasibility of variability monitoring and control during the design of composite fuselage and wings. For the assembly process of composite parts, Dong and Kang proposed an approach based on response surface method and analyzed the relationship between part variation and assembly variation/stress via virtual experiments and finite element model [9]. Zhang and Shi built a stream of variation (SoV) model for prediction and control of dimensional variations of composite part assembly in single-station [10], and multi-station process [11]. In their model, different sources of variabilities such as composite part manufacturing errors, fixture position errors, and relocation-induced errors were considered for analysis of dimensional variation and its propagation. 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 aforementioned literature gave a general framework of dimensional variation modeling of the composite parts assembly process and conceptual design of aircraft assembly line. However, there is no systematic analysis of the feasibility of the newly proposed automatic shape control system.

Feasibility analysis based on pure physical experiments is very expensive and time-consuming. Usually, before testing the real system with physical experiments, feasibility analysis based on computer simulation needs to be done. Finite element analysis (FEA) is a typical computer simulation method to analyze the complex properties of composite materials for aerospace applications [13]. The advantages of FEA include accurate representation of complex structures, inclusion of dissimilar material properties, capture of local effects, and accurate representation of the total solution. By using the commercial software like ANSYS or ABAQUS, it is viable to analyze the mechanical properties and predict dimensional, stress, and strain responses of the composite fuselage under different actuators' forces.

In order to implement the feasibility analysis of the new shape control system, an accurate finite element model is developed to mimic the fabrication process of a composite fuselage. The finite element model is calibrated and validated by physical experimental data, and the finite element model can accurately predict the dimensional shape change of the fuselage under different settings of actuators' forces. Then, feasibility analysis of the shape control system is conducted through dimensional control capability analysis, stress/strain analysis, and failure test.

The remainder of this paper is organized as follows. Section 2 introduces the detailed procedure of the finite element modeling of the composite fuselage and the actuator settings. Section 3 is the calibration and validation of the finite element model by comparing it with the physical experimental results. Section 4 consists of the feasibility analysis of the dimensional control capability, stress/strain analysis, and failure test. Section 5 provides the summary of the work.

2. Finite element modeling

In this section, we show the finite element modeling of the composite fuselage. With the commercial software ANSYS Composite

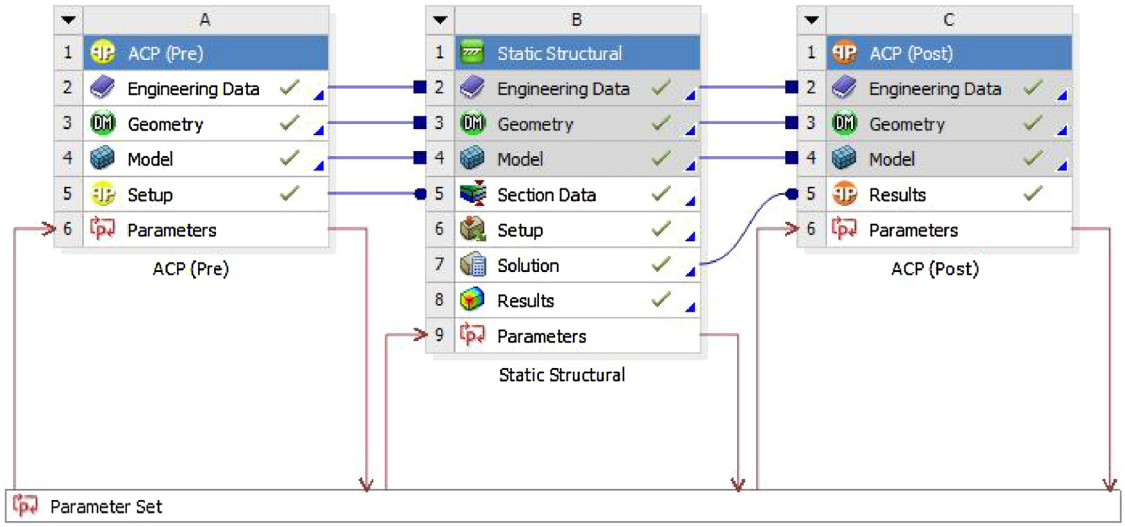

Fig. 2. The workbench of the finite element model.

PrepPost [14], we mimic the real fabrication process of the composite fuselage, including material introduction with engineering properties, ply definition and design, material orientation, geometrical setting and so on. The engineering fixture constraints and actuators' forces are considered, and dimensional deformation, stress/strain responses, and advanced failure test are analyzed.

The developed finite element model by the ANSYS Composite PrepPost (ACP) workbench is illustrated in Fig. 2. The ACP is an add-in to the workbench and is integrated with multiple functionalities for the analysis of layered composite structures. As shown in Fig. 2, the workflow for finite element modeling of the composite fuselage can be completed in three steps: (i) design and pre-processing, such as introducing composite materials and properties parameters in the engineering data module, designing the geometry of the composite fuselage, and setting up ply parameters and orientations; (ii) structural analysis including finite element meshing, assigning actuators' forces and engineering constraints, and response analysis; (iii) post-processing to evaluate the design performance and implement failure analysis.

2.1. Key material properties

The materials used to build the composite fuselage are unidirectional carbon fiber and epoxy resin. Unidirectional carbon fiber has been the standard material within the aerospace industry, and the carbon fiber is typically pre-impregnated with a thermosetting epoxy resin system, which is called prepreg. The common fabrication process is to draw collimated raw carbon fibers into the impregnation machine where hot melted resins are combined with the strands using heat and pressure [2]. The structure of prepreg for aircraft composite fuselage can realize high strength by carbon fibers, high toughness by epoxy resin, and improvement of impact resistance by maintaining superior heat resistance of epoxy matrices. Other advantages include good part uniformity, good repeatability, less waste, less curing time, and so on. The highly toughened carbon fiber-reinforced epoxy prepreg is used in the finite element model. The key properties of the epoxy carbon prepreg [15] are listed in Table 1.

