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Design Optimization of Double-array Bolted Joints in Cylindrical Composite Structures

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Abstract

A design optimization is performed for the double-bolted joint in cylindrical composite structures by using a simplified analytical method. This method uses failure criteria for the major failure modes of the bolted composite joint. For the double-bolted joint with a zigzag arrangement, it is necessary to consider an interaction effect between the bolt arrays. This paper proposes another failure mode which is determined by angle and distance between two bolts in different arrays and define a failure criterion for the failure mode. The optimal design for the double-bolted joint is carried out by considering the interactive net-tension failure mode. The genetic algorithm (GA) is adopted to determine the optimized parameters; bolt spacing, edge distance, and stacking sequence of the composite laminate. A purpose of the design optimization is to maximize the burst pressure of the cylindrical structures by ensuring structural integrity. Also, a progressive failure analysis (PFA) is performed to verify the results of the optimal design for the double-bolted joint. In PFA, Hashin 3D failure criterion is used to determine the ply that would fail. A stiffness reduction model is then used to reduce the stiffness of the failed ply for the corresponding failure mode.

Key words: Double-array bolted joint, Cylindrical composite structures, Optimization, Genetic algorithm (GA), Progressive failure analysis (PFA)

1. Introduction

Fiber-reinforced composite materials have been widely used in aircraft and space structures because they offer advantages such as higher specific stiffness and strength, better fatigue strength and improved corrosion resistance compared to conventional materials. These composite structures require joining structural components. So, there are many joining systems to connect composite parts in aerospace structures. The structural integrity of composite structures is often determined by the strength and durability of their respective joints [1]. The joining systems are divided into two types: mechanically fastened joints and adhesively bonded joints. The mechanically fastened joints require holes to be drilled for bolts and rivets. Although the mechanical joint causes unavoidable stress concentrations and a weight penalty due to the bolts and rivets, it has several advantages because it is relatively inexpensive to manufacture compared to the bonded joint and can be disassembled. The integrity of mechanically fastened composite joints depends mainly on the local laminate bearing strength, while that for adhesively bonded joints depends mainly on local inter-laminar shear strength. It is important to consider the local bearing strength when designing the fastened joints [1,2].

The design goal of the bolted composite joint is to ensure load transfer without failure of the joint. The required design is based on the failure strength analysis in order to guarantee

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the structural performance of the composite bolted joint. Many researchers make various efforts to predict the strength of composite joints. Hart-Smith [3] predicted joint strength by using the stress concentration factors. Whitney and Nuismer [4] suggested a characteristic length method based on the average stress criterion. Chang et al. [5,6] predicted the failure of composite pinned joints by using a characteristic curve and the failure criterion. Hollman [7] proposed a damage zone model (DZM) for the progressive failure analysis based on fracture mechanics. Choi et al. [8] suggested a method using the failure area index (FAI) to predict failure loads of mechanically fastened composite joints. Park et al. [9] studied on the stress analysis of bolted joint of cylindrical composite structure using finite element method. However, these prediction methods are very complex and most of them require some coupon tests and finite element analysis.

In the preliminary design phase, most engineers need a simple and low-cost method to design the initial configuration of the bolted joint. In NASA (National Aeronautics and Space Administration), Chamis [1] proposed simplified procedures for designing the composite bolted joints. He determined the failure criteria for major failure modes of composite bolted joints, and predicted the joint strength based on the geometric shapes and the laminate strength. This method is widely applied because of its simplicity and low costs, but it is only applicable to single-bolted joints. M. C. Y. Niu [2] presented typical simplified failure modes of the mechanical fasteners: shear out, net tension, bearing, and combined tension and shear out. Also, he suggested mechanical joint design guidelines including double-array bolted joints. Some aerospace structures use the multiple-bolted joints, and the zigzag array type of bolted joint is often used to connect the composite parts. The multi-array bolted joints must consider the interaction for each bolt array. Actually, outer rows of fastener carry most of load due to the low ductility of the composite materials. So, failure modes and criteria of single-array bolted joints are generally considered when designing the multi-array bolted joints. However, it is necessary to consider an interaction effect between the bolt arrays in the double-array bolted joint with zigzag arrangement. This paper considers an interactive net-tension failure mode which is determined by angle and distance between two bolts in different arrays and defines a failure criterion for the failure mode.

