Study on the influence of fiber layering on the tensile properties of carbon fiber composites

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Abstract. In order to study how the tensile properties of carbon fiber composites change under different layering angles and layering sequences, this paper analyzed the tensile process of CFRP laminates under six different layering modes by using numerical simulation method based on ABAQUS finite element software, and compared the major tensile mechanical properties parameters of CFRP laminates under different layering modes. For example, tensile strength, tensile stiffness, and other physical quantities can measure the mechanical properties of the laminates, and finally obtain a reasonable laminate way that can effectively improve the tensile properties of CFRP laminates. The simulation results show that, under the premise that the number of CFRP laminates is certain, the 0° laminates should be placed on the outside of the laminates as far as possible, and the proportion of 0° laminates should be increased appropriately, which can effectively improve the longitudinal tensile strength of the laminates. The tensile stiffness of laminates can be increased by the existence of positive symmetric or antisymmetric laminates.

Keywords: Carbon fiber composites; Tensile property; Laying-up mode; Finite element model; Numerical simulation.

1. Introduction

As a new material of high structural strength, high stiffness, strong fracture resistance and good corrosion resistance, Fiber Reinforced Polymer (FRP), especially FRP lamination plate laid by unidirectional prepreg material [1], is widely used in the field of aerospace repair. Its mechanical properties will inevitably have a great impact on the performance of the space vehicle structure. In fact, the mechanical properties of FRP laminates are closely related to the layering Angle, layering sequence and other factors [2], so it is of great significance to carry out research on this problem.

Nagaraj et al. [3] used jute fiber and e-glass to prepare composite materials, and measured the tensile strength of composite materials. It is found that the tensile strength of the reinforced composite specimens with 1 layer of e-glass, 1 layer of jute fiber and 1 layer of e-glass is greater than that of the reinforced composite specimens with 1 layer of jute fiber, 1 layer of e-glass and 1 layer of jute fiber. Hamad et al. [4] characterized the mechanical properties of laminates through mechanical tensile tests (tensile strength, Young's modulus, elongation) and physical tests (density), measured the specific strength and specific modulus of laminates, and found that the laminated composite specimens with 3 layers of jute and 4 layers of carbon fiber were better than those with jute and glass fiber or jute fiber alone. The tensile strength is at its maximum. Xian et al. [5] studied two kinds of carbon/glass fiber hybrid materials, including fiber random hybrid (RH) and core-shell hybrid (CH) modes. Exposed to continuous bending loading and soaking for 360 days, they studied the influence of fiber hybrid modes on mechanical properties, and found that compared with fiber shell core hybrid board, random fiber hybrid board has excellent corrosion resistance. The tensile strength of the material can be greatly improved. Jesthi et al. [6] mixed carbon fiber and glass fiber, and found that the tensile strength of seawater aging [GCG2C] S-type hybrid composite was 14% higher than that of ordinary glass fiber reinforced polymer composite (GFRPC). Najaraja et al. [7] studied the effect of layup sequence on the tensile properties of carbon glass/epoxy hybrid composite laminates, and the results showed that, from the perspective of composite design and cost, it is important to stack carbon fiber fabrics at appropriate positions to obtain better tensile properties.

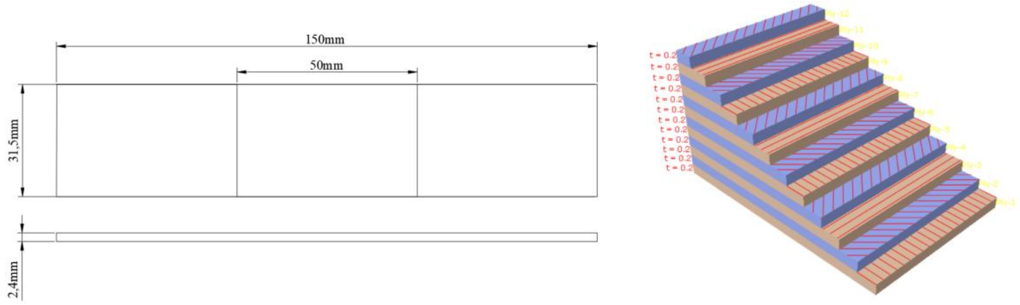
Azadi et al. [8] adopted the wavelet packet transform (WPT) and fuzzy C-mean (FCM) methods to analyze the AE signals of standard samples under tensile load. Under different loading rates, they conducted tensile tests on the samples of pure resin, pure fiber and composite materials, and found that with the increase of tensile loading rate, the maximum stress increases and the maximum strain decreases. Rajak et al. [9] prepared glass fiber (GF) and carbon fiber (CF) filled with epoxy resin by manual layering method, and significantly improved the tensile strength of the sample by changing the mass fraction of cobalt. Sampath et al. [10] produced unidirectional glass fiber composites by manual layup method. Taking the thickness, length and volume fraction of the fibers as process parameters, they measured the mechanical properties of the composites and found that the tensile strength of glass fiber reinforced composites was significantly higher than that of banana fiber composites. Liu et al. [11] studied the dynamic mechanical properties of Bio-HFRP composites by changing the composite sequence, and the mechanical properties of Bio-HFRP composites can be significantly improved by mixing glass fibers. Dumansky et al. [12] defined the mechanical properties of composite laminates based on the testing of composite specimens with different layering angles, and proposed the method of constructing constitutive equation, which can be used for the design and prediction of mechanical properties of laminated composites. Zhou et al. [13] established a micro-scale model of composite laminates including intra - and interlayer regions, and discussed the influence of intra - and interlayer pores on transverse damage behavior of composite materials. It was found that with the increase of layup temperature, the out-of-plane tensile strength of the material decreased by about 30%.

Although scholars at home and abroad have carried out some studies in these aspects, there are still some shortcomings. For example, there are few studies on positive symmetry and anti-symmetric layering, and most of the models are built on two-dimensional planes, and rarely on three-dimensional entities. These are problems that need to be solved. In order to solve these existing problems, this paper takes carbon fiber reinforced composite material as an example, and plans to use numerical simulation method, mainly to simulate the tensile process of laminates with 6 different layering methods, and to compare the influence of different layering methods on the mechanical properties of laminates by extracting some major mechanical property parameters (such as tensile strength and tensile stiffness).Finally, a reasonable layup method which can effectively improve the tensile properties of CFRP laminates is given.

