Chapter 4

Design Optimization and Higher Order FEA of Hat-Stiffened Aerospace Composite Structures

Bo Cheng Jin

Additional information is available at the end of the chapter

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Abstract

Sizing of hat-stiffened composite panels is challenging because of the broad design hyperspace in several geometric and material parameters available to the designer. Design tasks can be simplified if parameter sensitivity analysis is performed a priori and design data is made available in terms of a few important parameters. In this chapter, design sensitivity analysis is performed using finite element analysis (FEA) and analytical solution models. Manufacturing and experimental measurements of a hat-stiffened composite structure is performed to validate the FEA and idealized analytical solutions. This is an attempt to initiate a structural architecture methodology to speed the development and qualification of composite aircraft that will reduce design cost, increase the possibility of content reuse, and improve time-to-market. In particular, FEA results were compared with analytical solutions to develop a design methodology that will allow extensive reuse of parametric hat-stiffened panels in the design of composites structural components. This methodology is now widely utilized in developing a library of commonly used, built-in, composite structural elements in design of modern aircrafts. In this chapter, hat stiffened composite panels' geometric parameter sensitivity analysis work were parametrically investigated using finite element analysis (FEA), analytical solution models and experimental testing on manufactured parts in order to develop structural architectures that speed development and qualification of composite aircraft which has broad benefits in reducing cost, increasing content reuse and improving time-to-market. In particular, FEA results were compared with analytical solutions and a design methodology was developed to allow extensive reuse of parametric elements in structural design of composites and to achieve expedited design, verification, validation, and airworthiness certification and qualification. The goal of this work is to provide the aviation industry with the most up-to-date databases for the application of advanced composite materials incorporated into parametric models to eliminate redundancies in the current process. The work results include a correlated material database, an optimized model component library and a standardized way to design future complex composites structures, e.g. hat stiffened composites panels, with reliable and predictable quality and material weight/cost.

Keywords: design optimization, FEA, hat stiffeners, aerospace composite structures

1. Introduction

1.1. Background

In recent years the commercial aircraft industry is increasing their reliance on composite materials to produce lighter and more durable aircrafts. **Figure 1** shows a Boeing 787 aircraft contains 50% by weight of its materials as composites, which is about 32,000 kg of carbon-fiber-reinforced polymer (CFRP) [1].

The carbon fiber composites have a higher strength-to-weight ratio than traditional metal materials thus help making the aircraft lighter and to exceed the fuel efficiency target. Due to this important feature, the use of fiber reinforced composite laminates as primary structural components in these important large-scale and weight-critical applications has increased considerably (**Table 1**). Aircrafts with major composite parts including fuselage, wings, tail sections, doors and interior are presently being developed and gradually brought into service.

For better efficiency in terms of strength and weight-optimization, aerospace structures are frequently appended with stiffener components. **Figure 2** shows a 787's disassembled composite fuselage section which is composed of hat-stiffened composite panels that represent the design methodology of meeting the high stiffness while keeping the minimal weight requirements. This laminated composite stiffened panel is a critical component and extensively used structure in aircrafts, and can operate when subjected to harsh environments such as severe dynamic loading.

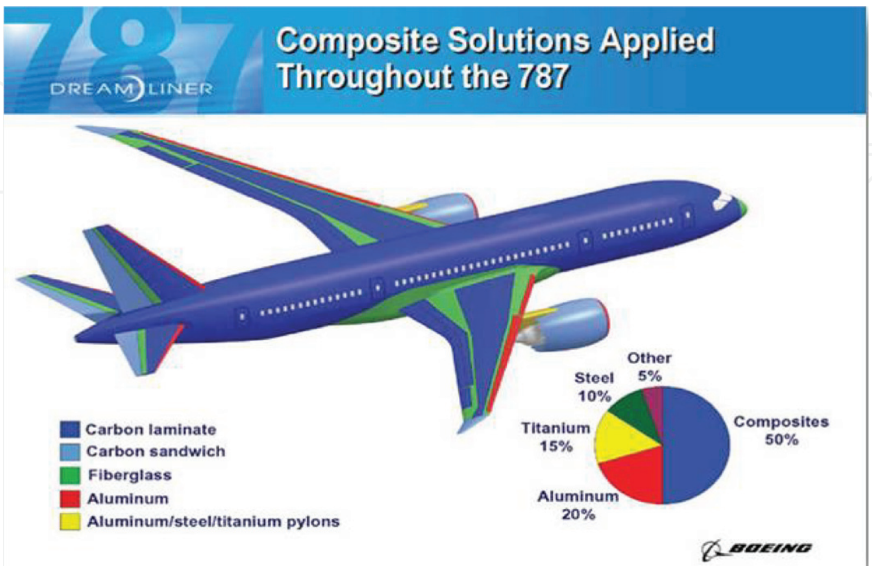

Figure 1. Boeing 787 aircraft contains 50% of composite materials.

