

The effect of tear straps on compressive carrying capacity of composite omega single-stringers

C H Geng, R X Bai, Z K Lei, W Wu, X Z Zhang and K W Peng

State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, China
Email: bairx@dlut.edu.cn

Abstract. In this paper, the progressive failure analysis method is used to analyze suppression effect and mechanism of tear straps, and study the effect of tear straps with varying coverage on compressive carrying capacity of composite omega single-stringers. Based on ABAQUS, several omega single-stringers with common, half-inclusive and all-inclusive configuration are established. Buckling and post-buckling processes of single-stringers subjected to axial compressive load are analyzed. Hashin failure criterion and Camanho model are adopted, respectively, as the failure criterion and degradation model of materials. Cohesive model is used to simulate the bonding interface. The results show that by strengthening the local stiffness of the stringer and skin, tear straps resist the local buckling deformation and control the occurrence and range of damage induced by local buckling, hence preventing the reduction of the carrying capacity. The all-inclusive configuration is more effective than half-inclusive. The conclusions obtained show that tear straps can improve overall stiffness and load-carrying capacity and the all-inclusive configuration has a higher effect than the half-inclusive configuration. Tear straps play a vital role in improving the carrying capacity of structures.

1. Introduction

Aircraft structures are required to fully withstand the ultimate design load no matter what the invisible damage or the visible impact damage is, hence structures should have a high damage tolerance [1]. The high damage-tolerant features include honeycomb sandwich configuration, discrete stiffeners, mechanical fasteners [2] and so on. Some studies [3] show that the composite thin-walled stiffened structures can obtain the buckling critical load with less weight, and have considerable damage tolerances and post-buckling bearing potentials. Boeing of the United States proposed a damage tolerance design configuration consisting of a soft skin, discrete stringers, and 0-deg tear straps embedded in the skin. The tear straps are located below the stringer and equal to the width of the stringer. This configuration prevents the reduction of the structure's carrying capacity by resisting and controlling the occurrence and range of damage. In order to further improve the damage tolerance of composite stiffened structures and fully exploit the post-buckling bearing potential of structures, it is of great significance to study the influence of tear straps on the carrying capacity of stiffened structures.

Bisagn C et al. [4] conducted experimental studies on the post-buckling response and failure mode of composite single-stringer specimens with and without embedded delamination damage. Masood S N et al. [5] tested the buckling mode and deformation of carbon-fiber composite stiffened plate, and obtained buckling, post-buckling behavior and final crushing results using finite element models with a zero-thickness cohesive model. McCarty et al. [2] impacted two kinds of stiffened panels with different stacking sequences in the doubler and conducted the tensile and compressive experiments. The result shows that the configuration with tear straps have a higher damage tolerance compared with other configurations. Wiggeraad et al. [1] impacted stiffened panels with tear straps at different



positions, and compared the results of the test and the finite element method for predicting impact damage. Ye J [6] used the progressive damage method to analyze the inhibition and crack arrest mechanism of tear straps on T-stiffened panels under axial tensile and compressive loads, and compared the effect of tear straps on carrying capacity of structures.

In this paper, finite element simulations of buckling and post-buckling process of composite omega single-stringers with varying-coverage tear straps subjected to axial compressive load are conducted, and the suppression effect and mechanism of tear straps on analyzing the damage propagation of the stringer and the skin are performed. The effect of tear straps with varying coverage on compressive capacity of composite omega single-stringers is discussed.

2. The Progressive Damage Analytical Method

Numerous studies show that the progressive damage analytical method can effectively simulate the damage process of composite materials. The progressive damage analysis assumes that damage materials can continue to carry the load according to properties after material degradation. The solution process consists of three parts: non-linear stress analysis, damage analysis based on strength theory and property degradation of damage materials.