2.2. Ply design

The finite element modeling of composite fuselage mimics the real fabrication process. Specifically, the composite material introduced in Section 2.1, such as carbon fiber prepreg, are used to form fabrics. From a production point of view, it is considered as one ply. The thickness of each ply is 0.008 in. and the properties of one ply including stretch stiffness parameters and shear stiffness parameter are shown in Fig. 3(a). The stretch stiffness and shear stiffness for one ply have orthogonal distribution pattern.

Table 1
Key properties of the Prepreg.

Property Parameters	Magnitude
Density	93.02 lb./ft^3
Young's Modulus X direction	1.21×10^5 MPa
Young's Modulus Y/Z direction	8.60×10^3 MPa
Shear Modulus YZ direction	3.10×10^3 MPa
Shear Modulus XY/XZ direction	4.70×10^3 MPa
Poisson's Ratio YZ	0.4
Poisson's Ratio XY/XZ	0.27

Fabrics are then stacked up depending on specified orientation that is ±45°. A stackup is a non-crimp fabric with a defined stacking sequence. The definition of the stackup can be given in both directions (Bottom-Up and Top-Down). In the Top-Down sequence, the first defined ply is placed first on the mold, which is on the bottom of the stackup and the other plies are placed over it. The sequence used for this study is Top-Down. The ply design and properties of one stackup are shown in Fig. 3(b). Next, fabrics and prepreg carbon fiber are used to manufacture sub-laminates with specified ply orientations and analysis of properties shown in Fig. 3(c). The layup sequence is Top-Down. Finally, the sub-laminates are integrated into the composite fuselage.

From Fig. 3, we can see that the properties change from fabrics, stackups, to sub-laminates. Besides, the 90° plies react to axial loads and ±45° plies react to shear loads and side loads. The strength design requirements are a function of the applied load direction, and ply orientation and ply sequence have to be correct [2]. To simplify the fabrication process and focus on the major factors, we do not consider the manufacturing defects such as delamination, resin starved areas, air bubbles, and wrinkles etc. in the finite element modeling process. Fig. 4(a) shows the total ply design of a sub-laminate and Fig. 4(b) shows the orientation of one ply in the finite element model.

2.3. Fuselage geometry, fixture structure and actuators

After introducing the key parameters and ply design, we illustrate the geometry of the fuselage, fixture setting, and actuators.

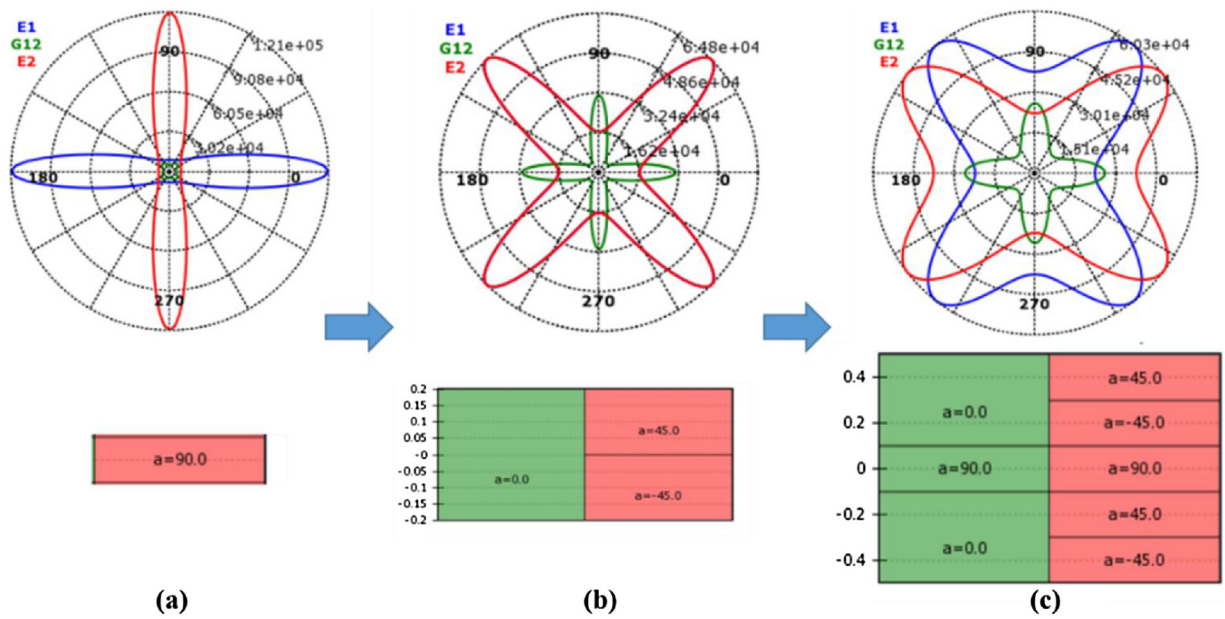

Fig. 3. Polar properties of (a) fabrics, (b) stackups, and (c) sub-laminates (Note: E1/E2: Young's modulus along different directions; G12: shear modulus).