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Year	1982	1995	2006	2008
Model	Boeing 767	Boeing 777	Airbus 380	Boeing 787
Structures	Secondary	Primary/Secondary	Primary/Secondary	Primary/Secondary
Amount of CFRP/aircraft	1.5 tons	Approx. 10 tons	Approx. 35 tons	Approx. 35 tons
Amount of CF/aircraft	1 ton	Approx. 7 tons	Approx. 23 tons	Approx. 23 tons.

Table 1. Increase of carbon fiber composites for aircraft application.

Figure 2. Disassembled composite fuselage section of the Boeing 787.

Many work have been done on design and analysis of hat-stiffener structures. Recent advances in performing global and detailed analyses have made it possible to determine failure modes, strength, durability, and damage tolerance of composite structures with confidence. Bhar et al. [2] performed linearly elastic static and natural vibration analysis using an extended HSDT (higher-order shear deformation theory). Kim et al. [3] manufactured stiffened panels using co-curing, co-bonding and secondary bonding processes and evaluated them using 3D measurement and ultrasonic tester. Lauterbach et al. [4] built analysis tools including an approach for predicting interlaminar damage initiation and degradation models for capturing interlaminar damage growth as well as in plane damage mechanisms. Gangadhara et al. [5] analyzed stiffened panels using formulation based on the concept of equal displacements at the shell-stiffener interface. Kumar et al. studied the transient response of laminated stiffened plates using MSC/Patran and LS-DYNA3D [6] and Kristinsdottir et al. [7] presented an optimization formulation for the design of large panels when loads vary over the panel. Junhou et al. and Shenoi et al. [8, 9] examined the key aspects defining the performance characteristics of hat-stiffener joints in marine structures. Paul et al. [10] performed an integrated step-by-step design and analysis procedure for the hat-stiffened panels loaded in axial compression using the computer code BUSTCOP. Xiong and coworkers [11] has tested and analyzed the buckling and failure loads of hat-stiffened composite panels. Other research work have been focused on FEA modeling [12–22], manufacturing [23–29], evaluation of microstructures and damage evolution [30–33], and the enhancement of the mechanical properties [34–37] of composites at both materials- and structures-level.

Most commercial CAD/FEA software has included some form of parameterization of design variables. Basic research-level higher order structural elements are also developed. These tools allow quick, easy and accurate topology and geometry model creation with design constraints, implicit parameterization for easy model variation, integrated Finite Element generator, models and components storage in library for generation of knowledge database and reusability, shape and size optimization in a closed batch loop, on-the-fly definition of design variables and design space, and integration of specific applications like commercial optimization and design tools. In this work, we plan to utilize these aspects to create a Higher Order Abstract Structural Elements, later abbreviated as HOASE.

1.2. Objectives and structure

The goals and key feature of this work include analyzing the geometric parameter sensitivity of the hat stiffener, and developing and demonstrating a proof-of-concept theoretical model which is a parametric analytical solution that is theoretically equivalent to hat-stiffener stiffened panels in mechanical response. The analytical solution contains parametric information incorporating geometric, design allowables, and manufacturing information such as laminate stacking order. The constructions of these equivalent analytical models will be stored in a database from which they can be easily retrieved and parametrically modified.

Achieving the above requires specific technical objectives including:

1. Select composite ply materials and corresponding stochastic material properties for tracking them to parametric design allowables.
2. Explore the design space and using Finite Element Method (FEM) to analyze the parametrical sensitivity of the basic composite structural elements: hat stiffeners.
3. Develop an equivalent model using analytical solution and run case studies for various loading conditions to develop the empirical relationships between design parameters and allowables/performance. This takes into account the key geometric and material parameters and gives a higher and lower boundary of the relatively equivalent hat-stiffener stiffened panel.
4. Manufacture hat-stiffened composite panel and perform experimental investigation to compare its mechanical response with FEA models' prediction and the mechanical response bounds resulting from the analytical models. Finally, this work would provide the aviation industry with a parametric databases of hat stiffener design and analysis.

2. Optimal design procedure

2.1. Basic structural configuration and FEA design parameters

In this work, hat stiffeners and plates were selected as basic elements for parametric analysis and for constructing an analytical solution. The plate element is an orthotropic laminated element with material, number of plies, stacking sequence, width, length, and thickness parameters. The hat stiffener element is also parametrically defined in terms of several geometric parameters as shown in **Figure 3**.

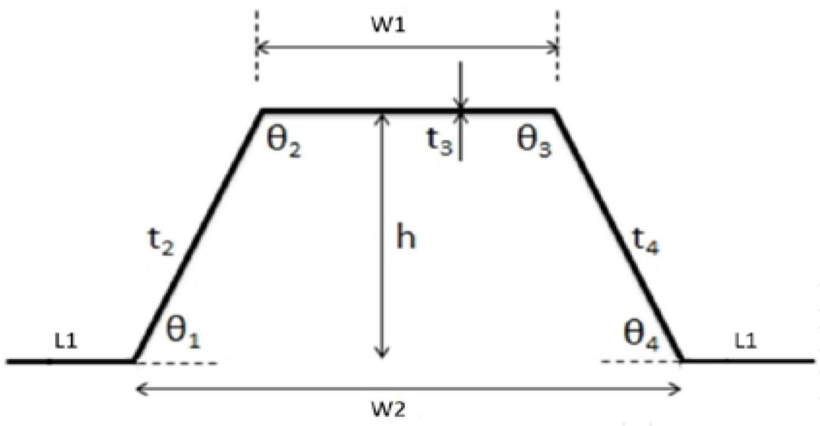

Figure 3. Hat stiffener basic element with geometric parameters.

