PAPER • **OPEN ACCESS**

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To cite this article: W Wu *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **504** 012059

IOP Conf. Series: Materials Science and Engineering **504** (2019) 012059 doi:10.1088/1757-899X/504/1/012059

Buckling analysis of stiffened composite panels with variable stiffness

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Abstract. Based on the deformation theory of Kirchhoff composites laminated shell and the variable-stiffness theory, the post-buckling method of composites laminates with variable stiffness is given. From the idea that the fiber orientation varies linearly from one element to another along one of the coordinates, a finite element model of fiber reinforced composites laminates with variable angle is developed. Considering the progressive damage, the buckling behavior including deformation and load bearing capacity of I-shaped stiffened curvilinear fiber under the uniaxial compression is investigated. The present method in this paper can be used as a reference for the design of variable angle laminated plates with automatic wire laying technology, as well as to improve the overall mechanical properties of the structure and reduce the weight of the structure.

1. Introduction

Fiber reinforced composite laminates have the characteristics of high specific strength and high specific stiffness, and have been widely used in aerospace and civil industries such as automobiles. With the development of the laying technology, it has been achieved that the laying angle of the laminate is laid out in the layer according to a predetermined trajectory. Compared with traditional composite laminates, the curvilinear fiber laminates have a larger design space and can fully exploit the mechanical advantages of the performance. Hyer [1] and others used the finite element method to take the idea of varying the fiber angle from one element to another, and analyzed the sensitivity of the element angle of the plate with hole to obtain the trajectory. It is proved that the curve laying can increase the buckling load, and at the same time, the tensile load can be improved. Gurdal et al. [2] deduced the finite element formula for the calculation of curvilinear fiber laminates, and obtained the closed form solution of the stress distribution under three boundary conditions.

Buckling is an important form of failure of laminate structures. In fact, the laminate does not break after buckling and can continue to bear, ie, post-buckling strength. There are many studies on the buckling and post-buckling of curvilinear fiber laminates [3-7]. Weaver [3] and others started from the traditional composite laminates design, designed and produced curved paving laminates, and carried out experiments and numerical calculations. The out-of-plane deflection, buckling load, the stiffness ratios of pre-buckling and post-buckling stages were compared, and the superiority of the curvilinear fiber laminates in these variables was proved. Abdacla [4] et al. used the reciprocal approximation method to take element angle as a design variable to obtain a superior to that of conventional laminates. Raju [5-6] et al. used the DQM method to derive the buckling and post-buckling equations of the curvilinear fiber laminates, focusing on the effects of shearing effects, and comparing the numerical results with the finite element results. Hao [7] and others use the IGA method to ensure the continuity of the fiber angle and improve the calculation efficiency greatly.

The composite stiffened plate or shell is one of the most effective ways to improve the stability of the laminate. The stiffened panel can greatly increase the buckling load of the flat-plate parts at a small weight, and is widely used in aircraft wing and fuselage structures. At present, there are few studies on the stiffened composite plate structure with variable angle. Coburn [8] et al. used the Rayleigh-Ritz method to perform buckling analysis on stiffened curvilinear fiber laminates and compared them with the results of finite element calculations. The error is within a reasonable range and the feasibility of the method is proved. Coburn [9] considered the discontinuity at the ribs and optimized the stiffened plate structure with a genetic algorithm to reduce the weight of the structure. However, the above studies only studied the representative single-ribbed form in the stiffened plate under uniaxial compression conditions.

In this paper, the finite element method is used to calculate the buckling and post-buckling of I-stiffened composite plates under compression conditions. From the analysis of mechanical properties, the idea of curve laying is used to improve the buckling load and carrying capacity. The buckling load and post-buckling of different ply designs were compared. In addition, progressive damage analysis was introduced during the buckling calculation process.

2. Analysis methods

2.1. Define of variable angle

In this paper, the function parameter method is used to define the trajectory [2], and the linear function is used to describe the tow path of the variable stiffness laminates. A rectangular coordinate system is established at the center point of the laminate, and the angle changes linearly along the x-axis direction. The angle between the tangential direction of the curve at the center and the boundary of the defined plate and the x-axis is T0 and T1, respectively, that is, the angle is linearly decreased or increased from T0 to T1. The curve passes through the origin and is symmetric about the origin. The expression is defined as below:

$$\theta(x) = \frac{2(T_1 - T_0)}{a}|x| + T_0 \tag{1}$$

Where, *a* indicates the length of the plate in the direction of x-axis. The schematic diagram of the <45|0> placement shown in Figure 1 below.