In this paper, the optimal design for double-bolted joints is carried out by considering the interactive net-tension failure mode. The genetic algorithm (GA) is adopted to determine the optimized parameters; bolt spacing, edge distance, and stacking sequence of the laminate, and the purpose of the design is to maximize the burst pressure of the cylindrical structures by ensuring the structural integrity. Finally a progressive failure analysis (PFA) is performed to verify the optimal design of the double-bolted joint. In PFA, Hashin 3D failure criterion is used to determine the ply that would fail. A stiffness reduction model is then used to reduce the stiffness of the failed ply for the corresponding failure mode.

2. Problem Statement

As shown in Fig. 1, the cylindrical composite structures can be joined with another structural component by the bolted joints. The bolted joint has the type of double zigzag array shown in Fig. 2. The double-bolted joint is determined by design parameters: bolt diameter (d), bolt spacing (w), edge distances (e_1, e_2), composite laminate thickness (t_c), and stacking sequence of the laminate. This joint receives axial stress (σ) due to the pressure (p) acting on the inner wall of the cylinder. The axial stress is defined as $pR/2t_c$, where R is the outer radius of the cylinder.

The problem posed is to design a bolted joint configuration for greatest burst pressure by using the GA while considering the spacing between the bolts, edge distance, and stacking sequence of the laminate as design variables. The burst pressure is predicted based on the simplified analytical method for failure strength and associated failure modes of the composite double-array bolted joint. The maximum value of the burst pressure is sought for the specified configuration of the bolted joint.

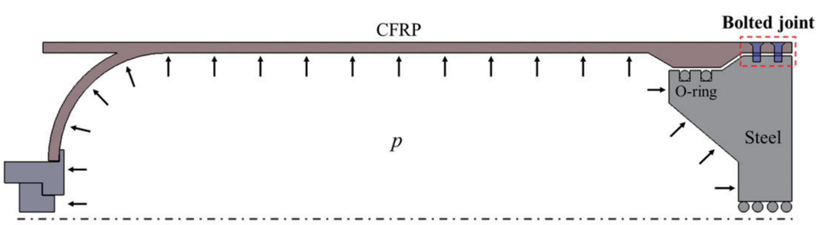

Fig. 1. Cylindrical composite structures with bolted joint

3. Failure modes and analysis for composite double-bolted joints

The bolted joints are generally designed to resist failure modes during the preliminary design phase. These failure modes most commonly occur in practical applications [1,2]. Typical failure modes of composite bolted joints consist of five failure modes as shown in Fig. 3: local bearing failure, net-tension failure, wedge-type splitting failure, shear-out failure, and tension with shear-out failure. These can be applied to the double-bolted joint with one simple change for failure modes such as wedge-type splitting, shear-out, and tension with shear-out failure which are affected by the edge distance. Specifically, the parameter of edge distance is used as the distance to the first bolt row, e_1.

For the double-bolted joint with zigzag arrangement, it is necessary to consider the interaction effect between the bolt arrays. This paper considers another type of net-tension failure mode which is determined by the angle θ and the distance w_2 between two bolts in different arrays as shown in Fig. 4. The angle is determined by the distance between two bolt arrays, and it is determined by the edge distances e_1, e_2 and bolt spacing w.

Actually, unlike the Fig. 3 and Fig. 4, stresses around bolts are not uniform, and there are high stress concentrations. However, this paper considers only average stresses to determine the simplified failure criteria. The failure criteria for each failure mode are determined using the average stresses and strength components in the composite laminate as shown in Eq. 1~6. The stress components (σ_i) and margin of safety (MOS) are calculated from applied force (F), laminate strengths, and the design parameters in Fig. 3 and 4. When any MOS is less than 0, the corresponding failure mode occurs.