Hashin criterion [7] based on the stress description is used in this paper. Hashin criterion has simple expressions and can predict each failure mode. The expressions are [7]:

Fiber tensile failure:

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

Fiber compressive failure:

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

Matrix tensile failure:

$$\left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 \geq 1 \quad (\sigma_{22} \geq 0) \quad (3)$$

Matrix compressive failure:

$$\left(\frac{\sigma_{22}}{2S_{23}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 + \frac{\sigma_{22}}{Y_C} \left[\left(\frac{Y_C}{2S_{23}}\right)^2 - 1 \right] \geq 1 \quad (\sigma_{22} \leq 0) \quad (4)$$

Fiber-Matrix shear failure:

$$\left(\frac{\sigma_{11}}{X_C}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 \geq 1 \quad (\sigma_{11} \geq 0) \quad (5)$$

$$\left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 \geq 1 \quad (\sigma_{11} \leq 0) \quad (6)$$

σ_{ij} , the stress component of the analysis element in material coordinate. 1, 2 and 3 represent the longitudinal direction, the transverse direction and the normal direction. X, Y and S represent the longitudinal, transverse and shear strength. T and C represent tension and compression.

The modified Camanho [8] degradation model commonly used in practice is adapted in this paper, and degradation coefficients of elastic parameters based on experiments are selected. The degradation of material properties is achieved by establishing damage constitutive relations.

The cohesive model [9] can effectively simulate the initiation and evolution of damage of interfaces. The square nominal stress strength criterion is used to judge whether the damage occurs. The power law criterion is used to judge whether the damage expands.

3. Finite Element Numerical Analysis

Composite omega single-stringers are subjected to axial compressive load in experiments. In order to control the damage in the effective area, the single-stringers are wrapped with resin at both ends. The basic dimensions of the single-stringers, the configurations of varying tear straps are shown in Figure 1, the length of skins is 270mm, and the width of skins is 111.641mm. Skins, stringers and fillers are made of carbon fiber reinforced composite materials; the tear strap is a layer of fabric prepreg. The parameters are shown in Table 1. The sequence of the skin layer is [45/0/0/-45/90]_s, The sequence of the stringer layer is [45/0/0/-45/90/-45/0/0/45]_s. Camanho [8] degradation coefficients are shown in Table 2. The parameters of the cohesive model are [9]: $E_{nn} = 10GPa, E_{ss} = 10GPa, E_{tt} = 10GPa$; $t_n^0 = 15MPa, t_s^0 = 30MPa, t_t^0 = 30MPa$; $G_{IC} = 0.3N/mm, G_{IIC} = 0.6N/mm, G_{IIIC} = 0.6N/mm$. t_n^0, t_s^0, t_t^0 are the normal nominal stress and two tangential nominal stress, respectively; $G_{IC}, G_{IIC}, G_{IIIC}$ are the fracture toughness of fracture models in the mode I, II, and III.

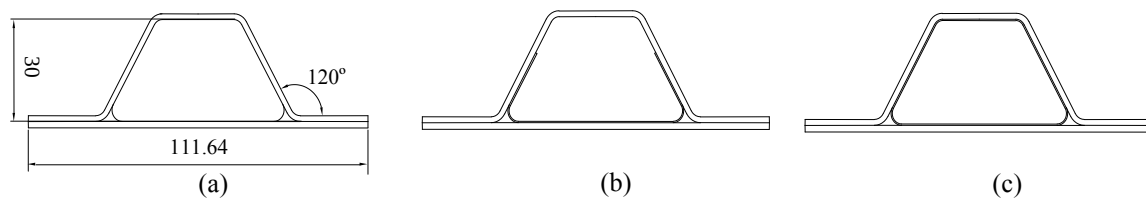


Figure 1. Dimensions and configurations of common, half-inclusive, all-inclusive single-stringers

Table 1(a). The parameters of single-layer panels.

	E_1 (GPa)	E_1 (GPa)	ν_{12}	G_{12} (GPa)	Thickness(mm)
Composite	154	8.5	0.35	4.21	0.1868
Prepreg	67.9	67.1	0.06	4.28	0.372

Table 1(a). The parameters of single-layer panels.