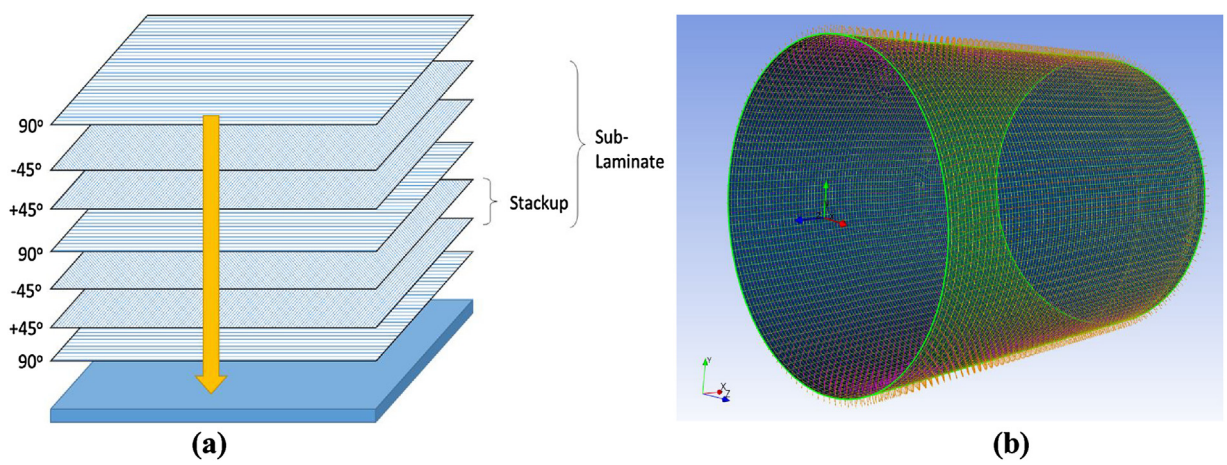

Fig. 4. (a) Ply design, (b) the orientation of carbon fiber.

The length of the fuselage in the finite element model is 24 feet and the diameter is 18 feet. The thickness of the fuselage is 0.295 in. After the design of the geometry, material parameters, and ply structures are completed, the weight of the fuselage is then computed, which is 3100 lbf.

There are three fixture structures, two bottom supports and one strap fixture shown in Fig. 5. The bottom supports are 3.14 feet long and 1 foot wide. The distance between the support and the edge of the fuselage is 6 feet. The bottom supports are realized by constraining the z directional deformation of the supporting area of the fuselage. The 4-in. width strap support is a band that attaches the fuselage surface and the bottom support. It prevents the fuselage from shifting due to the applied actuator forces.

The 10 actuators are realized by applying forces on the edge of the outer surface of the fuselage. The forces are equally distributed along the lower semi-fuselage. The distance between the actuator and the edge along x-direction is 12 in. The actuators are assigned across the edge of the lower semi-circle of the fuselage instead of the whole circle of the fuselage. The reasons for the layout of actuators are (i) the whole-circle actuators set-up may result in over-constraints of the shape control, this is a situation that should be prevented in the aircraft assembly system; (ii) with the consideration of the implementation in the assembly floor, the engineers of the sponsor company prefer to install the actuators in the lower half of the fuselage. If this layout can achieve the required shape control precision, it is desirable to avoid adding actuators in the upper fuselage. For the dimensional control in joining of two fuselages assembly, we mainly focus on the dimensional deformation around the edge of the fuselage. The reason is that the main purpose of this shape control system is to reduce the dimensional gap between the overlap edges of two fuselages during the assembly process.

3. Model validation

3.1. Set-up of the physical experiment

A physical experiment with a real fuselage is conducted to validate the accuracy of the finite element model. The physical experiment set-up is shown in Fig. 6. Under the fuselage, mounting bar, a force sensor, floor jack, and wood stand are installed successively. A three-dimensional laser metrology system is used to

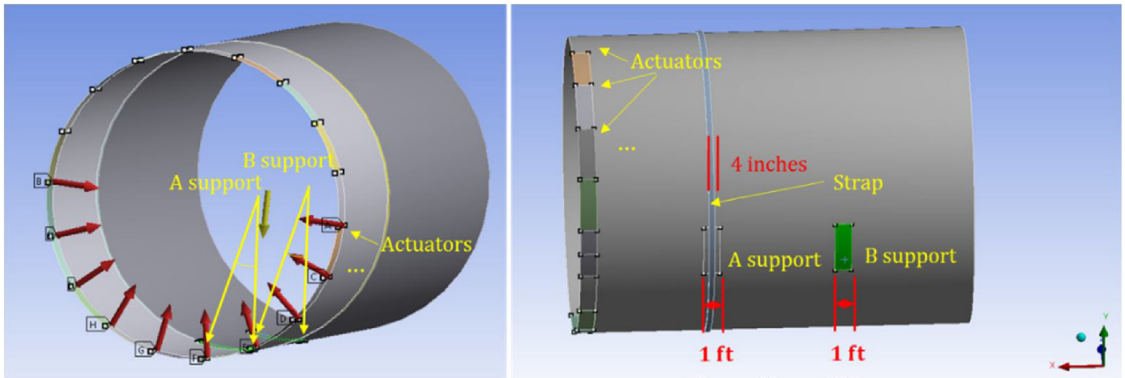

Fig. 5. Support structure of the fuselage in the FEA.

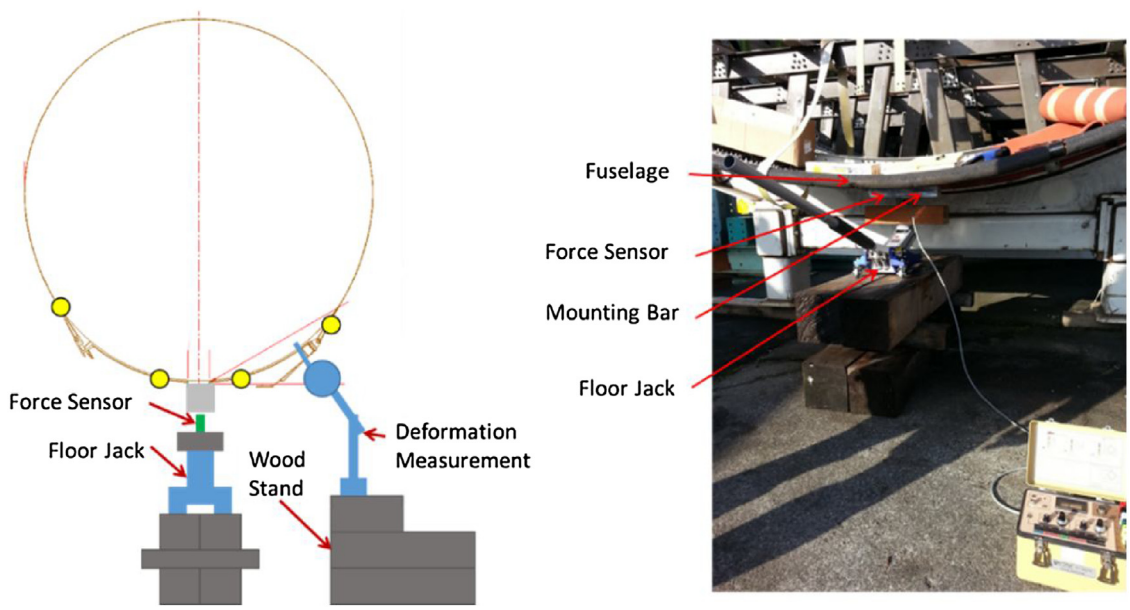

Fig. 6. The set-up of the physical experiment.