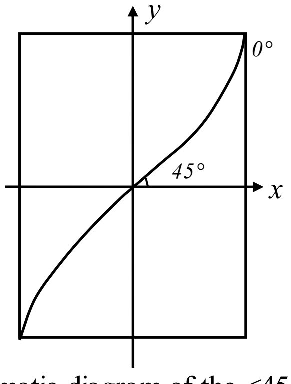


Figure 1. The schematic diagram of the <450> placement.

Generally, curvilinear fiber laminates in the finite element calculation is given to each element angle attribute in turn, which takes a lot of time. In this paper, parallel placement methods are used, and the positions of other paths can be obtained by paralleling adjacent tow paths. The displacement of the parallel placement method perpendicular to the parallel direction is constant, and the angular properties of the center points of the elements are consistent in the direction of parallel movement. By sequentially assigning each column of element property, the computational efficiency is greatly improved.

2.2. Damage failure criterion

In the strength analysis, the progressive damage analysis method can be used to effectively evaluate the damage failure process and critical strength values of the structure, and obtain good results consistent with the test. In the calculation process, the method continuously updates the material parameters according to the strength theory used and the failure criterion, thereby achieving the purpose of simulation failure. The strength theory uses the Hashin criterion [10], and the expression is:

Fiber tensile failure:

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 \geq 1 \quad (\sigma_{11} \geq 0) \tag{2}$$

Fiber tensile and compressive failure:

$$\left(\frac{\sigma_{11}}{X_C}\right)^2 \geq 1 \quad (\sigma_{11} \leq 0) \tag{3}$$

Matrix tensile failure:

$$\left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 \geq 1 \quad (\sigma_{22} \geq 0) \tag{4}$$

Matrix compressive failure:

$$\left(\frac{\sigma_{22}}{2S_{23}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 + \frac{\sigma_{22}}{Y_C}\left[\left(\frac{Y_C}{2S_{23}}\right)^2 - 1\right] \geq 1 \quad (\sigma_{22} \leq 0) \tag{5}$$

The degradation of composite properties is based on the modified Camanho [11] degradation model, in which the stiffness reduction factor is selected according to the test results, which is simple and effective. Combined with the Hashin strength criterion, it can effectively simulate the progressive damage process of composite materials. The Camanho degradation parameters are shown in Table 1 below.

Table 1. Camanho degradation coefficients.

	E_1	E_2	ν_{12}	G_{12}
Matrix Tensile Failure	1	0.2	0.15	1
Matrix Compressive Failure	1	0.4	0.15	1
Fiber Tensile Failure	0.07	0.07	0.07	0.07
Fiber compressive failure	0.14	0.14	0.14	0.14

The material failure calculation in this paper is carried out in secondary development on the commercial software ABAQUS. In general, the method used in this paper implements the progressive damage calculation function by updating the material constitutive under given criteria. Under the given model and boundary conditions, the element that assigns the material property performs the first iteration calculation. If the convergence condition is satisfied, the calculation is completed. Otherwise, it is necessary to judge whether the material is damaged according to the Hashin criterion, what kind of damage occurs, and the stiffness reduction is performed corresponding to the Camanho coefficient. The above process is cycled in sequence until the end of the calculation.

3. Numerical analysis based on finite element method

3.1. Geometric parameters and boundary condition of stiffened panel

The stiffened panel is mainly divided into two parts: the skin and the rib. The dimensions of the structure are shown in Figure 2 and Figure 3, the plate is 530mm ×405mm. The ribs are in the form of common I-shaped reinforcement, and the three ribs are equally spaced. Better simulate the real situation of resin impregnation at both ends of the test piece. The stiffened plate is simply supported by the upper side boundary of 40 mm, and the displacement load is applied. In the same case, a fixed constraint is adopted for the 40 mm from the lower boundary.