2. Finite element model

2.1 Geometric model and mesh division

The composite laminates used in this paper are shown in Figure 2.1. Among them, the length of the laminated plate is 150mm, the width is 31.5mm, and the thickness is 2.4mm.For the effective stretch area in grid division, the approximate cell size is 0.5mm. For the gripper end, the approximate cell size is 1.0mm.The shape of the grid is hexahedron. The scanning algorithm used in grid division is neutral axis algorithm, and the element type is 8-node continuous shell element SC8R. A total of 33165 nodes and 25600 mesh cells are divided into laminates by this algorithm. The entire laminate is divided into 12 layers, each of which is 0.2mm thick. The figure shows the layering of [0/45/90/-45]3. There are five other layering types in this paper: [45/-45/0/90/45/-45]s、[0/30/60/90/-60/-30]2、[0/30/60/90/-60/-30]s、[0/90]6、[0/90]3s.



(a)Geometric dimensions (b) Layering method

FIG. 2.1 Geometric size and laying-up mode of composite tensile specimen

2.2 Material Properties

The laminate is laid with T700GC prepreg. For such materials, the stress-strain relationship [14] should meet the following requirements:

$$\sigma=\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{zx}\\ \tau_{xy}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ & C_{22} & C_{23} & 0 & 0 & 0\\ & & C_{33} & 0 & 0 & 0\\ & & & C_{44} & 0 & 0\\ & sym. & & & C_{55} & 0\\ & & & & & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{yz}\\ \gamma_{zx}\\ \gamma_{xy}\end{bmatrix}=C\varepsilon$$

2-1

Where, σ is the stress component; ε is the strain component; C_{ij} is stiffness coefficient and meet $C_{ij}=C_{ji}$. The matrix C that composed of the stiffness coefficient C_{ij} is called the stiffness matrix. It is not only a symmetric matrix, but also an inverse matrix of flexibility matrix S. The expression of flexibility matrix S is

$$S=\begin{bmatrix}\frac{1}{E_1} & -\frac{\upsilon_{12}}{E_2} & -\frac{\upsilon_{13}}{E_3} & 0 & 0 & 0\\ -\frac{\upsilon_{21}}{E_1} & \frac{1}{E_2} & -\frac{\upsilon_{23}}{E_3} & 0 & 0 & 0\\ -\frac{\upsilon_{31}}{E_1} & -\frac{\upsilon_{32}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}\end{bmatrix}$$

2-2

According to Equation (2-2), the flexibility matrix S contains 9 independent material constants, which determine various mechanical behaviors of orthotropic materials. The nine mechanical property parameters of the above T700GC prepreg are shown in Table 2.1 [15]

Table 2.1 Main mechanical property parameters of T700GC prepreg

parameter	symbol	Numerical value	unit	parameter	symbol	Numerical value	unit
Longitudinal modulus of elasticity	E_1	130	GPa	1-3 in-plane shear modulus	G_{13}	4.8	GPa
Transverse modulus of elasticity	E_2	7.7	GPa	1-2 In-plane Poisson's ratio	ν_{12}	0.33	-
Normal modulus of elasticity	E_3	7.7	GPa	2-3 In-plane Poisson's ratio	ν_{23}	0.35	-
1-2 in-plane shear modulus	G_{12}	4.8	GPa	1-3 In-plane Poisson's ratio	ν_{13}	0.33	-
2-3 in-plane shear modulus	G_{23}	3.8	GPa				

In addition, two-dimensional Hashin failure criterion are used in this paper to judge the failure behavior of laminates, and the failure criteria parameters are shown in Table 2.2.Let the normal stresses of a single layer plate along directions 1 and 2 be σ_1 and σ_2 respectively, and the shear stresses τ_{12} in planes 1-2, then the Hashin failure criterion [16] can be specifically expressed as follows:

(1) fiber tensile failure

$$\left(\frac{\sigma_1}{X_t}\right)^2+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \quad \text{2-3}$$

Where, X_t is the longitudinal tensile strength of the fiber; S_{12} is the shear strength in planes 1-2.

(2) fiber compression failure

$$\left(\frac{\sigma_1}{X_c}\right)^2=1 \quad \text{2-4}$$

Where, X_c is the longitudinal compressive strength of the fiber.

(3) tensile failure of matrix

$$\left(\frac{\sigma_2}{Y_t}\right)^2+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \quad \text{2-5}$$

Where, Y_t is the transverse tensile strength of the fiber.

(4) matrix compression failure

$$\left(\frac{\sigma_2}{Y_c}\right)\left[\left(\frac{Y_c}{2S_{23}}\right)^2-1\right]+\left(\frac{\sigma_2}{2S_{23}}\right)^2+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \quad \text{2-6}$$

Where, Y_c is the transverse compressive strength of the fiber; S_{23} is the shear strength in planes 2-3.

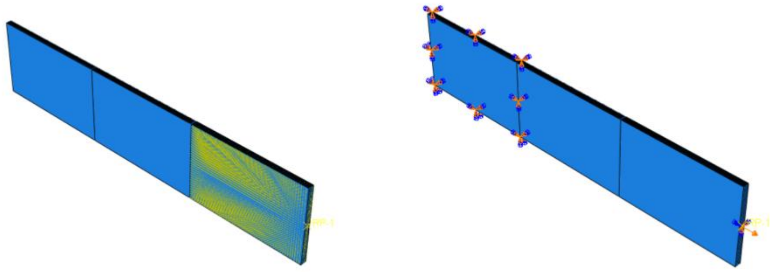
Table 2.2 Hashin failure criteria parameters of T700GC prepreg

symbol	Numerical value	unit	symbol	Numerical value	unit
X_t	2080	MPa	Y_c	140	MPa
X_c	1250	MPa	S_{12}	110	MPa

Y_t	60	MPa	S_{23}	110	MPa

2.3 Boundary conditions

In order to get closer to the actual tensile situation, two gripper ends are set on the left and right side of the laminate respectively, and a standard distance segment is set aside in the middle as an effective stretching area. The left side of the distance section is a fixed end, which fixes all nodes and limits their displacement and angle in all directions. At the same time, all nodes on the right side of the range segment are fixed to a reference point through coupling binding constraints (FIG. 2.2a), and then longitudinal forced displacement along the laminate is applied to the reference point to simulate the stretching situation of the entire laminate (FIG. 2.2b).