	X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	S_{12} (MPa)
Composite	2610	1450	55	285	105
Prepreg	808	837	753	794	107.6

Table 2. Camanho degradation coefficients.

Failure type	E_1	E_1	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
Fiber-matrix shear failure	1	1	0.01	0.01

3.1. Numerical Model and Solution

ABAQUS/Standard is used to simulate the compressive process of composite omega single-stringers. Skins, stringers and tear straps are modeled using continuum shells element type SC8R, fillers are modeled by the usage of solid element type C3D6, the mesh size is 2 mm. The finite element model of omega single-stringers with all-inclusive tear-strap is shown in Figure 2. An axial displacement is applied to the loading end in resin package, and the remaining translational and rotational degrees of freedom are limited. All translational and rotational degrees of freedom of the fixed end are limited. The out-of-plane displacements on both sides are constrained.

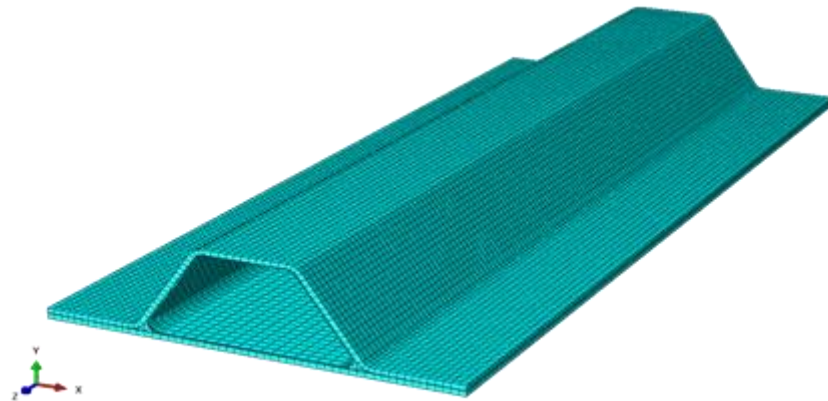


Figure 2. The finite element model of the all-inclusive single-stringer

The eigenvalue buckling analysis is performed for all single-stringers. The lateral displacement of the first-order buckling mode is added as an initial perturbation to the analysis of single-stringers under compressive load, and the disturbance coefficient takes 0.01. Risk method is used in nonlinear analysis, considering material and geometric nonlinearity.

3.2. Failure Analysis

The comparisons of the carrying capacity for entireties and stringers with tear straps in three configurations are shown in Table 3. Displacement-loading curves of entireties, stringers with tear straps and skins in three configurations are shown in Figure 3.

Table 3. The comparison of the carrying capacities for all configurations.

Configuration	The ultimate load of entirety(KN)	Promotion (%)	The ultimate load of stringer(KN)	Promotion (%)
Common	241.15	-	134.92	-
Half-inclusive	251.07	4.11	146.34	8.46
All-inclusive	268.55	11.36	159.85	15.60

According to the data in Table 3, the ultimate loads of entireties and stringers of half-inclusive configuration and all-inclusive configuration have obvious improvement compared to common configuration. All-inclusive configuration's ultimate load is higher than half-inclusive configuration's. This is because, as shown in Figure 3, tear straps enhance the stiffness of the stringers and the overall structures, and the ratio of stiffness of stringers and skins. The greater the degree of coverage is, the greater the enhanced stiffness and stiffness ratio are.

During the entire loading process, adhesive cracking does not occur in all configurations.

In the early loading process of all configurations, local buckling occurs at the skin and stringer, and there are three half waves on the skin, hence the overall stiffness decreasing slightly.

Matrix tensile failure and fiber-matrix shear failure occur at the buckling location of 0° and $+45^\circ$ ply for the skin and stinger in common configuration. Then, fiber compressive failure occurs at 0° ply in the buckling location of the skin and stinger and rapidly expands in the horizontal direction, then the carrying capacity decreases. Hence, the main failure mode of the common configuration is fiber compressive failure of 0° ply induced by local buckling of the skin and the stringer.