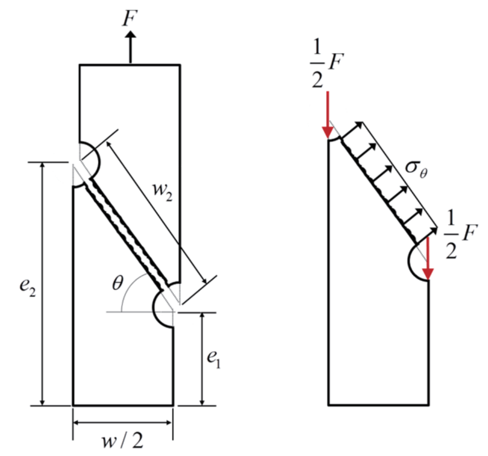

Fig. 4. Interactive net-tension failure mode for different bolt arrays

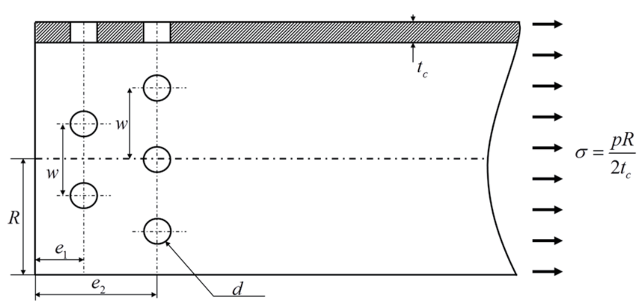

Fig. 2. Design parameters of double-bolted joint with zigzag array

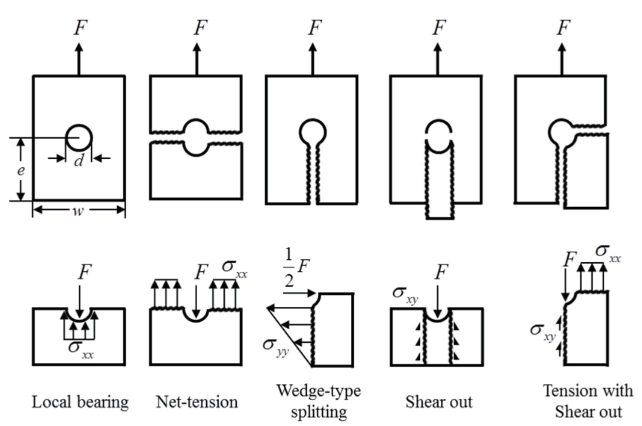

Fig. 3. Typical failure modes of composite bolted joint

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Local bearing failure mode:

$$MOS_{br} = \frac{S_{xxC}}{\sigma_{xx} \cdot SF} - 1, \quad \sigma_{xx} = \frac{F}{dt_c} \tag{1}$$

Net-tension failure mode:

$$MOS_{nt} = \frac{S_{xxT}}{\sigma_{xx} \cdot SF} - 1, \quad \sigma_{xx} = \frac{F}{(w-d)t_c} \tag{2}$$

Wedge-type splitting failure mode:

$$MOS_{wt} = \frac{S_{yyT}}{\sigma_{yy} \cdot SF} - 1, \quad \sigma_{yy} = \frac{2F}{(2e_1 - d)t_c} \tag{3}$$

Shear-out failure mode:

$$MOS_{so} = \frac{S_{xyS}}{\sigma_{xy} \cdot SF} - 1, \quad \sigma_{xy} = \frac{F}{2e_1 t_c} \tag{4}$$

Tension with shear-out failure mode:

$$MOS_{tso} = \frac{F_{tso}}{F \cdot SF} - 1, \quad F_{tso} = \frac{t_c[(w-d)S_{xxT} + 2e_1 S_{xyS}]}{2} \tag{5}$$