（a）coupling binding constraints （b）A forced displacement is applied to the right

FIG. 2.2 Boundary conditions of laminates

3. Result analysis and discussion

3.1 Stress state of laminates

Firstly, the stress state changes of laminates during tensile process are discussed. Taking the group [0/45/90/-45]3 as an example, 0°, 45°, -45° and 90° layering were selected as research objects (FIG. 3.1, 3.2, 3.3, 3.4).Firstly, the 0° layup is discussed. At the beginning of the laminate, the stress is relatively concentrated, and most of it is concentrated in the right area in the middle of the standard distance segment of the laminate. With the increase of time, a strip area through the laminate is formed in the middle of the laminate, and then gradually expands to the left of the laminate.During the expansion process, the width of the strip area is increasing, and the area under the greatest stress is also moving to the left.With the expansion of the stress zone, the right side of the zone will be damaged.With the increase of time, the failure area becomes larger and larger, so does the tensile failure. Finally, the failure of the specimen occurs.The direction of stress is transverse, which may be related to the fact that the 0° lay-up is mainly used to bear axial load, and the 0° lay-up is stressed first. In addition, the fiber direction is transverse, and the fiber in the composite material bears most of the stress, resulting in a large number of fiber shear during the tensile process of the laminate.At the same time, since the fibers in the composite material exist in the matrix, the matrix will also be stretched during the simulation process, resulting in an increasing width of the failure area in the stretching process.

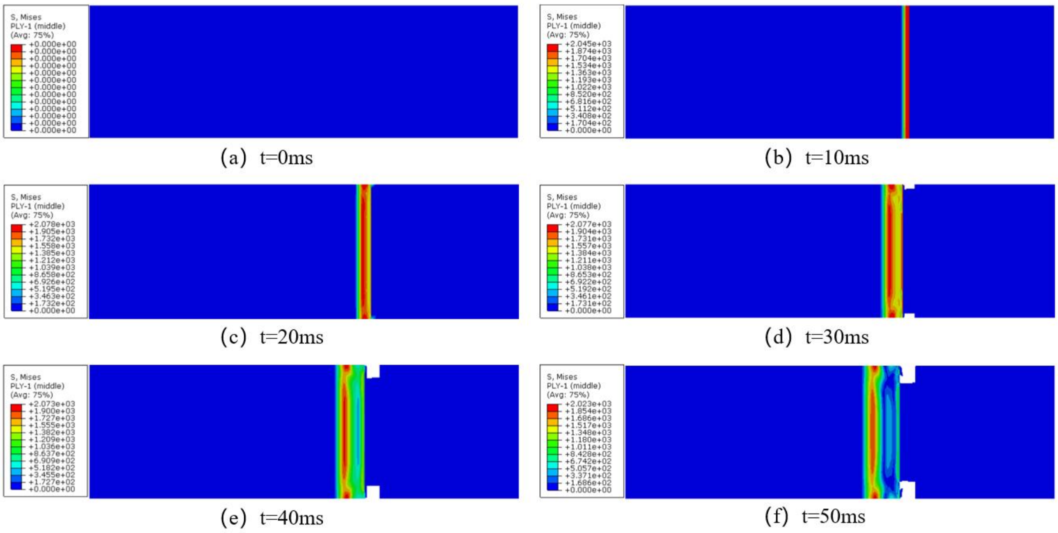


FIG. 3.1 Mises stress under 0° laminate during tensile process

It can be seen from FIG. 3.2 and FIG. 3.3 that in the tensile process of laminates, the failure locations and failure areas of 45° layering and -45° layering are similar at every moment, and the stress they are subjected to is similar, which may be similar to that of ±45° layering, which is mainly used to bear shear load. Meanwhile, the layering direction has little influence on the stress of laminates during the layering process while the size of layering angle has more influence on it.