do deflection measurement along the side direction. The dimensional information of the fuselage is consistent with our simulation model parameters. Besides, contacting area between the fuselage and the actuator is a rectangle with the same size for both the finite element model and the physical experiment set-up. The physical experiment records the dimensional deformation of the fuselage under an actuator force changing from 100 lbf to 600 lbf.

3.2. Calibration of the finite element model based on physical observations

After obtaining the physical experimental observations, we need to calibrate the finite element model to make it as accurate as possible. We apply an effective model calibration method via sensible variable identification and adjustment [16]. Calibration variables include thickness of fuselage, thickness ratio of carbon fiber and epoxy resin, temperature, ply orientation angle, support parameters and so on. In the calibration, the concept of sensible variables is introduced. Sensible variables are model parameters which are sensitive in the engineering modeling, and whose optimal values are different from the pre-specified design values. The effective calibration method to identify and adjust the sensible variables with limited physical experimental data is discussed in detail in [16]. We show the results under three actuator's force 200 lbf, 400 lbf and 600 lbf in Fig. 7. The differences between FEA simulation data and physical experimental data before calibration are shown in Fig. 7(a–c), and the ones after calibration are shown in Fig. 8(a–c). By quantifying the difference between the FEA simulation data and physical experimental data, the calibration can improve the weighted summation of square error from 353.15 to 53.29 [16]. We can find that after calibration, the response of the finite element model matches the physical experimental data well. Model validation is also accomplished by comparing FEA simulation results and physical experimental data in Fig. 8(a–c).

4. Feasibility evaluation and analysis

The feasibility evaluation analyzes whether the actuators are capable of adjusting the shape of the composite fuselage to the desired shape without damage to the composite fuselage. The feasibility evaluation has two sections. First, the dimensional control feasibility evaluates if the actuator can adjust the fuselage within the actuator force limitation. Second, the stress analysis will show

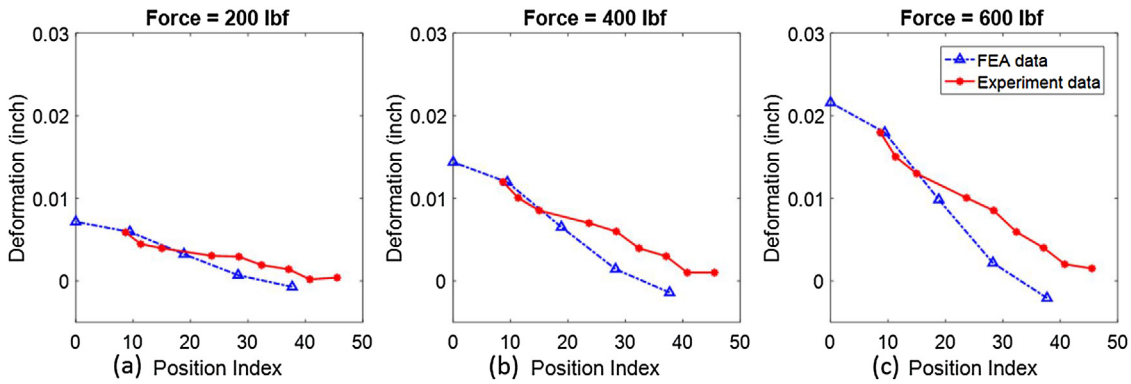

Fig. 7. Comparison of FEA data and physical experimental data before calibration under the actuator's force is equal to (a) 200 lbf, (b) 400 lbf, and (c) 600 lbf.

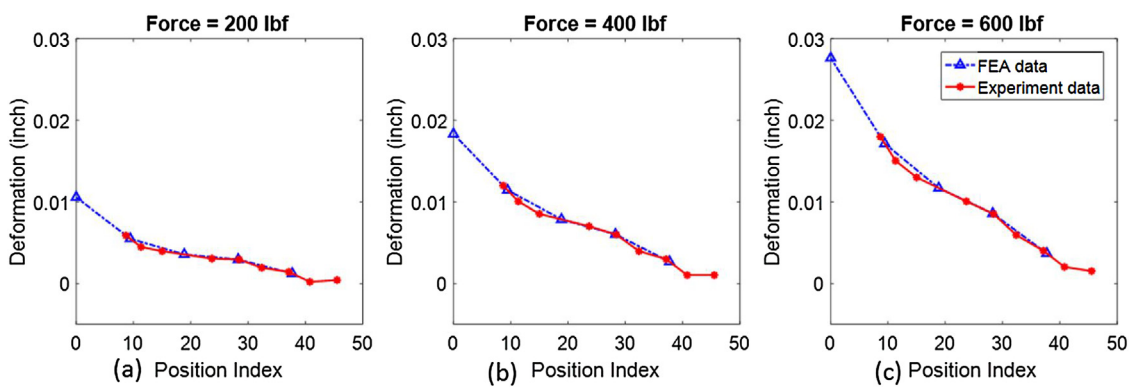

Fig. 8. Comparison of FEA data and physical experimental data after calibration under the actuator's force is equal to (a) 200 lbf, (b) 400 lbf, and (c) 600 lbf.

whether the fuselage is at the risk of being damaged during the shape control process.