FEM was utilized to produce sensitivity of structural behavior (deflection, stresses) to basic elements' parameters and for comparing final experimental results with modeling. Laminated plate, hat-stiffener, hat-stiffener bonded to base plate were modeled in MSC NASTRAN for this purpose. Laminated plate modeling in FEM is routine and therefore not discussed for the sake of brevity. The hat stiffener (with and without plate to which it is bonded) are modeled as follows. Height of the stiffener web (h), width of the stiffener cap (W_1), bottom width in between stiffener flanges (W_2), width of the stiffener flange (due to symmetric, the left and right width are the both L_1) are the geometric parameters considered in addition to thickness of a ply, ply orientation and the stacking sequence. The length of the hat stiffener is fixed at 508 mm (which is 20 inches).

Material properties are taken from Cytec information sheet CYCOM 5320 [12–37]. These unidirectional fiber tape tensile properties are:

E1 = 1.59E5 MPa;

E2 = 9.3E3 MPa;

Poisson's Ratio v = 0.336;

Shear modulus G12 = G13 = 5.6E3 MPa.

QUAD4 MSC Nastran element and PCOMP material properties input was used for analysis. A uniform pressure of 6.89E-2 MPa is applied on each of the two bottom flange surfaces for the hat-stiffener simulation. For the second set of simulations, same magnitude of pressure, 6.89E-2 MPa is applied on the plate to which hat-stiffener is bonded. Longitudinal edges are free to rotate but not translate (T_x = T_y = T_z = 0). The transverse direction edges are free. These longitudinal edge boundary conditions represent fixed edges rather than simply supported, because edge cross sections are constrained from rotation. Same boundary conditions for flat plates will represent simply supported conditions.

Longitudinal edges (the two edges of the skin plate only, not including hat stiffener web and top cap) are simply supported as T_x = T_y = T_z = 0 for hat stiffener bonded to the plate. The transverse edges of the plate are subjected to the boundary conditions T_x = R_y = R_z = 0, corresponding to all four edges simply supported. These boundary conditions are chosen to demonstrate extreme sensitivity of structural response to boundary conditions.

2.2. Parametric sensitivity analysis on hat-stiffener structures

To study the sensitivity of hat-stiffener's geometric parameters, hat-stiffener models are created first. The hat-stiffener element is modeled and analyzed using MSC NASTRAN to construct parametric design space. As presented in the last section, design parameters were defined for hat-stiffeners. The parametric range and increments we defined here covered most of the practical design exploration space and are summarized in **Table 2**.

These parametric variations represent 1680 models and design points. A smaller set of parameter combinations are analyzed to get the design trends. We explored maximum specific bending rigidity contribution of hat-stiffeners to membrane skin which is designed to take torsional shear. Representative 10 psi uniform pressure loading and simply supported boundary conditions on a 508 mm (20 inches) long hat cross section beam are analyzed. The cross-sectional area of hat-stiffeners varies with design parameters. A baseline configuration with minimum cross-sectional area is chosen to illustrate effect of parameters on bending. This configuration represents 12.7 mm (0.5 inch) bottom flange length, 25.4 mm (1 inch) bottom hat width, 12.7 mm (0.5 inch) top hat width, 12.7 mm (0.5 inch) hat height, 1.016 mm (0.04 inch) thickness and [0/90/45/−45]s stacking order.

Figure 4 shows the mid-point transverse deflection and maximum flexural stress at mid-point on the beam as a percent change from the baseline configuration. Stacking sequence and therefore corresponding laminate thickness is kept constant. The ratio of top and bottom hat widths is kept constant at 0.5 for all parametric variations. Three curve-sets show variation of deflection and flexural longitudinal stress with hat height, width and bottom flange length, respectively. As expected, it is evident that bottom flange length contribution is minimal to the

All dimensions are in **mm**

Parameter	Top Hat 1	Top Hat 2	Top Hat 3	Top Hat 4	Average	Std. Dev	CV (%)
Bottom Left Angle (θ_1)	50.2°	50.2°	51°	48.6°	50.0°	1.01°	2.01
Top Left Angle (θ_2)	130.3°	130.2°	129.4°	131.1°	130.3°	0.70°	0.53
Top Right Angle (θ_3)	130°	130.8°	131.0°	130.6°	130.6°	0.43°	0.33
Bottom Right Angle (θ_4)	49.5°	48.8°	48.6°	49.6°	49.1°	0.50°	1.02
Inside Length Top (l_t)	18.7	18.2	18.7	18.4	18.5	0.2	1.32
Inside Length Bottom (l_b)	59.4	61.1	61.7	62.5	61.2	1.3	2.15
Inside Height (h)	24.3	24.4	24.7	24.6	24.5	0.20	0.75
Thickness 1 (t_1)	1.11	1.13	1.14	1.09	1.12	0.02	1.98
Thickness 2 (t_2)	1.16	1.16	1.18	1.18	1.17	0.01	0.99
Thickness 3 (t_3)	1.20	1.24	1.19	1.21	1.21	0.02	1.79
Thickness 4 (t_4)	1.16	1.18	1.13	1.18	1.16	0.02	2.03
Thickness 5 (t_5)	1.10	1.11	1.09	1.15	1.11	0.03	2.36

Table 2. Hat-stiffener parametric design exploration space.