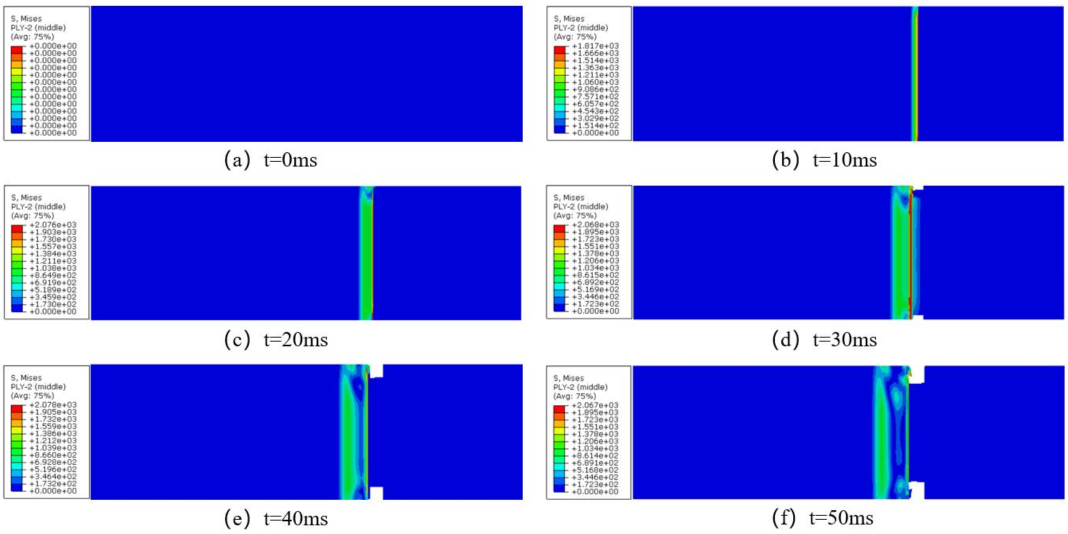


FIG. 3.2 Mises stress under 45° laminate during tensile process

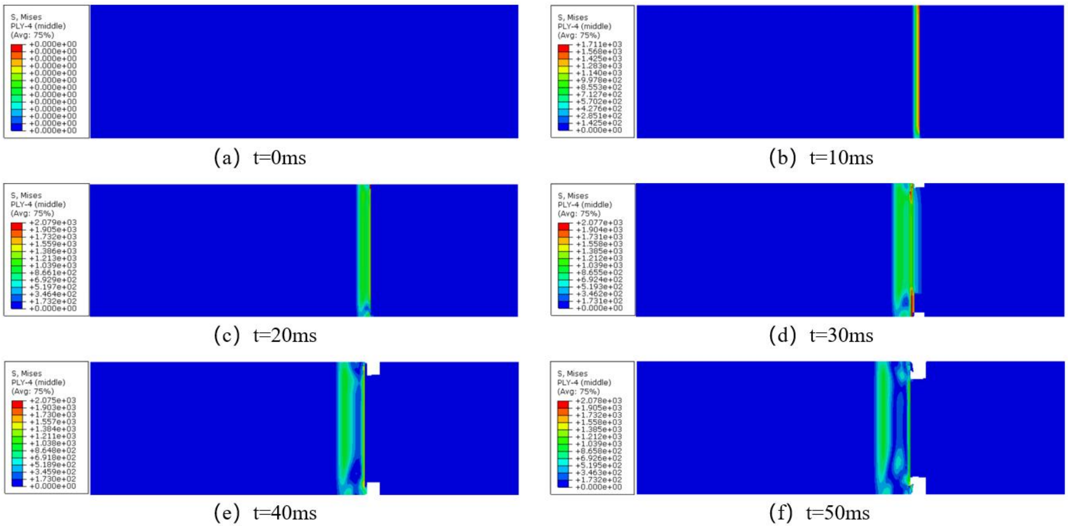


FIG. 3.3 Mises stress under -45° laminate during tensile process

Observation of Figure 3.4 reveals that during the tensile process of the laminate, the stress state of the 90° is significantly different from that of the above three layering modes.The failure of 90° layup starts from the upper and lower sides of the laminate. Meanwhile, with the increase of time, the failure area gradually expands to the surrounding, and the stress is subjected to increases constantly. With the expansion of the stress area, the failure area of 90° layup will appear from the upper and lower sides of the laminate, and the failure area will increase continuously. However, the failure area of the 90° layering is significantly smaller than that of the above three groups. This is because in the process of tensile CFRP laminates, the tensile direction is axial, and the 0°layering mainly bears the axial load, the ±45° layering mainly bears the shear load, and the 90°layering mainly bears the transverse load. As a result, the 0° lay-up is stressed first and the 90° lay-up is stressed later in the tensile process. As a result, the failure area of the 90° lay-up is significantly smaller than that of the other three groups.

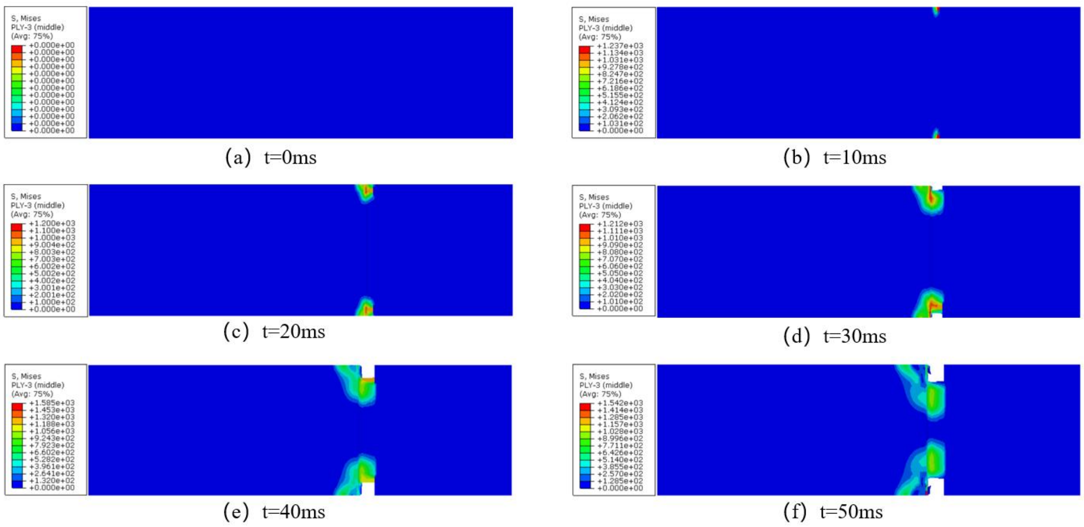
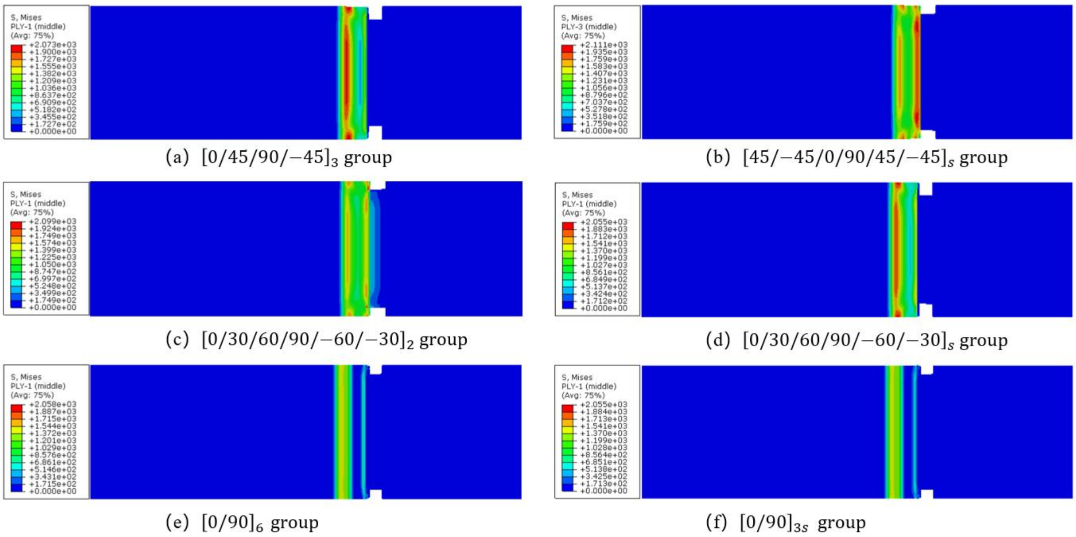