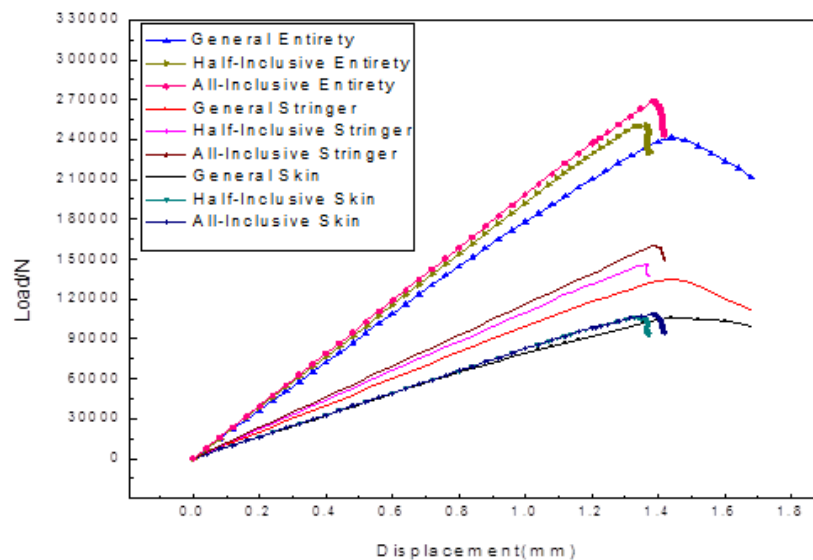


Figure 3. Displacement-loading curves of different parts for three configurations

As for half-inclusive configuration, fiber compressive failure occurs at the 0° ply of the skin at the site where the local buckling is the most severe after local buckling and failure expands rapidly, and matrix tensile failure and fiber-matrix shear failure occur at the same location during the expansion process, then the carrying capacity drops significantly. But no damage occurs at the stringer and the tear strap. Therefore, the fiber compressive failure of 0° ply induced by local buckling of the skin determines the ultimate load. The post-buckling process of all-inclusive configuration is similar to that of half-inclusive configuration, only a small area of shear failure occurs in the local buckling site during the expansion of the fiber compressive failure of skin's 0° ply. However, the factors that determine the ultimate bearing capacity of the structure are the same.

Deformation and major failure form of three configurations when the ultimate loads are reached are shown in Figure 4-6. It can be seen that when the ultimate loads are reached, the maximum buckling out-of-plane displacement absolute values of the skins of common, half-inclusive, and all-inclusive configuration are 2.256mm, 1.861mm, and 1.657mm, respectively; The areas of the main failure form i.e. fiber compressive failure, narrow down successively, and the failure only occurs at the skins of the latter two configurations. In addition, the types of failure modes and corresponding areas of the three configurations also reduce successively. This is because tear straps enhance the stiffness of stringers and skins, and resist local buckling deformations, and the stress components of the corresponding material elements are also reduced, hence suppressing the damage induced by buckling deformation. The comparison results show that by strengthening the local stiffness of the stringer and the skin, tear straps reduce the types of damage, resist and control the propagation and range of damage induced by local buckling, hence preventing the reduction of the structure's carrying capacity. The all-inclusive configuration is more effective than the half-inclusive configuration. Therefore, tear straps can improve stiffness and load-carrying capacity of the overall structure, and they play a vital role in improving the load-carrying capacity of structures.