4.1. Single-plane dimensional control feasibility

The dimensional control feasibility test aims to verify whether a fuselage with dimensional errors and natural deformation due to its weight can be compensated to the target shape under bounded actuators' forces. In order to test the deformation of the composite fuselage under different actuators' forces, we set up actuators scheme shown in Fig. 9(a). All actuators are installed in a single plane with the same X-axis. To mimic the actuators' adjustments during the shape control process, the odd numbers of the actuators push outwards while the even numbers of the actuators push inwards. Each actuator's force has a range from 0 to 1000 lbf and we apply the same magnitude of forces for all the actuators. The deformation result of the composite fuselage is shown in Fig. 9(b). The dimensional deformation of the composite fuselage at the bottom half semi-circle is smaller than the top half due to the constraints of the fixtures. The patterns of the shape deformation are similar for different actuators' forces from 100 to 1000 lbf. We are particularly interested in the deformation at 1000 lbf because that it is the upper limit of forces specified for the actuators in design. The deformations at circumferential angle that is smaller than 45° and greater than 130° are larger than 1 in., and the maximum deformation under 1000 lbf is about 5 in. Thus, the shape control capability is beyond the general maximum manufacturing deviation of a real composite fuselage. Hence, it is feasible to adjust the composite fuselage deformation due to weight back to the ideal shape with less than 1000 lbf actuators' forces.

4.2. Double-plane dimensional control feasibility

In Section 4.1, the single-plane dimensional control feasibility has been studied. The necessity of using double-plane actuators to do shape control will be evaluated in this section. Shape control with more actuator planes has a potential to realize better shape control results. However, it will increase the complexity of the fixture system, and may also result in an over-constraints issue. In the FEA, we install actuators in two force planes. As shown in Fig. 10(a), ten actuators are installed in the force plane I, with circumferential angles equal to [0°,20°,. . ., 180°]. The direction of the actuators' forces at adjacent positions are opposite in this study. As shown in Fig. 10(b), nine actuators are installed in the force plane II, with circumferential angles equal to [10°,30°,. . ., 170°]. The direction of the actuators' forces at adjacent positions are also opposite in this force plane. The distance between force plane I (or force plane II) and the edge is 6 in. (or 24 in.). We consider the dimensional response in the plane 1–7, shown in Fig. 10(c). The distance between two neighboring response planes is 6 in. The force plane I coincides with the response plane 2, and the force plane II coincides with the response plane 5.

Let F_I denote the equivalent actuators' forces in the force plane I, and F_{II} for the forces in the force plane II. The results under F_I = 100 lbf and F_{II} = 0, 100, 200, . . ., 600 lbf are shown in Fig. 11. By adding extra nine actuators in the second force plane, the capability of the shape control becomes larger. Specifically, it can adjust about 0.3 in. more with F_{II} = 600 lbf compared with F_{II} = 0 lbf. In addition, with fixed actuators' forces in the force plane I, the deformation patterns under different forces in plane II over circumferential angles have nonlinear characteristics. When F_{II} is small, the shape deformation is relatively smooth. However, it tends to have more waves

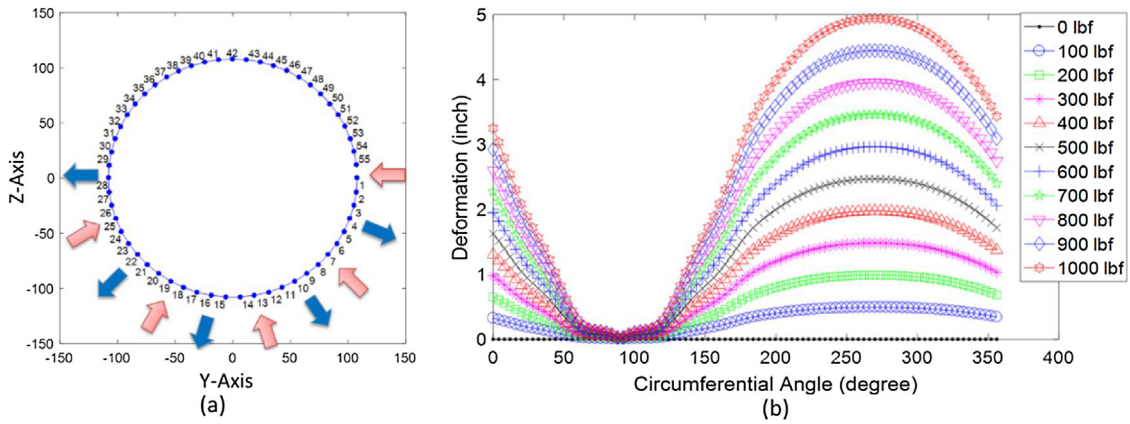

Fig. 9. (a) Scheme of actuators' forces, (b) deformation over circumferential angle under different actuators' forces.