FIG. 3.4 Mises stress and failure of 90° laminates during tensile process

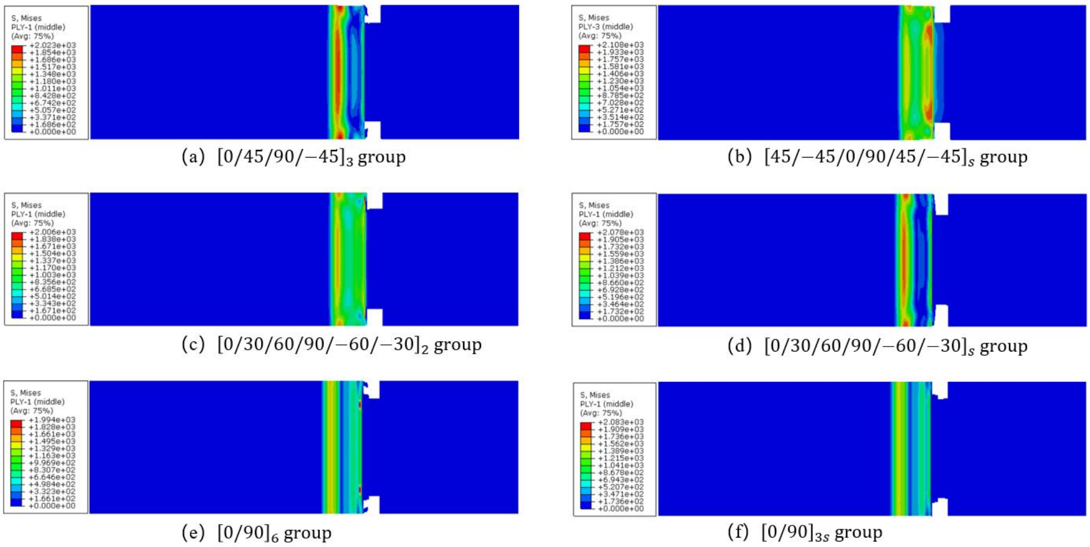
According to FIG. 3.5, under 6 layering modes, the failure mode of 0° layering is different when t=40ms. The maximum stress in group [0/45/90/-45]3 and group [0/30/60/90/-60/-30]s is far away from the fracture of laminate plate. However, the position where the maximum stress appears in [45/-45/0/90/45/-45]s group is close to the fracture of laminates, because the 0° layering in [0/45/90/-45]3 group and [0/30/60/90/-60/-30]s group is relatively outside the laminates. And the 0°

layup of [45/-45/0/90/45/-45]s group is on the inner side of the laminate, so the stress of [45/-45/0/90/45/-45]s group is relatively close to the fracture. The maximum stress occurred in the area nearest and farthest from the fracture [0/30/60/90/-60/-30]2 groups, while the stress near the fracture was small in the group [0/90]6 and the group [0/90]3, and the maximum stress location was far away from the fracture. This is because in the group [0/30/60/90/-60/-30]2,Since the ±30° and ±60° layering will be subjected to shear stress, component forces will be generated in the lateral direction, which can cooperatively transfer the stress of the 0° layering, while this is not the case in the [0/90]6 and [0/90]3 groups. As shown in FIG. 3.6, under the six lay-up modes, the area under stress increases when t=50ms, and the stress near the fracture decreases (compared with t=40ms). This is because the tensile strength of CFRP laminates decreases as time goes by after reaching the maximum degree of tensile fracture (i.e. tensile strength).



(a) $[0/45/90/-45]_3$ group (b) $[45/-45/0/90/45/-45]_s$ group
(c) $[0/30/60/90/-60/-30]_2$ group (d) $[0/30/60/90/-60/-30]_s$ group
(e) $[0/90]_6$ group (f) $[0/90]_{3s}$ group

FIG. 3.5 Mises stress and failure of the six groups of 0°layering at 40ms



(a) $[0/45/90/-45]_3$ group (b) $[45/-45/0/90/45/-45]_s$ group
(c) $[0/30/60/90/-60/-30]_2$ group (d) $[0/30/60/90/-60/-30]_s$ group
(e) $[0/90]_6$ group (f) $[0/90]_{3s}$ group

FIG. 3.6 Mises stress and failure of the six groups of 0° layering at 50ms

Through observing Figure 3.6, it can be seen that in [0/45/90/-45]3、[45/-45/0/90/45/-45]s、[0/30/60/90/-60/-30]2、and [0/30/60/90/-60/-30]s layering modes, when t=40ms, the stress area of 90° laminates is similar, and the failure zone extends to all sides. However, in group [0/90]6 and group [0/90]3, the stress of 90° laminates is transverse, and the failure zone extends along the transverse, which may be due to the existence of ±30°, ±45° and ±60° laminates. As a result, the laminates will be subjected to shear stress and generate component forces in the longitudinal direction, which can cooperatively transfer the stress of the 0° lay-up and make the failure area of the laminates expand to the four sides. However, such a situation does not exist in group [0/90]6 and group [0/90]3. At the same time, in groups [0/45/90/-45]3, [45/-45/0/90/45/-45]s, [0/30/60/90/-60/-30]2, and [0/30/60/90/-60/-30]s，the stress will be concentrated in one point. This has to do with the fact that the laminate has been severely damaged here. As shown in Figure 3.8, when t=50ms, the stress area of the lower composite plate under the six layering methods all has an increasing trend. And [0/30/60/90/-60/-30]2, [0/30/60/90/-60/-30]s, the stress near the fracture has a tendency to increase (compared with t=40ms).