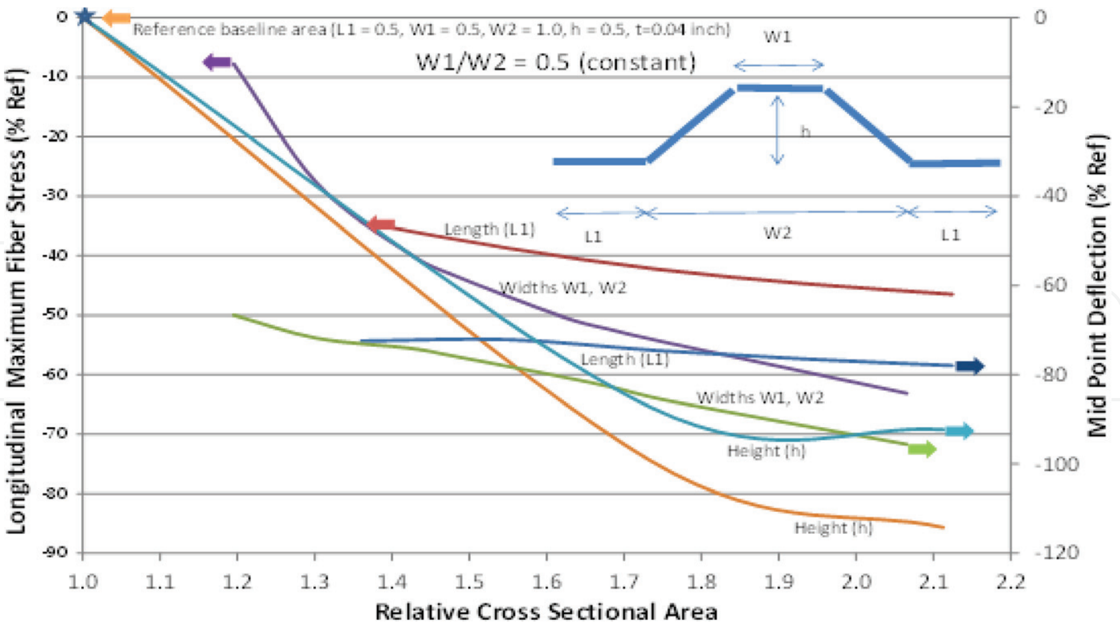

Figure 4. Hat stiffener basic element bending behavior.

flexural behavior of the stiffener. The maximum change in bending rigidity is achieved by changing hat height up to three times the top flange width.

2.3. Analytical solution of hat stiffener with base plate

A proof-of-concept analytical model consists of a rectangular plate stiffened by several hat stiffeners was established in MATLAB.

Figure 5 shows steps incorporated in constructing the analytical model. Composite ply properties, stacking sequence for hat and plate laminates, plate and hat stiffener geometric parameters, stiffener spacing, boundary conditions and loading are specified for the analytical model. Orthotropic plate properties are obtained by scaling, homogenizing and distributing stiffener properties over the space between the stiffeners.

Let θ be the angle between x-axis (stiffener longitudinal direction) and j is the ply fiber direction in sections plane, a is the equal distance between stiffeners. The bottom and top flanges as well as webs are defined as continuous plies of the orthotropic plate as follows:

For bottom flange:

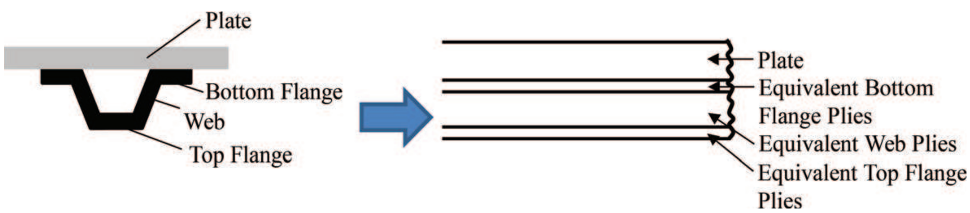

Figure 5. Equivalent orthotropic plate for hat-stiffener stiffened skin.

$$\overline{Q}^{j}_{11bf} = \frac{2L1}{a}\left[Q^{j}_{11}\cos 4\theta + Q^{j}_{22}\sin 4\theta + 2\left(Q^{j}_{12} + 2Q^{j}_{66}\right)\sin 2\theta\cos 2\theta\right] \tag{1}$$