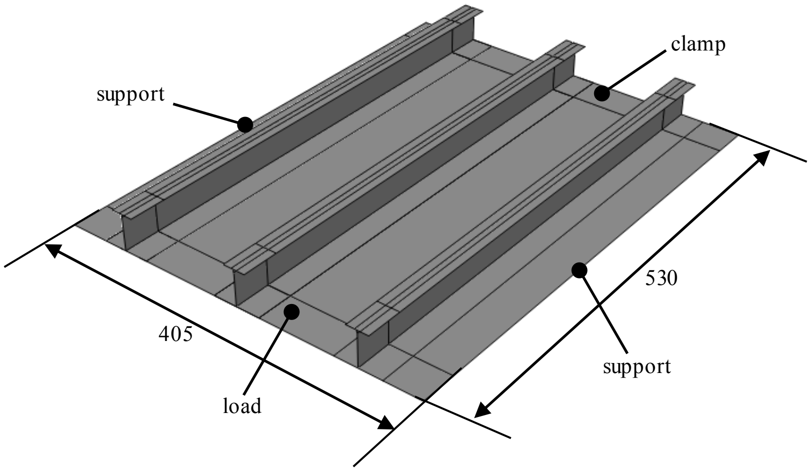


Figure 2. Geometry of the composite panel reinforced by I-type ribs.

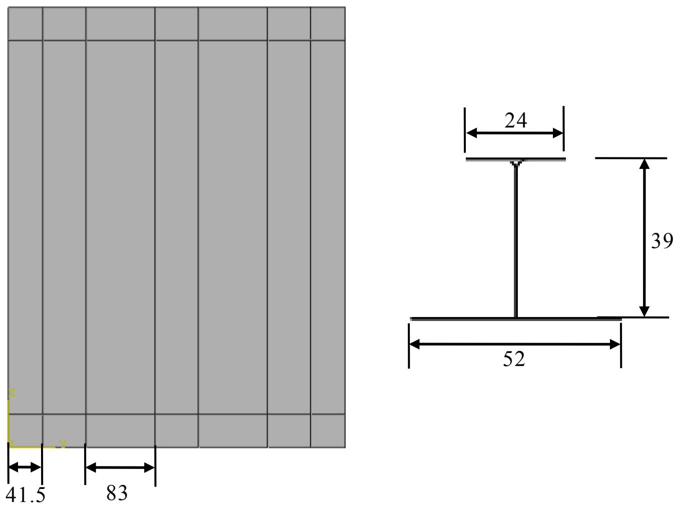


Figure 3. The configuration of ribs in skin and section of rib.

Based on the ABAQUS commercial software platform, finite element calculation were performed. Compile scripts to achieve the assignment of lay-up properties. The skin is in the form of a curved lay-up, and the ribs are still in the form of a conventional lay-up. Five different layers were designed for the skin to study its effects on the buckling load and the post-buckling. The design of the lay-up is as follows, and T, V1, V2, V3, V4 are used to represent different lay-ups, where T is a conventional straight fiber lay-up and the rest is a curved lay-up.

Lay-up design of skin:

T: (-45/45/0/90/-45/45/0/90)s
V1: (<-45|0>/<45|0>/<0>/<90|45>/<-45|0>/<45|0>/<0>/<90|45>)s
V2: (<-45>/<45>/<0>/<90|45>/<-45|0>/<45|0>/<0>/<90|45>)s
V3: (<-45|0>/<45|0>/<-45|-90>/<45|90>/<-45|0>/<45|0>/<-45|-90>/<45|90>)s
V4: (<-45>/<45>/<0>/<45|90>/<-30|0>/<30|0>/<0>/<45|90>)s
Lay-up design of rib:
(-45/0/0/45/90/45/0/0/-45/45/0/0/-45/90/-45/0/0/45)

The elasticity parameters during the finite element calculation are shown in Table 2, and the strength parameters for determining the failure are shown in Table 3.

Table 2. The elastic parameters of composite materials.