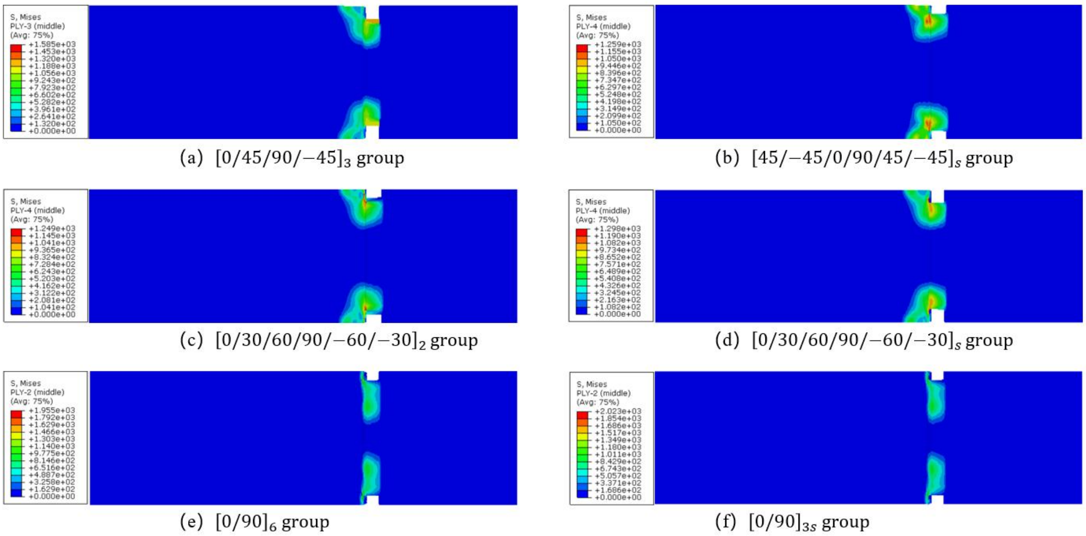


FIG. 3.7 Mises stress and failure of the six groups of 90° layering at 40ms

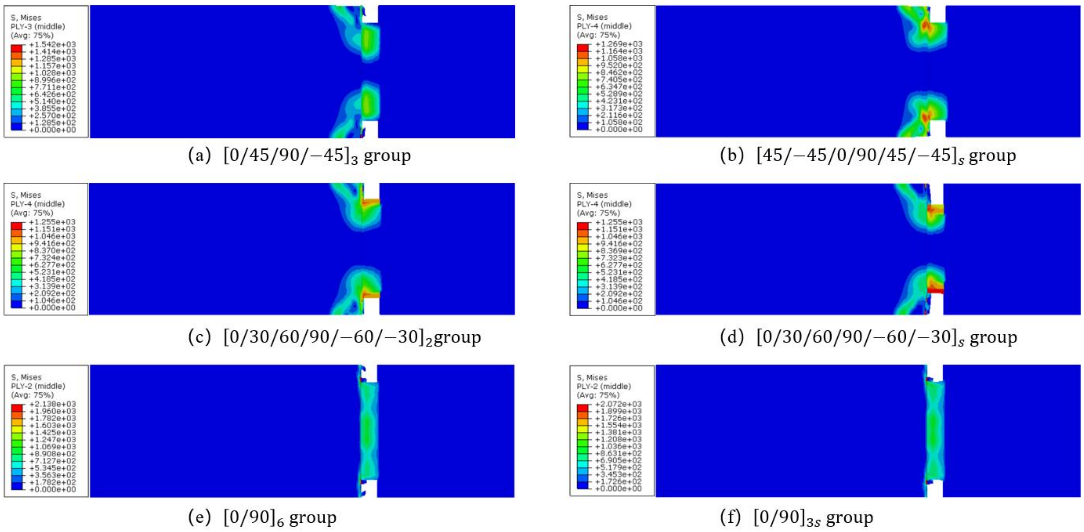


FIG. 3.8 Mises stress and failure of the six groups of 90° layering at 50ms

3.2 Forms of fiber tensile failure of laminates

By observing FIG. 3.9 and FIG. 3.10, it can be found that the tensile failure of [0/45/90/-45]3 and [0/30/60/90/-60/-30]2 fibers mostly occurs at the right position in the middle. Combined with the above discussion, the stress on the laminate is also mostly concentrated at the right position in the middle. It shows that the stress concentration area is more likely to make the laminates reach the strength limit and fail. However, the degree of fiber tensile failure of 90° layering is much less than that of other angle layering, which may be because the direction of 90° layering and fiber is not consistent, and when the laminate is subjected to tensile load, the stress is mainly borne by the fiber.

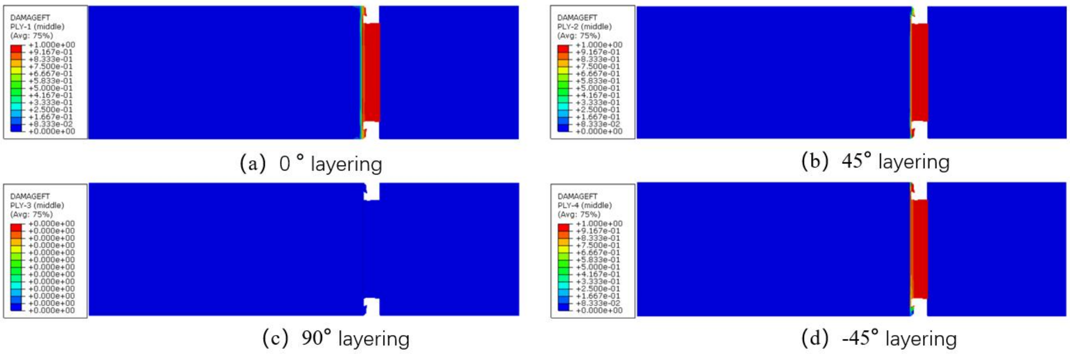


FIG. 3.9 Fiber tensile failure of group [0/45/90/−45] 3 at different layering angles