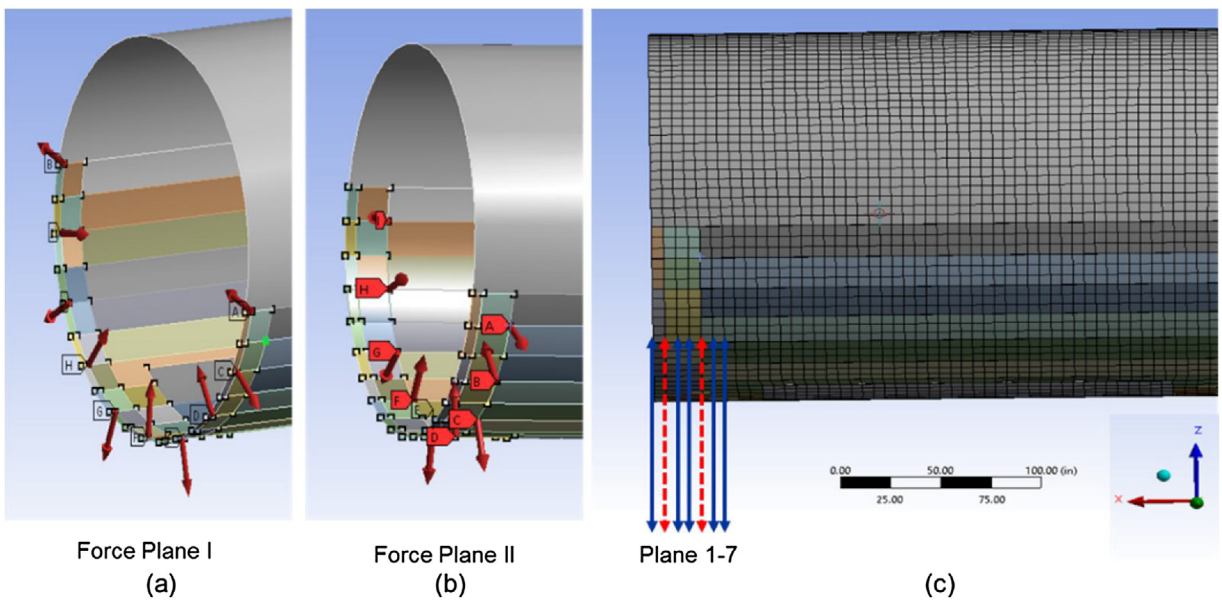

Fig. 10. (a) Actuators in the force plane I, (b) actuators in the force plane II, (c) response plane 1–7 (Note: the force plane I coincides with the response plane 2, and the force plane II coincides with the response plane 5).

when F_{II} becomes larger. One reason of the wave shape deformation in the top of the fuselage is the in-plane opposite directions of the forces of adjacent actuators. And this effect is augmented when F_{II} becomes larger. Another reason is that the actuators' forces in two force planes become unbalanced as F_{II} becomes larger. Furthermore, there exists twist effect in the lower semi-fuselage part, as shown in Fig. 11(b). That means when the circumferential angle ranges from 40° to 120°, the angles correspond to the peak deformations becomes smaller from plane 1 to plane 7. The twist effect results from the opposite forces applied by adjacent actuators. From Fig. 11(b) the period of each twist wave is 20°, which is the distance between two adjacent actuators. Based on the study, our conclusion is as follows. (i) The double plane strategy has more dimensional control and compensation capabilities with less forces applied for each individual actuator. This has merits to introduce less local stress or tension during the shape control process. With a well-designed control algorithm, double plane strategy can lead to better shape control results. (ii) The double plane strategy will lead to more complexity in the fixture design and maintenance. It also puts more demands in the design and optimization of the shape control algorithm. It should be pointed out that the double plane strategy studied here is to evaluate the shape control capability with multiple actuators installed in two different planes. In practice, further research needs to be done to study the optimal locations of the actuators on the fuselage. The locations of the actuators do not need to be constrained in two planes, but can be any locations on the fuselage with optimal decisions. This should be one of the future research topics.

4.3. Stress/strain analysis and failure test

In order to make sure the actuators do not damage the composite fuselage, a stress/strain analysis needs to be conducted. Since the maximum force can be applied to the actuator is 1000 lbf by engineering knowledge, we analyze the stress/strain response when actuators' forces range from 100 to 1000 lbf. The results of stress/strain analysis are shown in Fig. 12. We explore the equivalent (von Mises) stress, maximum principal stress, middle principle stress, minimum principal stress, and maximum shear stress in Fig. 12(a). Even for the situation of 1000 lbf, the maximum principal stress is 35.33 MPa, which is lower than the threshold 100 MPa. The maximum shear stress is 18.9 MPa, which is within the threshold 32 MPa. The strain is the response of a system to an applied stress. We are also interested in whether the strain of the compos-

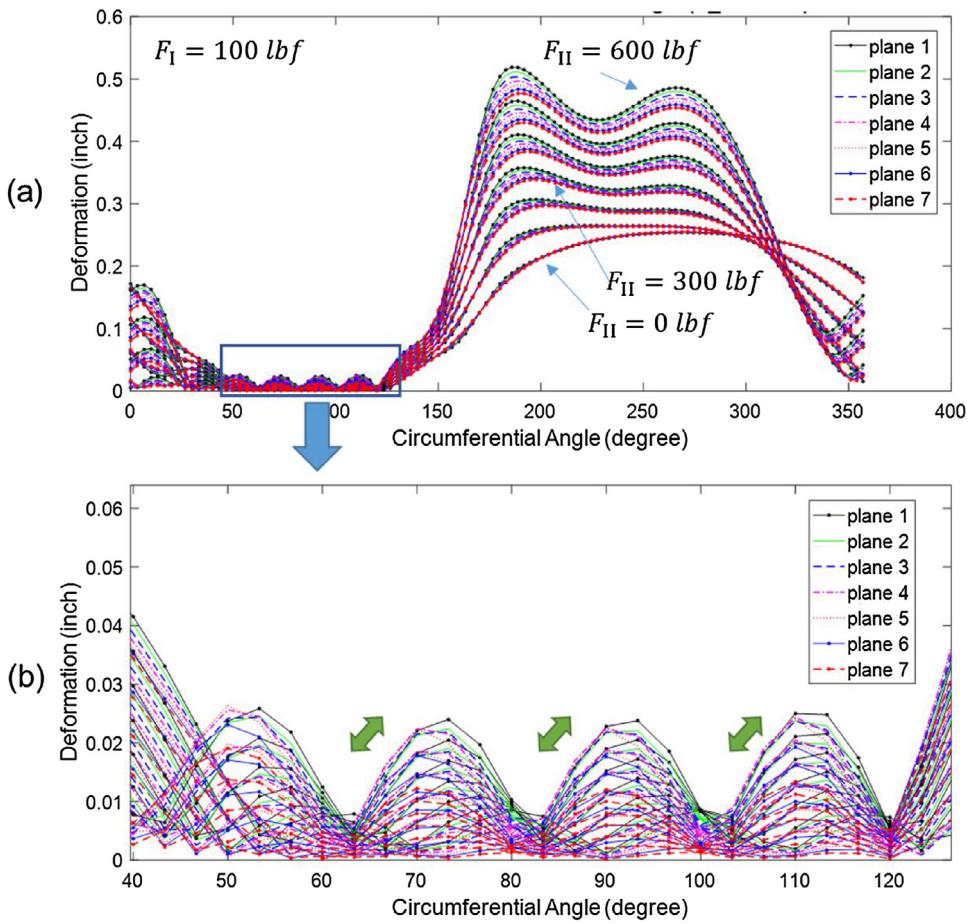

Fig. 11. (a) Deformation over circumferential angle under different actuators' forces (F_I = 100 *lbf*, and F_{II} = 0–600 *lbf*), (b) enlarged local deformation pattern.