For top flange:

$$\overline{Q}^{j}_{11tf} = \frac{w1}{a}\left[Q^{j}_{11}\cos 4\theta + Q^{j}_{22}\sin 4\theta + 2\left(Q^{j}_{12} + 2Q^{j}_{66}\right)\sin 2\theta\cos 2\theta\right] \tag{2}$$

For webs, define:

$$\cos x = \frac{h}{\left[\left(\frac{w_2 - w_1}{2}\right)^2 + h^2\right]^{1/2}} \tag{3}$$

And therefore, contribution from two web laminates is:

$$\overline{Q}^{j}_{11web} = \frac{2}{a\cos x}\sum_{j=1}^{n} t_j\left[Q^{j}_{11}\cos 4\theta + Q^{j}_{22}\sin 4\theta + 2\left(Q^{j}_{12} + 2Q^{j}_{66}\right)\sin 2\theta\cos 2\theta\right] \tag{4}$$

These equivalent $\overline{Q}^{j}_{11}$ contributions can be used in traditional ABD matrix construction. Similarly, other Qs, the equivalent reduced stiffness matrix components are also calculated, and their contributions are used in the traditional A, B and D matrix construction. The analytical solution of the equivalent panel was input into MATLAB for the center point deflection prediction. Future work will be focusing on analytically representing the homogenized panel equivalent to the stiffened panel with multiple hat-stiffeners on it. Also, it should be noted that for the analytical solution for large panel with a sparse distribution of multiple stiffeners, these relationships may not be valid but may still give the bounding values of the possible deflection of points on the plate.

2.4. FEA model for the demonstration part: Panel with multiple hat-stiffeners

To better understand and predict the mechanical behavior of the structure, a demonstration FEA model of one panel with multiple hat stiffeners bonded onto it was built in MSC Nastran (**Figure 6**). A few composite ply material properties were selected from the Cytec Cycom 5320 prepreg data sheet for creating the model and database.

For the geometric configuration of the model: this demonstrator model comprises a base panel of in-plane dimensions 304.8 mm (which is 12 inches) × 863.6 mm (which is 3 inches) with four hat stiffeners on it., each separated by approximately 85.725 mm (which is 3.37 inches). The bottom width of the hat stiffener is approximately 86.36 mm (which is 3.4 inches) with 60.96 mm (which is 2.4 inches) as the distance between the lower two corners of the hat stiffeners and 12.7 mm (which is 0.5 inch) overhang (i.e., flange) on the either side. The base panel has 8 plies of laminates with 5320 unidirectional prepreg properties and they are in a quasi-isotropic layup as follows: [90,−45,+45,0]S. Each of the four hats also consists of eight unidirectional fiber plies in the same quasi-isotropic layup.

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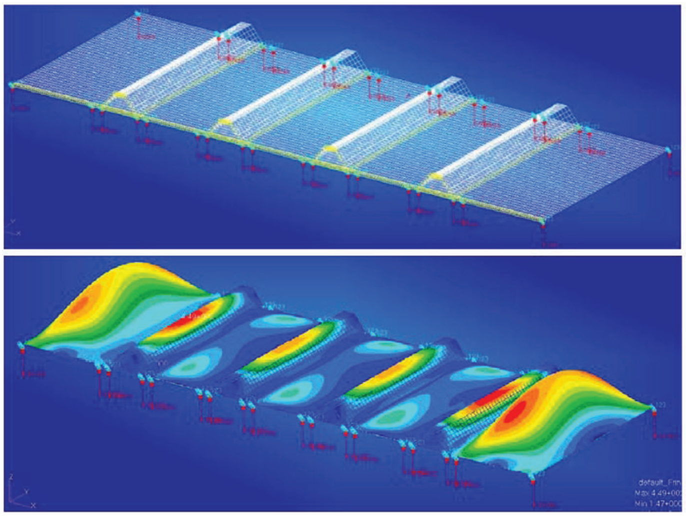

	Parameters
Number of Top Hats	4
Top Hat "W2"	57.15mm (2.25 inches)
Top Hat "W1" (always<W2)	15.875mm (0.625 inches)
Top Hat "h"	23.8125mm (0.9375 inches)
Top Hat "L1"	15.875mm (0.625 inches)
Width of base plate	863.6mm (34 inches)
Length in Y direction	For both Top Hat and Skin Plate: 304.8mm (12 inches)
t (Single Ply Thickness)	For both Top Hat and Base Plate: 0.127mm
Number of Ply	For both Top Hat and Skin Plate: 8 Plies
Stacking	For both Top Hat and Skin Plate: [90/+45/-45/0/0/-45/+45/90]

Figure 6. Midpoint deflection of the demonstration part FEA model.

Simulation of panel-level hat-stiffeners requires understanding of global and local effects of the parameters. One should consider local maximum deflection occurring in between the stiffeners on the panel, because that may become a dominant parameter for deformation constraints satisfaction.

2.5. Manufacturing of the demonstration part

To validate the modeling prediction of the center point deflection of the stiffened panel, a composite panel bonded with multiple hat-stiffeners was manufactured as a demonstrator part. During fabrication of the structural element and the final demonstration part, unidirectional Cytec Cycom 5320 prepreg material, out-of-autoclave curing, and secondary bonding technique were used.