Interactive net-tension failure mode:

$$MOS_{int} = \frac{S_{\theta xxT}}{\sigma_\theta \cdot SF} - 1, \quad \sigma_\theta = \frac{F\cos\theta}{(w_2 - d)t_c} \tag{6}$$

Herein, MOS_i (i=br, nt, wt, so, tso, int) is the margin of safety for the corresponding failure mode, and *br*, *nt*, *wt*, *so*, *tso*, *int* mean the local bearing, net-tension, wedge-type splitting, shear-out, tension with shear-out, and interactive net-tension failure mode, respectively. S_{xxT}, S_{xxC}, S_{yyT}, S_{yyC}, S_{xyC} are the longitudinal tensile/compressive, transverse tensile/compressive, and in-plane shear strength of the laminate. $S_{\theta xxT}$ is the interactive tensile strength of the laminate, which is determined by using the longitudinal tensile strength of the θ off-axis laminate. The applied force F is obtained by the product of the axial stress and its area (F=$\sigma w t_c$), and the applied safety factor SF is 1.6. These failure criteria are applied to design constraints in the optimization problem of composite double-bolted joints. Also, the strengths of fiber-reinforced composite materials are generally determined for the unidirectional laminate. So, the strength of multi-layered laminate should be predicted by using a specific composite failure theory. In this paper, the five strength components (S_{xxT}, S_{xxC}, S_{yyT}, S_{yyC}, S_{xyS}) of the multi-layered laminate which has any stacking sequence are predicted based on the first-ply failure and the maximum stress failure criteria.

4. Optimal design of composite double-bolted joints

In this paper, the genetic algorithm (GA) is used as the optimization method to design the composite double-bolted joint. An optimization problem is formulated based on the failure criteria and some design parameters of the bolted joint. The optimal design code is generated using MATLAB.

4.1 Genetic algorithm (GA)

The genetic algorithm (GA) is a direct, parallel, stochastic search method widely used for global searches and an optimization tool based on principles of natural selection and genetics described by Darwin. This optimization algorithm uses the three processes of selection, cross-over, and mutation for a population consisting of a combination of binary numbers. The GA starts with the generation of the initial random population about design variables, and each number of the population is then evaluated based on the fitness value by the process of selection. Each member of the next generation is created by the cross-over process that represents the exchange of genes of the parents to produce offspring. The processes of mutation and permutation are also applied to some members in the new generation by perturbing the genes in order to expand the search space. The GA is suitable for finding the global optimum because the best design is always transferred from the previous generation to the next generation [9,10]. For this reason, the GA is selected as an optimization algorithm in this paper.

4.2 Formulation of the optimization problem

The purpose of formulation is to create a mathematical model of the optimal design problem, which can then be solved using an optimization algorithm. In this paper, the design objective is to maximize the burst pressure (p_f) by ensuring safety margins for the critical failure modes of the double-bolted joint in cylindrical composite structures. We consider three design variables, including bolt spacing (w), edge distance to the first low (e_1), and stacking sequence of the laminate. The edge distance to the second bolt row (e_2) and the thickness of the laminate (t_c) are assumed as constant values in order to simplify the optimization problem. Also, the bolt diameter (d) is not considered as a design variable because the bolt type and specifications are generally determined before the structural design stage for bolted joints. The stacking sequence of the laminate is determined by combining three plies which have angles of 0°, ±45°, 90°. The designed laminate is laid on the basal laminate which is determined by designing the other parts in cylindrical composite structures.