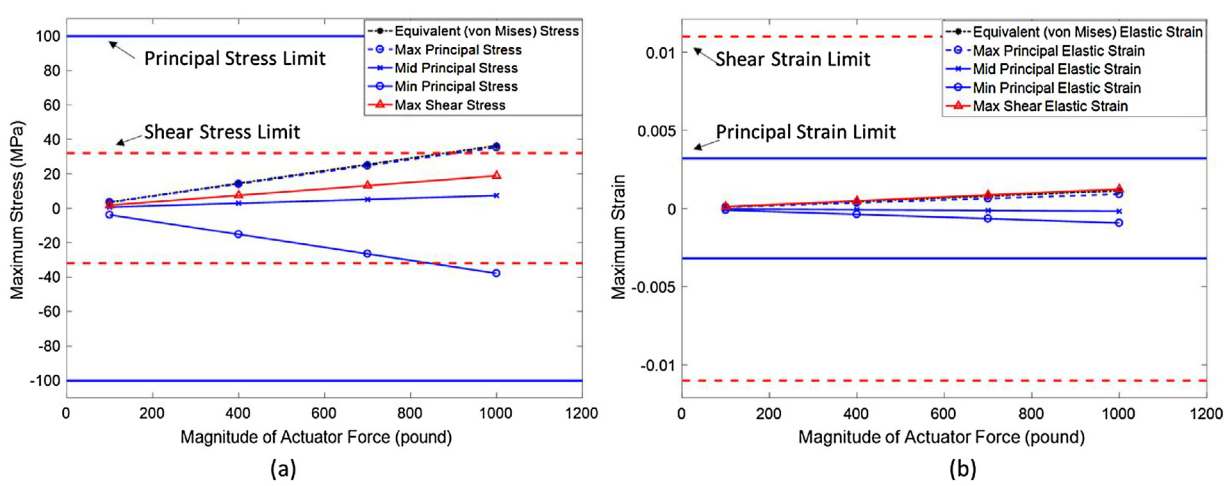

Fig. 12. Maximum (a) stress, (b) strain, under different magnitudes of actuators' forces.

ite fuselage under the bounded actuators' forces, and make sure it will not exceed the strain limit. As shown in Fig. 12(b), the maximum equivalent elastic strain under 1000 lbf is 0.0011, which is lower than the limit 0.0032. The maximum shear elastic strain is 0.0012, which is lower than the shear strain limit 0.011. From the result, we can conclude that there is no plastic strain that results in unwanted failure of material, such as cracking.

We also explore the stress distribution in each ply. Fig. 13(a) shows the setup of actuators with the magnitude of forces equal to 1000 lbf. The corresponding equivalent stress map and equivalent elastic shear stress map are shown in Fig. 13(b, c). For the stress distribution in each kind of interior plies, stress maps in a bottom ply of carbon fabrics, a core ply of epoxy resin, and a top ply of carbon fabrics, are shown in Fig. 13(d–f). The majority of stress resulted from the actuators is located at the bottom plies of carbon fabrics, while the stress from the bottom fixture supports is located at the top plies of carbon fabrics.

Furthermore, failure test has been conducted based on multiple popular criteria including maximum strain/stress, Tsai-Wu, Tsai-Hill, Hoffman, Hashin criteria [3]. The results show that the inverse