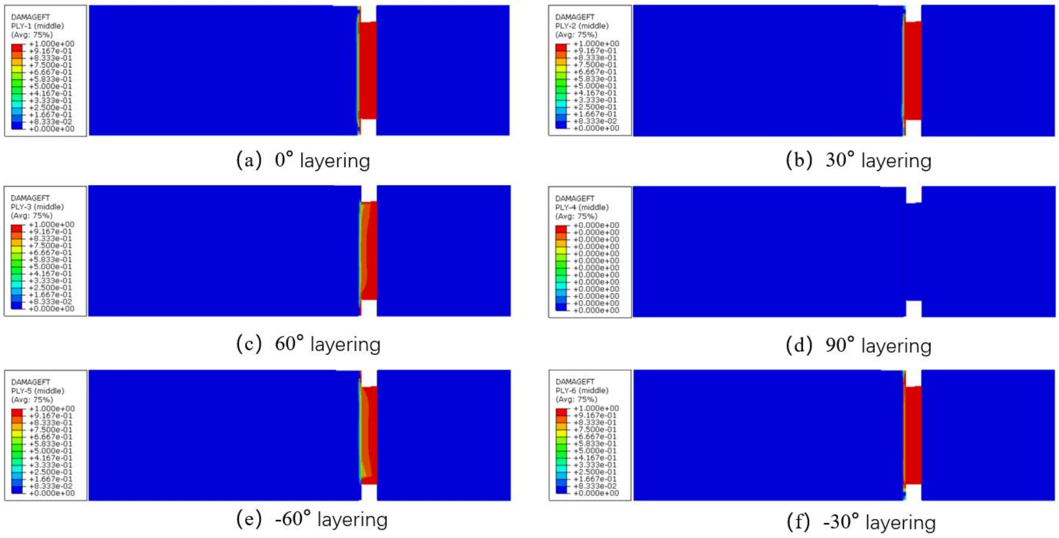


FIG. 3.10 Fiber tensile failure of group [0/30/60/90/−60/−30]2 at different layering angles

Next, the failure of laminates under the same layering angle and different layering modes is discussed (FIG. 3.11 and FIG. 3.12).Taking groups [0/45/90/-45]3, [0/30/60/90/-60/-30]2, and [0/90]6 as examples, it can be found that the degree of tensile failure of laminate fiber is almost unchanged when the layering angle is unchanged (0°, 90°).It indicates that different layup modes have little influence on fiber tensile failure under a certain layup angle. The degree of fiber tensile failure of 0° layering is greater than that of 90° layering, which is consistent with the above discussed result that the stress of 0° layering is greater than 90° layering.

(a) $[0/45/90/-45]_3$group 0° layering

(b) $[0/30/60/90/-60/-30]_2$ group 0° layering

(c) $[0/90]_6$ group 0° layering

FIG. 3.11 Tensile failure of 0° laminated fibers under different layering modes

(a) $[0/45/90/-45]_3$ group 90° layering

(b) $[0/30/60/90/-60/-30]_2$ group 90° layering

(c) $[0/90]_6$ group 90° layering

FIG. 3.12 Tensile failure of fibers at 90° under different layering modes

Taking group [0/45/90/-45]3 of laminates as an example, the failure conditions of laminates under the same layering angle and at different time are discussed. According to FIG. 3.13, under the condition of constant layup angle (45° layup), the position of fiber tensile failure was concentrated in the right position in the middle of the laminate. With the increase of time, the width of the failure area increased continuously, and finally the specimen was damaged, which was consistent with the above stress discussion results.

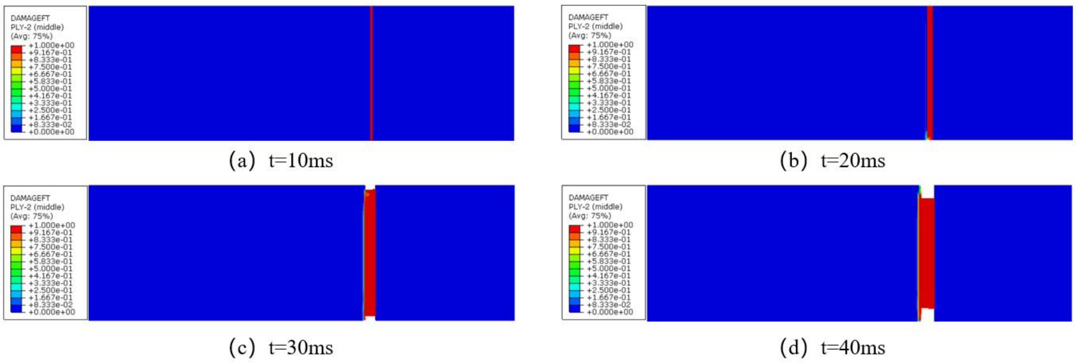


FIG. 3.13 Fiber tensile failure at 45° layering at different times

3.3 Quantitative analysis

Combined with FIG. 3.1 and FIG. 3.3, the failure area of laminates under three groups of different layering angles [0/45/90/-45] was obtained, and 1/2 of the failure area of underlayer laminates under 45° layering was defined as the unit area, and the relative area was used to plot the relative failure area of underlayer laminates at different times.According to FIG. 3.14, it can be clearly observed that with the increase of time, the failure area of the lower laminates at three different layering angles all presents an increasing trend, which is consistent with the result mentioned above that in the process of tensile failure of laminates, both fibers and matrix are subjected to tensile action, resulting in the continuous increase in the width of the strip area of the failure area during the stretching process.