The safety margins to be calculated by the failure criteria are specified as design constraints to ensure the structural integrity of the composite bolted joint. The bearing failure mode shows progressive failure characteristics (no catastrophic failure of the laminate) among the failure modes, so it is more desirable than other failure modes. For this reason, the margin of safety for local bearing failure is determined to be a smaller value than the minimum safety margin of the other failure modes. And, the MOS_{br} is set to zero when the pressure reaches the burst pressure. Also, the design variables are constrained within geometry configuration limits. A formulated model for the optimization problem is shown in Eq. 7.

$$
\begin{aligned}
&\text{Max}\ \ (p_f) \\
&\text{S.T.}\ \ (MOS_{br})_{@p_f} = 0 \\
&\qquad (MOS_{br})_{@p_f} < \min(MOS_{nt}, MOS_{wt}, MOS_{so}, MOS_{tso}, MOS_{int})_{@p_f} \\
&\qquad e_1^l \le e_1 \le e_1^u \\
&\qquad w^l \le w \le w^u
\end{aligned} \tag{7}
$$

Herein, the superscript, l and u mean the lower and upper bounds of side constraints, respectively. These boundary conditions are determined by the geometric configuration of the cylindrical composite structures. The ranges of design variables used in this paper are 13mm≤e_1≤38mm, and 17mm≤w≤260mm. The MOS_i s are calculated from Eq. 1~6 at the burst pressure. Since the MOS_{br} is 0 at the burst pressure, the first failure of the double-bolted joint will occur within the local bearing failure mode. Also, the other failure modes have a greater safety margin than the bearing failure mode. Based on the design criteria, the constraints functions are defined by Eq. 8 ~ 13.

$$G_1 = (MOS_{br})_{@p_f} = 0 \tag{8}$$

$$G_2 = (MOS_{br} - MOS_{nt})_{@p_f} < 0 \tag{9}$$

$$G_3 = (MOS_{br} - MOS_{wt})_{@p_f} < 0 \tag{10}$$

$$G_4 = (MOS_{br} - MOS_{so})_{@p_f} < 0 \tag{11}$$

$$G_5 = (MOS_{br} - MOS_{tso})_{@p_f} < 0 \tag{12}$$

$$G_6 = (MOS_{br} - MOS_{int})_{@p_f} < 0 \tag{13}$$

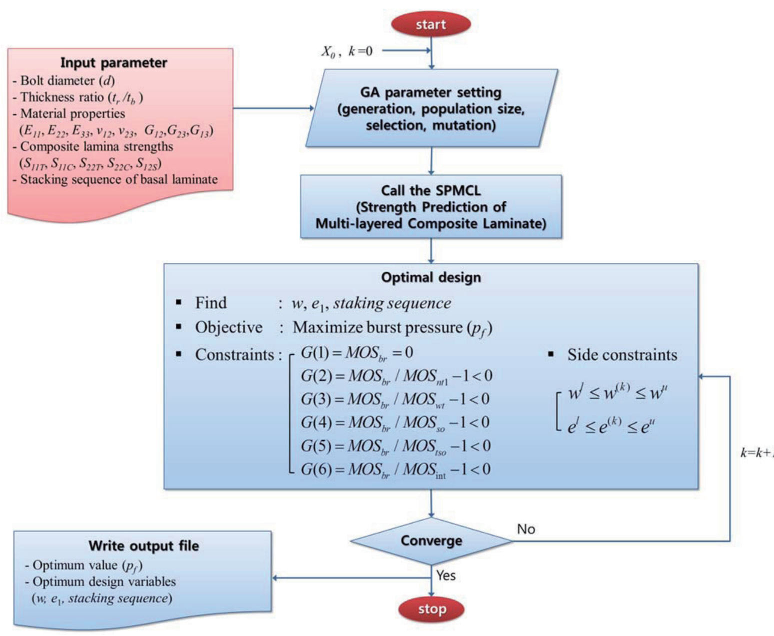

Fig. 5. Flow chart of design optimization program for composite double-bolted joint

Table 1. Mechanical properties and strengths of T800 carbon/epoxy composite material

Properties	Values [MPa]	Strengths	Values [MPa]
E_{11}	170,500	X_T	2,894
E_{22}=E_{33}	8,830	X_C	1,962
G_{12}=G_{13}	4,900	Y_T	43
G_{23}	2,450	Y_C	164
v_{12}=v_{13}	0.3	S	93
v_{23}	0.4	S_T	77

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From the formulated model, a design optimization program is coded based on GA and the simplified failure criteria of the composite double-bolted joint. The flow chart of the program is shown in Fig. 5. The SPMCL is an in-house code for the strength prediction of multi-layered composite laminate based on the composite failure criteria. This is implemented when a stacking sequence of laminate is determined for each increment in the process of optimization.