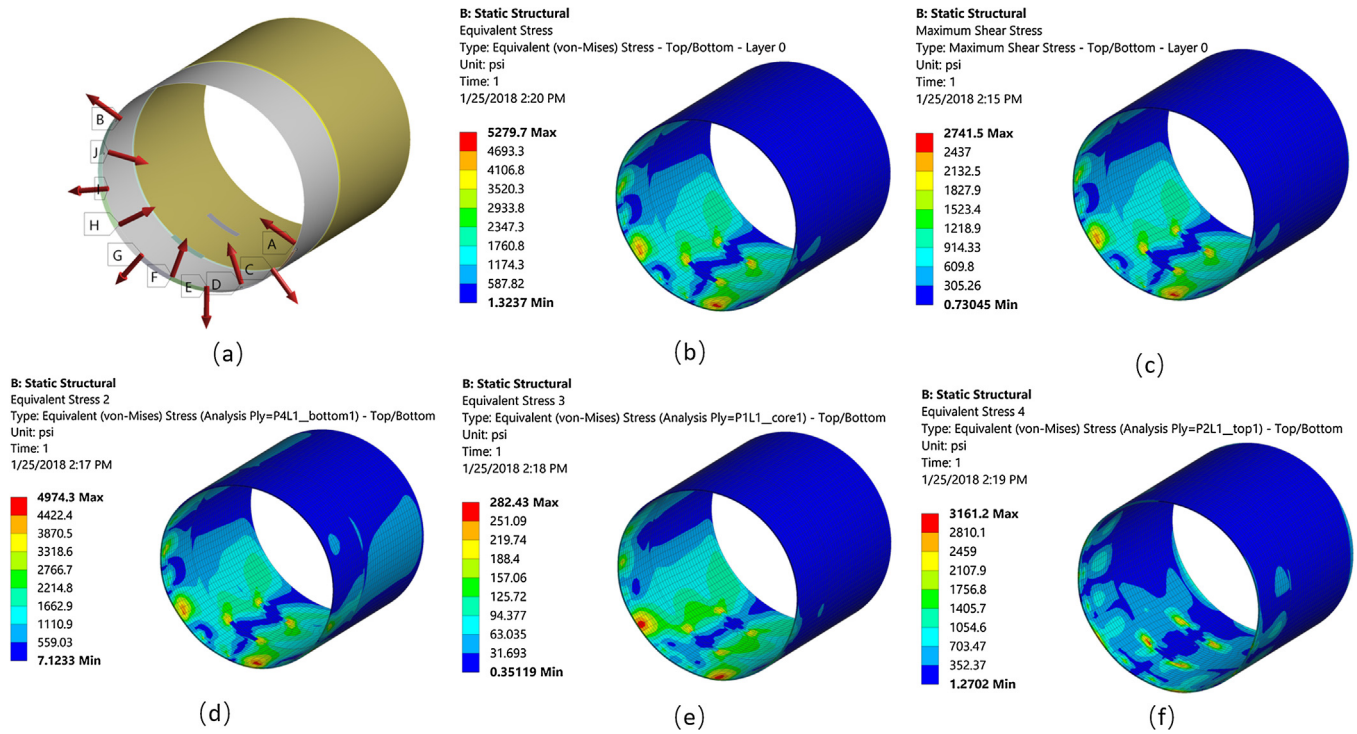

Fig. 13. (a) Setup of actuators, (b) equivalent stress map, (c) equivalent elastic strain map, (d) stress in a bottom ply of carbon fabrics, (e) stress in a core ply of epoxy resin, (f) stress in a top ply of carbon fabrics.

reserve factor, which defines the inverse margin to failure, is 0.27, which is lower than the failure threshold 1.00. Therefore, the actuators will not damage the composite fuselage when the maximum actuators' force is 1000 lbf.

5. Summary

Composite parts have been widely used in aircraft industry due to their superior mechanical properties. Dimensional variability reduction and shape control of composite fuselages are bottleneck problems for the massive production of high-quality aircrafts. In order to address the dimensional control problem, a new concept of shape control system is proposed and it can (i) compute the optimal actuators' forces to minimize the dimensional deviations of current composite parts and the ideal shape, (ii) implement the adjustment automatically, (iii) release the workload of highly skilled engineers.

In this paper, a feasibility study is conducted to evaluate the proposed shape control concepts. In order to do the feasibility analysis, an accurate finite element model is developed to mimic the fabrication of composite fuselage, including the detailed materials setting, ply design, geometry and fixture structures. The finite element model is validated and calibrated based on physical experimental data with a real fuselage on the production floor. Based on the validated FEA model, the feasibility analysis has been conducted, which confirms that

(i) Single-plane shape control system has the capability of adjusting the deformed composite fuselage back to the ideal shape with less than 1000 lbf actuators' forces.
(ii) Double-plane scheme has better capability of dimensional shape control, but it increases the complexity of the fixture design and shape control algorithm.
(iii) The distribution map of stress for each typical ply is investigated. The stress/strain analysis and failure test indicate that the actuators do not damage composite fuselages under the single-plane with ten actuators' scheme.

In summary, the proposed shape control of fuselage dimension is feasible and worthy of further investigation. The future R&D efforts should address the following issues: (i) optimal number of actuators and their locations on the fuselage, (ii) optimal control algorithms for the shape control, (iii) uncertainty quantification and dimensional control accuracy assessment, and (iv) physical testing and validation of the fuselage control system.

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References

[1] Jones RM. Mechanics of composite materials. Boca Raton, USA: CRC Press; 1998. ISBN: 1-56032-712-X.
[2] United States Department of Transportation Administration Federal Aviation. Aviation maintenance technician handbook – airframe, chapter 7, advanced composite materials; 2012. p. 1–57.
[3] Chawla KK. Composite materials: science and engineering. New York, USA: Springer Science & Business Media; 2012. Chap. 5. ISBN: 978-0-387-74364-6.
[4] Gates D. Boeing finds 787 pieces aren't quite a perfect fit. In: Seattle Times aerospace report, Seattle Times; 2007.
[5] Yue X, Wen Y, Hunt JH, Shi J. Surrogate model based control considering uncertainty for composite fuselage assembly. ASME J Manuf Sci Eng 2017, http://dx.doi.org/10.1115/1.4038510 (in press).
[6] Pinkerton JL, Moses RW. A feasibility study to control airfoil shape using THUNDER. In: NASA Technical Report; 1997.
[7] Sofla AYN, Meguid SA, Tan KT, Yeo WK. Shape morphing of aircraft wing: status and challenges. Mater Des 2010;31(3):1284–92.
[8] Sodano HA, Park G, Inman DJ. An investigation into the performance of macro-fiber composites for sensing and structural vibration applications. Mech Syst Signal Process 2004;18(3):683–97.
[9] Dong C, Kang L. Deformation and stress of a composite–metal assembly. Int J Adv Manuf Technol 2012;61(9):1035–42.

[10] Zhang T, Shi J. Stream of variation modeling and analysis for compliant composite part assembly—part I: single-station processes. ASME J Manuf Sci Eng 2016;138(12):121003–3-15, http://dx.doi.org/10.1115/1.4033231.

[11] Zhang T, Shi J. Stream of variation modeling and analysis for compliant composite part assembly—part II: multistation processes. ASME J Manuf Sci Eng 2016;138(12):121004–4-15, http://dx.doi.org/10.1115/1.4033282.

[12] Gómez A, Ríos J, Mas F, Vizán A. Method and software application to assist in the conceptual design of aircraft final assembly lines. J Manuf Syst 2016;40:37–53.

[13] Barbero EJ. Finite element analysis of composite materials using ANSYS®. CRC Press; 2013.

[14] ANSYS. ANSYS composite preppost user's guide; 2013. https://support.ansys.com/staticassets/ANSYS/Conference/Irvine/downloads/.

[15] ANSYS. ANSYS engineering data sources, composite materials; 2016.

[16] Wang Y, Yue X, Tuo R, Hunt JH, Shi J. Effective model calibration via sensible variable identification and adjustment, with application to composite fuselage simulation, technical report. Georgia Institute of Technology; 2017.