The basic structural elements comprise of flat panels and hat cross section beams. The assembly of these basic structural elements forms the demonstrator part represented by a large panel stiffened by four equidistant hat beams, as shown in **Figure 7**. To accurately predict and compare with the FEA results, the demonstration part has identical set up with the MSC Nastran FEA model built and explained in the last section.

2.6. Testing and validation of the demonstration part

The demonstration part was tested under near-uniform 1 psi loading and the center point deflection was recorded so it can be compared with FEA results. Photographs of the testing setup are shown in **Figure 8**. The experimental testing of the demonstrator part involves simply supporting the edges and subjecting it to a uniform pressure loading condition by placing sandbags at the center. Experimentally measured panel displacements are then compared to predictions from both analytical constructs as well as FEA models.

The demonstration plate midpoint deflections are experimentally obtained for 150, 225, 300, 375 and 400 lb. load are 0.022, 0.032, 0.039, 0.045 and 0.047 in, respectively. The first increment

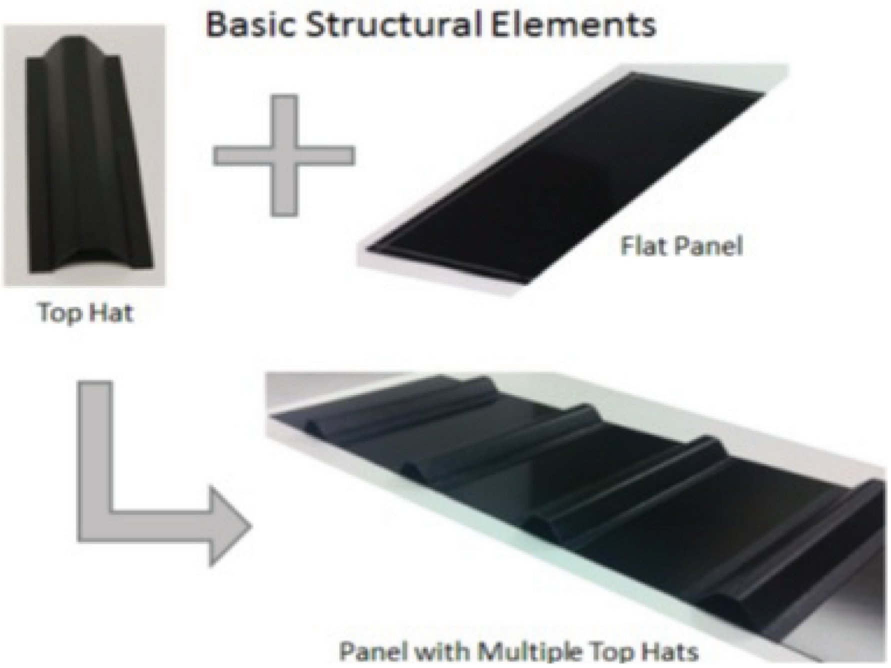

Figure 7. Manufacturing and assembly of basic structural elements into a demonstration part.

Figure 8. Simply supported hat-stiffened composite panel under near-uniform pressure loading.

(150 lb) was using lead balls filled bags providing close to uniform loading. The remaining increments were obtained using iron discs that did not provide as uniform loading as lead balls filled bags would have. As the results are shown in **Figure 9**, the midpoint deflection is 1.52 mm (0.06 in) for 1 psi uniform loading while FEA simulation gave 1.83 mm (0.07 in).

The analytical bounds for stiffened plates were also obtained. The midpoint deflection from the homogenized orthotropic plate gives the lower bound and simply supported idealized plate between the stiffeners gives upper bound. The lower bound provides better approximation for plates with closely spaced stiffeners. The real deformation starts to approach the upper bound as spacing between stiffeners increases. The lower bound for midpoint deflection under 1 psi is 0.133 mm (0.0052 in) and the upper bound is 2.85 mm (0.11 in).

The work performed establishes the basis for continuing future work to further develop a set of parametric models. The conceived process of designing advanced composite aircraft structural

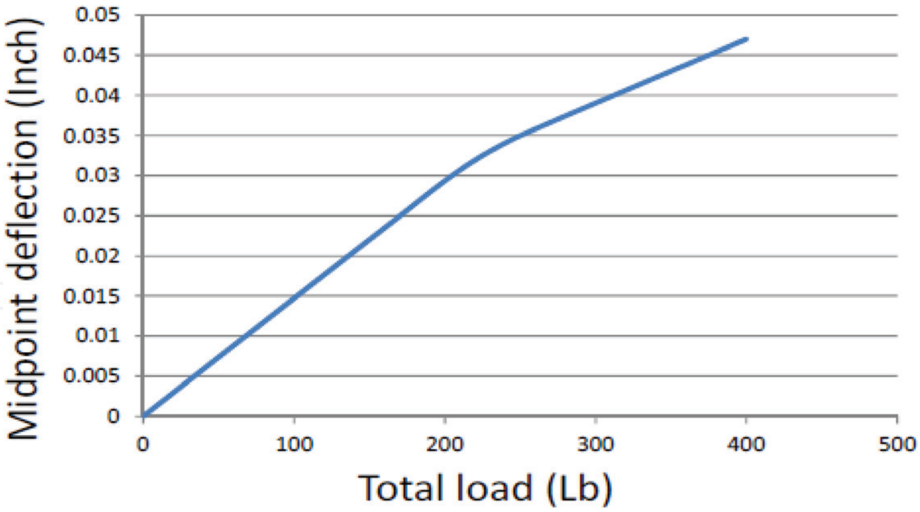

Figure 9. Midpoint deflection of the demonstration part.