E_X/MPa	E_Y/MPa	G_{XY}/MPa	PR_{XY}
177000	8050	4370	0.32

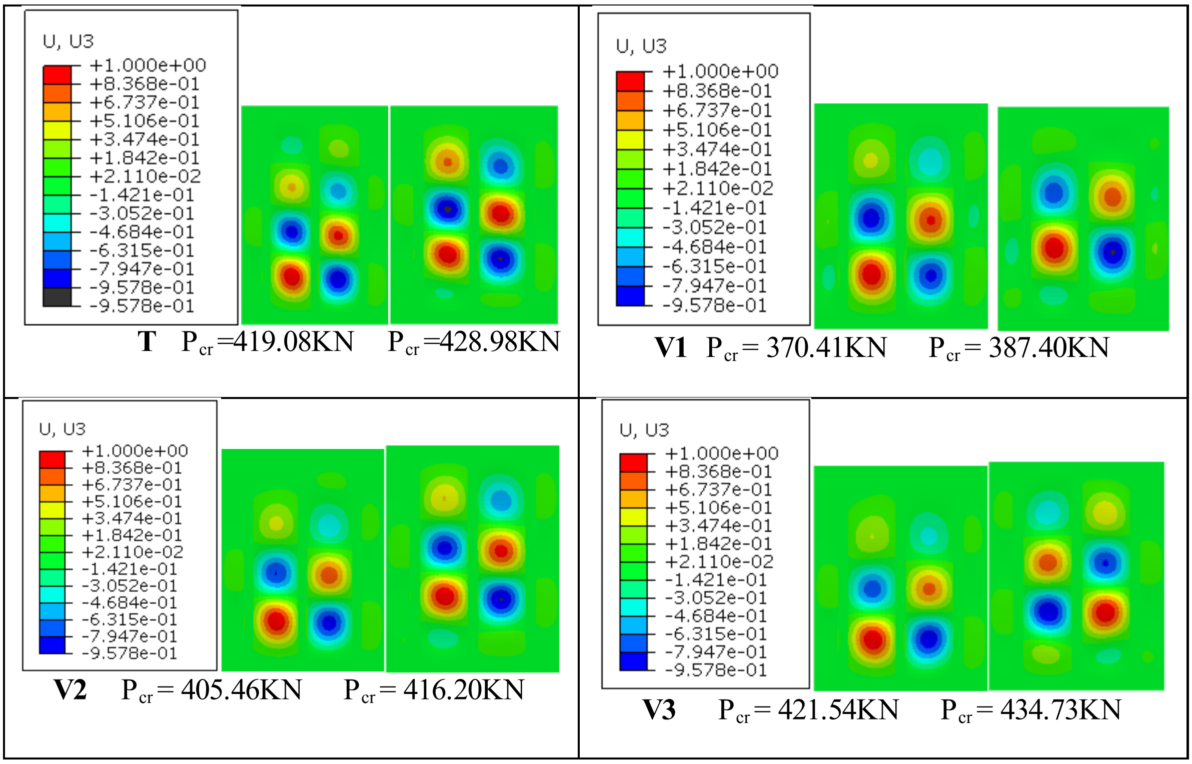
Table 3. The strength parameters of composite material.

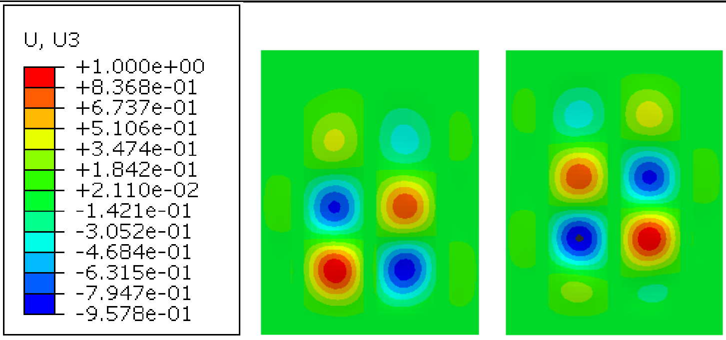
Xt /MPa	Xc/MPa	Yt/MPa	Yc/MPa	S/MPa
2700	1500	86.4	212.8	111

The free edge on both sides of the stiffened plate constrains the out-of-plane displacement. The stiffened plate constrains all translational degrees of freedom from the lower end 40mm, and the upper end 40mm constrains the degrees of freedom U_1, U_3, UR_2, and applies the displacement load in the U_2 direction (parallel to the length of the plate surface). The mesh density is 5mm, and the ribs and skins are all S4R elements.

3.2. Buckling analysis

The buckle solver in the Standard module is used to solve the buckling load. The first two orders of buckling mode and the buckling load are output. The results are as follows:





V4 P_{cr} = 392.82KN P_{cr} = 403.73KN

Figure 4. The buckling models for five lay-up designs.

Based on the traditional layer form, different types of curved layers are introduced to observe the influence on the buckling load and buckling mode. Overall, there is little effect on the first-order buckling mode, and the modal profile does not change. The layered form of V2 has an effect on the contour of the second-order buckling mode. Table 4 lists the buckling load change rates for various ply designs compared to conventional lay-up. V1 all adopt curve paving, and the first-order and second-order buckling loads are reduced by 11.61% and 9.69%, respectively. In general, ±45° lay-up plays an important role in pre-buckling, and orthogonal laying plays a key role in post-buckling. The design of V1 obviously does not fully take this into consideration. We replace the outermost <45|0>/<45|0> with <-45>/<45> to get the V2 laying design. It can be seen from Table 4 below that the first-order and second-order critical loads of V2 are increased by 9.46% and 7.43% compared with T, respectively. This is due to the fact that the outermost layer is laid with ±45°, which plays an important role in increasing the buckling load. Other rates of change will be discussed in the next section.