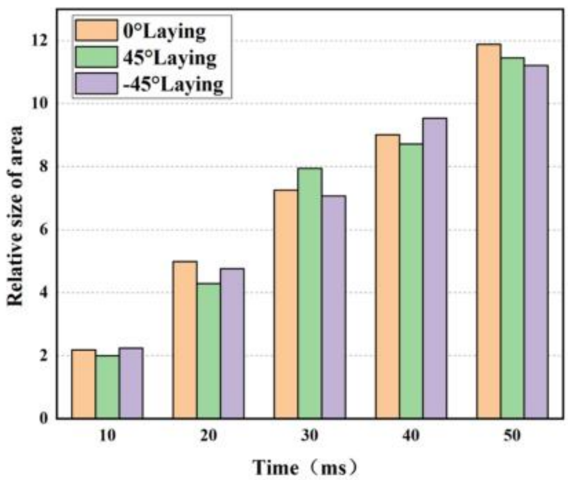


Figure 3.14 [0/45/90/-45] The relative failure area of the lower panels in three groups at different times

According to FIG. 3.15, the tensile process of CFRP laminates can be roughly divided into three stages: proportional stage, strengthening stage and failure stage.In the proportional stage, there is no obvious deformation of laminates, and the relationship between stress and strain is linear.When the ratio limit is exceeded, the stress-strain relationship is no longer a simple linear relationship, accompanied by the appearance of material failure and damage, but the phenomenon is not very obvious.At the maximum load (i.e. tensile strength), the material will be significantly damaged, and with tensile failure, the laminate will appear obvious fracture;Subsequently, the load on the laminates does not increase and slowly drops.

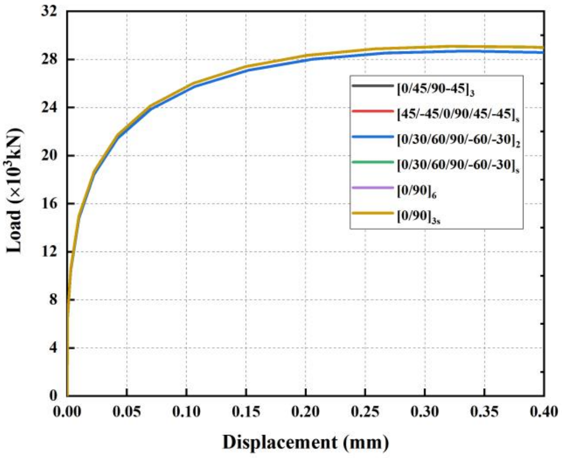


FIG. 3.15 6 Load displacement curves of lower laminated plates with different layering methods

It can be seen from FIG. 3.16 that the tensile strength of laminates is basically around 29000kN.In addition,in groups [0/90]6 and [0/90]3s, the tensile strength of laminates reaches the maximum. The tensile strength of laminates in group [0/45/90/-45]3 and group [0/30/60/90/-60/-30]s are similar. Under the layup mode of [45/-45/0/90/45/-45]s, the tensile strength of laminates is the minimum, which is consistent with the phenomenon described in Figure 3.5 of the above stress cloud diagram, indicating that the greater the tensile strength of laminates, the stronger the failure resistance of laminates, and the smaller the degree of damage caused by the stress. At the same time,, under the layering modes of [0/90]6 and [0/90]3s, the content of 0° paving reaches 50%, which is the largest among the 6 paving methods. In combination with the above discussion, the 0°layering is subjected to more stress during the tensile process of laminates. Therefore, if the longitudinal tensile strength of CFRP laminates is to be increased, the proportion of 0° layup should be increased as far as possible.

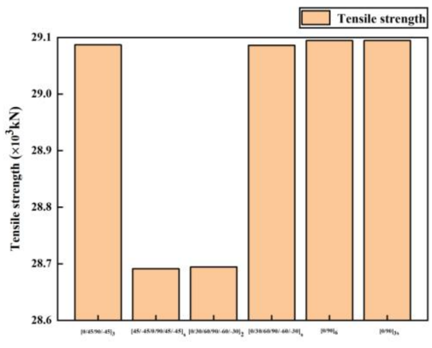


FIG. 3.16 6 Tensile strength of composite plates under different layering methods

It can be seen from FIG. 3.17 that the tensile stiffness of CFRP laminated plates is significantly lower than that of the other four groups under the two layering modes of [0/45/90/-45]3 and [0/30/60/90/-60/-30]2, indicating that we should try our best to keep a positive symmetric or anti-symmetric layering structure of the laminated plates when designing the layering. In this way, the deformation resistance and tensile stiffness of laminates can be further improved.

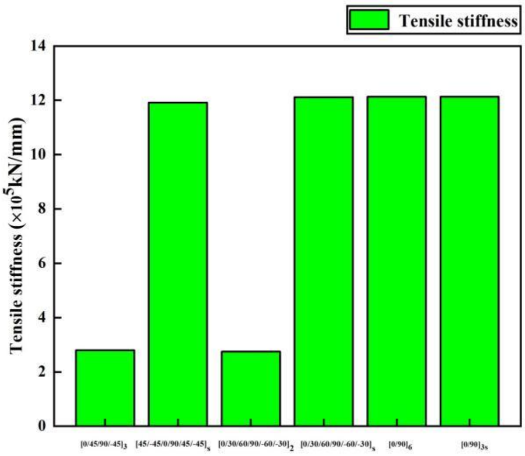


FIG. 3.17 6 Tensile stiffness of composite plates under different layering modes

4. Conclusion

In this paper, on the basis of describing the tensile strength and tensile stiffness of CFRP laminates when tensile fracture occurs under axial tensile load, a 12-layer finite element model containing different layering angles and layering modes is established in commercialized finite element software ABAQUS to simulate the influence of different layering angles and layering modes on the mechanical properties of CFRP laminates. The following conclusions are obtained:

(1) During the tensile process of CFRP laminates, the fibers in the carbon fiber composite bear most of the stress, so that the fibers are cut during the tensile process of the laminates. At the same time, different layering angles have a great influence on the tensile failure of the laminates.

(2) The 0° layup is placed on the outermost side of the laminate, which can effectively reduce the stress near the fracture of CFRP laminate, so that the laminate will not break instantaneously.

(3) The longitudinal tensile strength of CFRP laminates can be increased to a certain extent by increasing the proportion of 0° layup.

(4) The ability to resist deformation and increase the tensile stiffness of CFRP laminates can be improved by keeping the positive symmetric or anti-symmetric laminate structure.

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