components from these parametric modeling constructs will be matured, implemented and validated to demonstrate the benefits of starting the design with validated parametric design elements.

3. Conclusions

This work has illustrated the process of developing an analytical model and the design and analysis of the parametric composite hat-stiffened panels. The amount of the work involved in designing to this level of abstraction is a significant part of the design of an aircraft. This work is needlessly repeated by designers again and again and can be standardized to abbreviate the design process, and has successfully shown most of the processes involved in creating parametric models with a hat-stiffener stiffened composite laminated plate model development.

Most commercial CAD/FEA software includes some form of parameterization of design variables. Basic research level higher order structural elements have also been developed. These tools allow quick, easy and accurate topology and geometry model creation with design constraints; implicit parameterization for easy model variation; integrated Finite Element generator; models and components storage in library for generation of knowledge database and reusability; shape and size optimization in a closed batch loop; on-the-fly definition of design variables and design space; and integration of specific applications like commercial optimization and design tools. Our future work includes integrating these models in similar design tools, such as a combination of MSC Nastran, ABAQUS, MATLAB and C++ platform.

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Author details

Bo Cheng Jin[1,2,3]*

*Address all correspondence to: bochengj@usc.edu

1 Department of Aerospace and Mechanical Engineering, University of Southern California, USA

2 Department of Chemical Engineering and Materials Science, University of Southern California, USA

3 MSC NASTRAN (NASA Structural Analysis) Development, USA

References

[1] Toray Industries. Market Research Report: Strategic Business Expansion of Carbon Fiber, Torayca. The Original; April 12, 2005

[2] Bhar A, Phoenix S, Satsangi S. Finite element analysis of laminated composite stiffened plates using FSDT and HSDT: A comparative perspective. Composite Structures. 2010;**92**:312-321

[3] Kim G-H, Choi J-H, Kweon J-H. Manufacture and performance evaluation of the composite hat-stiffened panel. Composite Structures. 2010;**92**:2276-2284

[4] Lauterbach S, Orifici AC, Wagner W, Balzani C, Abramovich H, Thomson R. Damage sensitivity of axially loaded stringer-stiffened curved CFRP panels. Composites Science and Technology. 2010;**70**:240-248

[5] Prusty BG. Linear static analysis of composite hat-stiffened laminated shells using finite elements. Finite Elements in Analysis and Design. 2003;**39**:1125-1138

[6] Kumar Y, Mukhopadhyay M. Transient response analysis of laminated stiffened plates. Composite Structures. 2002;**58**:97-107

[7] Kristinsdottir BP, Zabinsky ZB, Tuttle ME, Neogi S. Optimal design of large composite panels with varying loads. Composite Structures. 2001;**51**:93-102

[8] Junhou P, Shenoi RA. Examination of key aspects defining the performance characteristics of out-of-plane joints in FRP marine structures. Composites: Part A. 1996;**27**:89-103

[9] Shenoi RA, Hawkins GL. An investigation into the performance characteristics of top-hat stiffener to shell plating joints. Composite Structures. 1995;**30**:205-209

[10] Paul TK, Sinha PK. Design of hat-stiffened composite panels loaded in axial compression. Composite Structures. 1992;**21**:205-209

[11] Lee S, Xiong Y, Benak TJ, Heath J. Design, analysis, manufacture, and experimental performance of hat-stiffened composite panel. Science and Engineering of Composite Materials. 1997:37-50

[12] Jin B, Pelegri A. Three-dimensional numerical simulation of random fiber composites with high aspect ratio and high volume fraction. Journal of Engineering Materials and Technology. 2011;**133**:41014

[13] Wu H, Xu W, Shan D, Jin B. An extended GRN model for low stress triaxiality and application in spinning forming. Journal of Materials Processing Technology. 2019;**263**: 112-128

[14] Jain A, Jin B, Nutt S. Mean field homogenization methods for strand composites. Journal of Composites Part B. 2017;**124**:31-39

[15] Jin B, Li X, Jain A, Wu M, Mier R, Herraez M, et al. Prediction of stiffness of reused carbon fiber/epoxy composite oriented strand board using Finite Element Methods. Recycling Materials & Structures. Feature Article. Society for the Advancement of Material and Process Engineering (SAMPE) Journal. 2017;**53**:32-39