4.3 Optimal design results

The cylindrical composite structure considered in this paper has an outer radius (R) of 82.5 mm. In the composite double-bolted joint, the edge distance to the second bolt row (e_2), bolt diameter (d), and thickness of the laminate (t_c) are fixed as 42 mm, 8 mm, and 7 mm, respectively. The composite material used for this study is T800 carbon/epoxy, and the ply thickness is 0.25 mm. The basal laminate has a stacking sequence of [90°/±10°] and a thickness of 2.0 mm. The mechanical properties and strengths of the T800 carbon/epoxy composite material are listed in Table 1.

The GA needs to determine the optimization parameters such as generation and population sizes, and the factors of selection and mutation. In this paper, the generation and population sizes are set to 500 and 20, and the factors of selection and mutation are 0.5 and 0.2, respectively. The results of design optimization based on GA are shown in Table 2. Table 3 shows the safety margins for each failure mode in regard to the optimal design. In the optimization process as shown in Fig. 5, the strengths of the designed total laminate are predicted by the SPMCL function. Table 4 represents the strengths of the composite laminate which has an optimum stacking sequence. The history of the design variables, objective function, and constraints are shown in Figs. 6 and 7.

Table 2. Results of the design optimization

Objective function	p_f [MPa]	28.7613
Design variables	e_1 [mm]	24.5159
	w [mm]	25.9181
	stacking sequence	$[90°/\pm10°/(\pm45°)_5/0_6/90_4]$
Constraints	G_1	-0.0000
	G_2	-0.0203
	G_3	-0.0104
	G_4	-0.8766
	G_5	-0.4484
	G_6	-0.0065

Table 3. Results of margin of safety for optimum design

Margin of safefy	Values
MOS_{br}	0
MOS_{nt}	0.0203
MOS_{wt}	0.0104
MOS_{so}	0.8766
MOS_{tso}	0.4484
MOS_{int}	0.0065

5. Numerical verification

To verify the results of optimization, a failure mode at the burst pressure of the optimized double-bolted joint is evaluated by the progressive failure analysis (PFA). The Hashin 3D failure criterion is used to determine the ply that would fail [12]. Four failure modes are assumed by the Hashin's failure theory, which are given by Eq. 14~17.

Fiber tension:

$$\left(\frac{\sigma_{11}}{X_T}\right)^2+\frac{(\sigma_{12}^2+\sigma_{13}^2)}{S^2}=1 \tag{14}$$

Fiber compression:

$$|\sigma_{11}|=X_C \tag{15}$$

Matrix tension:

$$\frac{(\sigma_{22}+\sigma_{33})^2}{Y_T^2}+\frac{(\sigma_{23}^2-\sigma_{22}\sigma_{33})}{S_T^2}+\frac{(\sigma_{12}^2+\sigma_{13}^2)}{S^2}=1 \tag{16}$$

Matrix compression:

$$\frac{(\sigma_{22}+\sigma_{33})}{Y_C}\left[\left(\frac{Y_C}{2S_T}\right)^2-1\right]+\frac{(\sigma_{22}+\sigma_{33})^2}{4S_T^2}+\frac{(\sigma_{23}^2-\sigma_{22}\sigma_{33})}{S_T^2}+\frac{(\sigma_{12}^2+\sigma_{13}^2)}{S^2}=1 \tag{17}$$

Also, the material property degradation model (MPDM) is used to reduce the stiffness of the failed laminate in the

Table 4. Strengths of laminate for optimum design

Strength of laminate	Values [MPa]
S_{xxT}	400.24
S_{xxC}	878.58
S_{yyT}	346.17
S_{yyC}	767.11
S_{xyS}	269.00

corresponding failure mode. The assumption of the MPDM is that a damaged material can be replaced by an equivalent material with degraded properties [13]. In this paper, the material properties of the damaged lamina are reduced by Eq. 18 and 19.