Table 4. The comparison of buckling load for five lay-up designs.

Number	First-order buckling load/KN	Second-order buckling load /KN	Post-buckling peak load /KN	Change rate of first-order buckling load/%	Change rate of second-order buckling load /%	Change rate of post-buckling peak load /%
T	419.08	428.98	985.18	\	\	\
V1	370.41	387.40	934.02	-11.61	-9.69	-5.19
V2	405.46	416.20	1012.28	9.46	7.43	8.38
V3	421.54	434.73	983.80	3.97	4.45	-2.81
V4	392.82	403.73	997.16	-6.81	-7.13	1.36

It can be seen from the above figure that the difference of buckling load between the modes in the same ply types is small, indicating that the initial disturbance needs to be introduced in the post-buckling calculation, otherwise the expected calculation result cannot be obtained.

3.3. Post-buckling analysis

According to the nonlinear buckling theory, the stability and strength problems of the structure are related to each other. Therefore, the reduction of the stiffness performance of the material is considered in the nonlinear calculation, and the post-buckling problem can be expressed more clearly. In this paper, the static, general solver in the Standard module is used to solve the post-buckling problem. A disturbance factor of 0.1 is introduced from the first-order mode of the linear buckling calculation to improve the computational convergence. The post-buckling of each lay-up design is drawn and the results are shown in Figure 5 below:

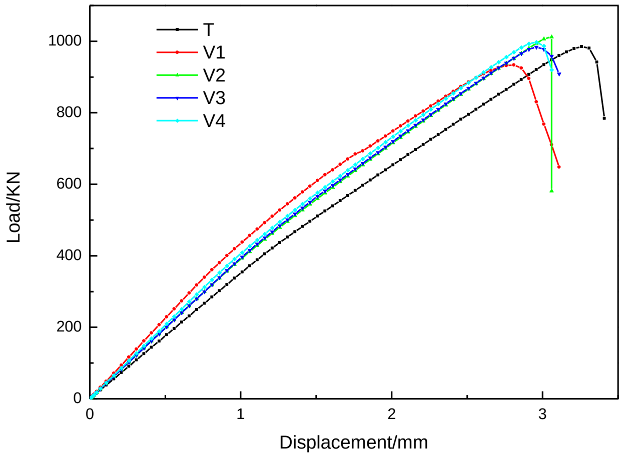


Figure 5. The displacement-load curves of post-buckling for different lay-ups.

Comparing the calculation results of T and V1, the post-buckling peak load and buckling load are both decreased. In addition, the stiffness of V1 is increased and the fracture displacement is reduced. In the V2 ply design, the buckling load and ultimate load carrying capacity are improved due to the arrangement of the outermost ±45° ply. The V3 ply design is attempted to combine 0°, ±45°, 90° by periodically circulating the following four ply design <-45|0> /<45|0>/ <-45|-90> /<45|90>.The calculation results show that the buckling load increases, but the ultimate load carrying capacity shows a slight decrease. This is because the V3 design reduces the layering parallel to the load direction and perpendicular to the load direction to some extent. In order to increase the ratio of 0°, we reduced the range of angle change to 0° to 30° based on the V2 layer design. From the results, we found that the post-buckling load did increase, but the buckling load decreased. Similarly, the inconsistency between the buckling load and the ultimate load carrying capacity also appears in the calculation of V4.

4. Conclusions

Through the finite element simulation of buckling and post-buckling behavior of composite stiffened plates with traditional lay-up design and different curved lay-ups, it shows that the outermost layer is laid with ±45° linear lay-up, which can effectively improve buckling load and ultimate bearing force. The change in buckling load and ultimate load carrying capacity may be asynchronous, ie, the ultimate load carrying capacity may be reduced in the case of increased buckling load. Variable-stiffness panel with curvilinear fibers can effectively increase the buckling load and ultimate load carrying capacity of the structure. The above conclusions have certain guiding significance for the designer's layer design.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (11572070, 11772081, 11472070 and 11422219), the Fundamental Research Funds for the Central Universities of China (DUT18ZD209), and the National Basic Research Program of China (No. 2014CB046506).

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