[16] Jin B, Li X, Jain A, Herraez M, Gonzalez C, LLorca J, et al. Development of a finite element model for reused carbon fiber epoxy composite oriented strand board. In: Proceedings of SAMPE 2016; Long Beach; 2016

[17] Jin B, Li X, Mier R, Pun A, Joshi S, Nutt S. Parametric modeling, higher order FEA and experimental investigation of hat-stiffened composite panels. Journal of Composite Structures. 2015;**128**:207-220

[18] Jin B, Joshi S, Pun A, Nutt S. Design sensitivity of hat-stiffened composite panels. In: Proceedings of American Society for Composites Conference 2014; San Diego; 2014

[19] Jin B, Liu W, Patel H, Nutt S. Application of MSC NASTRAN UDS in modeling and analysis of a hybrid composite reinforced conductor core. In: Proceedings of MSC NASTRAN Conference 2013; Los Angeles; 2013

[20] Jin B, Li X, Jain A, Wu M, Mier R, Herraez M, Gonzalez C, et al. Mechanical properties and finite element analysis of reused UD carbon fiber/epoxy OoA VBO composite oriented strand board. In: Proceedings of SAMPE 2016; Long Beach; 2016

[21] Jain A, Jin B, Li X, Nutt S. Stiffness predictions of random chip composites by combining finite element calculations with inclusion based models. In: Proceedings of SAMPE 2016; Long Beach; 2016

[22] Jain A, Jin B, Nutt S. Development of chip composites with improved mechanical performance attributes using hybrid multi-scale modelling methods. In: Proceedings of CAMX 2016; Anaheim; 2016

[23] Jin B. Recent Development of Reused Carbon Fiber Reinforced Composite Oriented Strand Boards. Chapter 8 of Book: Recent Developments in the Field of Carbon Fibers. Rijeka, Croatia: IntechOpen. DOI: 10.5772/intechopen.71346

[24] Jin B, Neidert K, Ellis M. Sustainable and efficient hydroforming of aerospace composite structures. Chapter of Book: Green Sustainable Composites. Rijeka, Croatia: IntechOpen. In Print

[25] Wu H, Fan G, Jin B, Geng L, Cui X, Huang M. Fabrication and mechanical properties of TiBw/Ti-Ti (Al) laminated composites. Journal of Materials and Design. 2016;**89**:697-702

[26] Chen Z, Huang T, Jin B, Hu J, Lu H, Nutt S. High yield synthesis of single-layer graphene microsheets with dimensional control. Journal of Carbon. 2014;**68**:167-174

[27] Huang T, Li T, Xin Y, Jin B, Chen Z, Su C, et al. Preparation and utility of a self-lubricating and anti-wear graphene oxide nano-polytetrafluoroethylene hybrid. Journal of RSC Advances. 2014;**4**:19814

[28] Jin B, Li X, Jain A, Gonzalez Carlos, LLorca J, Nutt S. Optimization of microstructure and mechanical properties of composite oriented strand board from reused prepreg. Journal of Composite Structures. 2017;**174**:389-398

[29] Wu M, Jin B, Nutt S. Processing and performance of recyclable composites for wind turbine blades. Advanced Manufacturing: Polymer & Composites Science. In Print

[30] Ma H, Xu W, Jin B, Shan D, Nutt S. Damage evaluation in tube spinnability test with ductile fracture criteria. International Journal of Mechanical Sciences. 2015;**100**:99-111

[31] Jin L, Niu Z, Jin B, Sun B, Gu B. Comparisons of static bending and fatigue damage between 3D angle-interlock and 3D orthogonal woven composites. Journal of Reinforced Plastics and Composites. 2012;**31**(14):935-945

[32] Ma Q, Wang K, Wang S, Liu H, Jin B, Jin L. Tensile damage mechanism of 3-D angle interlock woven composites using acoustic emission events monitoring. Autex Research Journal, ARJ-D-16-00031R1. 2017

[33] Jin B, Li X, Wu M, Jain A, Jormescu A, Gonzalez C, et al. Nondestructive testing and evaluation of conventional and reused carbon fiber epoxy composites using ultrasonic and stitched micro-CT. In: Proceedings of SAMPE 2016; Long Beach; 2016

[34] Wu H, Fan G, Jin B, Geng L, Cui X, Huang M, et al. Enhanced fracture toughness of TiBw/Ti3Al composites with a layered reinforcement distribution. Journal of Materials Science and Engineering: A. 2016;**670**:233-239

[35] Wu H, Jin B, Geng L, Fan G, Cui X, Huang M, et al. Ductile-phase toughening in TiBw/Ti-Ti3Al metallic-intermetallic laminate composites. Journal of Metallurgical and Materials Transactions A. 2015;**46**:3803-3807

[36] Huang T, Jin B, Li X, Li T, Nutt S. Experimental and finite element analysis study of load carrying capacity of modified polyimide. In: Proceedings of SAMPE 2013; Wichita; 2013

[37] Jin L, Jin B, Kar N, Nutt S, Sun B, Gu B. Tension-tension fatigue behavior of layer-to-layer 3D angle-interlock woven composites. Journal of Materials Chemistry and Physics. 2013;**140**:183-190