Fiber tensile/compressive failure:

$$E_{11} = \nu_{12} = \nu_{13} = 0 \tag{18}$$

Matrix tensile/compressive failure:

$$E_{22} = \nu_{23} = G_{12} = G_{23} = 0 \tag{19}$$

From these failure mechanisms, the progressive failure analysis for the optimized double-bolted joint is carried out. Finite element analysis is performed using ABAQUS/Standard. A total of 134,960 eight node linear brick elements (C3D8 in ABAQUS) are employed to model the composite double-bolted joint. To consider the contact between bolt and hole, the surface to surface contact condition is applied to the contact faces of each of them. The 3D finite element model and the boundary and loading conditions are represented in Fig. 8.

A progressive failure analysis is implemented using a USDFLD subroutine in ABAQUS which allows the material properties to be a direct function of predefined field variables. Stresses are called into the subroutine at the current increment and used to evaluate the failure of composite lamina. If a failure occurs, the field variable is updated and the material properties are then reduced according to the corresponding failure mode. Fig. 9 shows the damage progression in the composite bolted joint.

6. Conclusions

In this paper, design optimization is performed for the double-bolted joint in cylindrical composite structures by using the simplified analytical method. For the mechanical fastened joint with a zigzag double bolt arrangement, the failure criteria are defined for the six failure modes: local