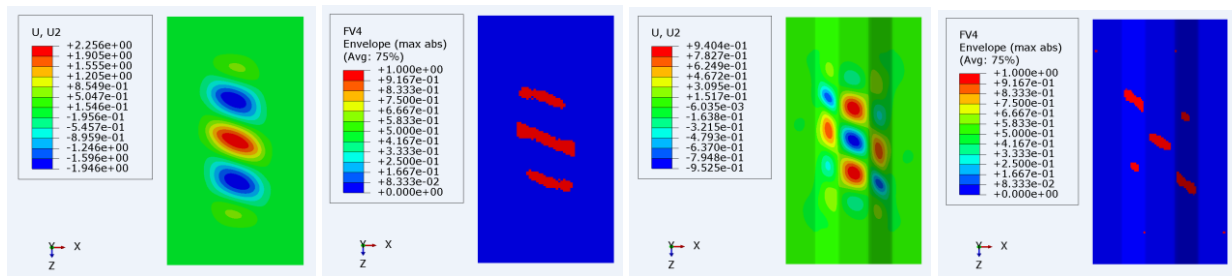


Figure 4. Deformation and main failure form of common configuration.

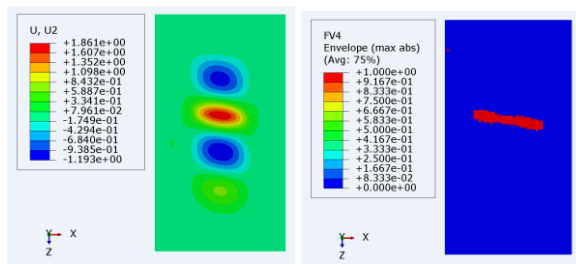


Figure 5. Deformation and main failure form of half-inclusive configuration.

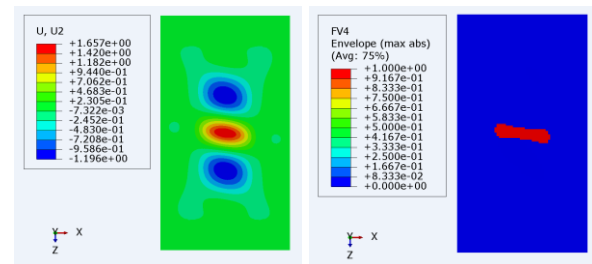


Figure 6. Deformation and main failure form of all-inclusive configuration

4. Conclusion

Finite element simulations of buckling and post-buckling process of composite omega single-stringers with varying-coverage tear straps subjected to axial compressive load are conducted. The results show that the main failure mode of the common configuration is fiber compressive failure of 0° ply induced by local buckling of the skin and stringer. Fiber compressive failure of 0° ply induced by local buckling of the skin determines the ultimate load of half-inclusive and all-inclusive configuration. By strengthening the local stiffness of stringers and skins, tear straps resist local buckling deformations, and resist and control the propagation and range of damage induced by local buckling, hence preventing the reduction of the structure's carrying capacity. Tear straps can improve stiffness and carrying capacity of the overall structure. The all-inclusive configuration is more effective than the half-inclusive configuration.

Acknowledgments

Authors thank to the funding of the National Natural Science Foundation of China (Nos. 11472070, 11772081, 11572070).

References

- [1] Wiggensraad J F M, Zhang X and Davies G A O 1999 *Composite Structures* vol 45 pp 81 – 103
- [2] McCarty J W and Roessler W G 1984 NASA CR - 003767
- [3] Shao Q, He Y T, Zhang T and Wu L M 2014 *Journal of Mechanical Engineering* vol 20 p 93
- [4] Chiara B, Carlos G D 2014 *Composite Structures* vol 108 pp 493 - 503
- [5] Masood S N, Rohit D, Saurabh C, Parashuram H, Viswamurthy S R, Kotresh M G 2017 Nineteenth National Seminar on Aerospace Structures Nasas
- [6] Ye J 2012 Designing tear straps in composite stiffened panel, Njing University of Aeronautics
- [7] Hashin Z 1980 *Journal of applied mechanics* vol 42 pp 329 - 334
- [8] Camanho P and Matthews F L 1999 *Journal of Composite Materials* vol 33 pp 2248 - 2280
- [9] Diehl T 2008 *International Journal of Adhesion and Adhesive* vol 28 pp 237 - 255