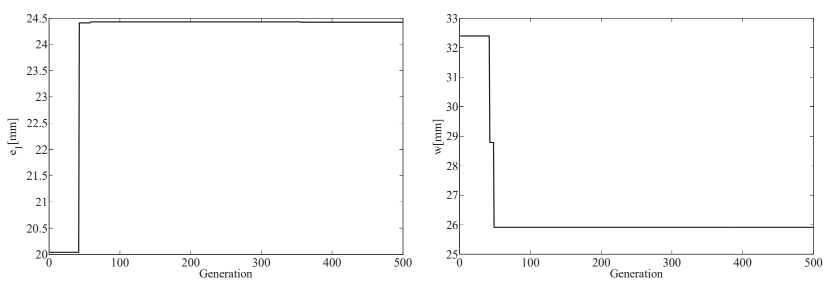

Fig. 6. History of design variables

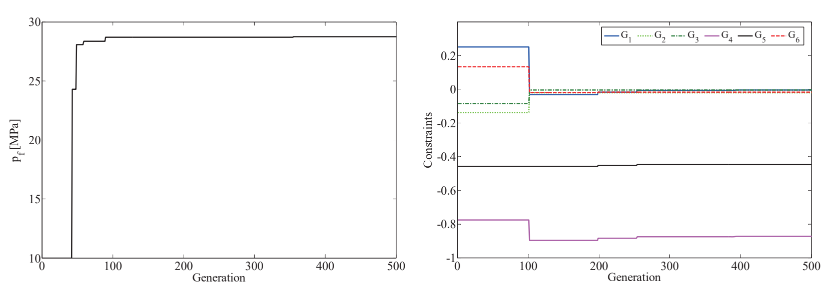

Fig. 7. History of objective function and constraints

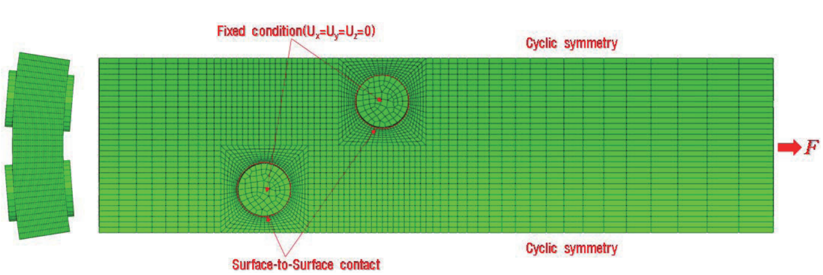

Fig. 8. FE model and boundary/loading conditions of double-bolted joint

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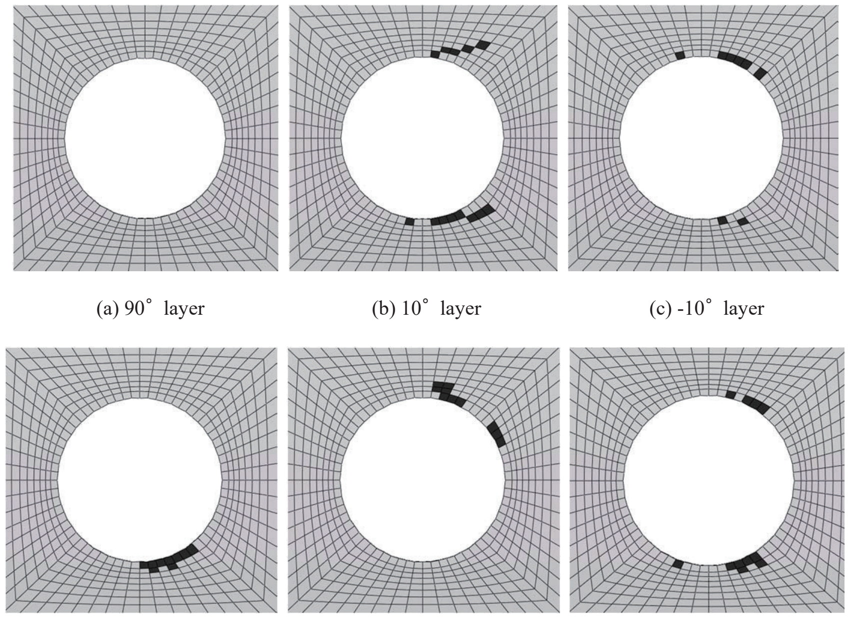

(a) 90° layer (b) 10° layer (c) -10° layer

(d) 45° layer (e) -45° layer (f) 0° layer

Fig. 9. Failed elements of the double-bolted joint (Fiber compressive failure mode)

bearing, net-tension, wedge-type splitting, shear-out, tension with shear-out, and interactive net-tension failure modes. The interactive net-tension failure mode is newly proposed by the simplified analytical method considering the effect of the angle θ and the distance w_2 between two bolts in different arrays. Based on these failure criteria, the optimal design for a double-bolted joint is carried out. The genetic algorithm (GA) is adopted as the optimization tool. The purpose of design optimization is to maximize the burst pressure of the cylindrical structures by ensuring structural integrity. We consider three design variables, including bolt spacing (w), edge distance to the first low (e_1), and stacking sequence of the laminate. The stacking sequence of the laminate is determined by the combination of three plies which have angles of 0°, ±45°, 90°. The safety margins to be calculated by the failure criteria are specified as design constraints to ensure the structural integrity of the composite bolted joint. The local bearing failure mode shows progressive failure characteristics (no catastrophic failure of the laminate) among the failure modes. So, the margin of safety for local bearing failure is set to 0 at the burst pressure, and safety margins of the other failure modes are designed larger than the bearing failure. To verify the results of optimization, a failure mode at the burst pressure of the optimized double-bolted joint is evaluated by the progressive failure analysis (PFA). The Hashin 3D failure criterion is used to determine the ply that would fail. Also, the material property degradation model is used to reduce the stiffness of the failed laminate within the corresponding failure mode. A progressive failure analysis is implemented using a USDFLD subroutine in ABAQUS. The damage progression is predicted in the ply that has 90 degrees. The results of numerical analysis show that the optimized double-bolted joint has a local failure mode similar to the local bearing failure at the burst pressure loading condition. These failure criteria and the optimization process can be applied in the initial stage of structural design for composite double-bolted joints in composite aerospace structures.

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