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Numerical Analysis of Composite Panels in the Post-Buckling Field taking into account Progressive Failure

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Summary

The research here presented shows the numerical results for progressive failure of stiffened composite panels into the post-buckling field. In particular, a strength reduction procedure is implemented in the commercial finite element code ABAQUS where the stiffness properties of the material are removed in the failed areas. The results show a good correlation with experimental data obtained from a post-buckling test of a stiffened panel with a notch, that can be found in literature.

Introduction

Due to the complex nature of composites, failure modes in laminated composites are strongly dependent on geometry, loading direction, and ply orientation.

There are basically five different in-plane failure mechanisms: matrix tensile cracking, matrix compression, fiber breakage, fiber-matrix shearing, and fiber buckling. To simulate accurately the damage growth in composite structures, the numerical analysis must be able to predict the failure mode in each ply, and then apply the corresponding reduction in material stiffness as the loading level is increased.

Consequently, the damage evolution and progressive failure phenomena in the composite materials result very complex and till now not-well known. Both the failure index and the degraded properties are not easily determined as there are several factors that influence the failure mode and make difficult to represent correctly the behavior in the finite element models. This problem is evident in buckling tests, where the post-buckling field is reached and some failure can start and propagate till the collapse [1-3].

Several failure criteria for composite structures can be found in literature [4-5]. The failure in laminated composite structures is here determined by the simple Hashin criterion [6]. Then, to evaluate the material properties within the damaged area, a user defined subroutine elaborated in FORTRAN is implemented in ABAQUS/Standard [7]. The analyses, able to get the buckling and post-buckling of the stiffened composite panels, are performed using a dynamic implicit analysis at fixed step.

Hashin Failure Criterion

At first, the Hashin criterion [6] is implemented in a subroutine for ABAQUS [7], so to use it in a non-linear dynamic analyses to investigate possible initial failures during buckling analyses till the structural collapse [8].

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It considers three different failure mode: matrix failure, shear failure and fiber breakage. Besides, it distinguishes tensile stress from compression stress. Consequently there are the following failure modes:

Matrix failure:

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

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

Shear failure:

$$\sigma_{11} > 0 \quad \left(\frac{\sigma_{12}^2}{S_{12}^2} \right)^{\frac{1}{2}} \geq 1 \tag{3}$$

$$\sigma_{11} < 0 \quad \left(\frac{\sigma_{11}^2}{X_C^2} + \frac{\sigma_{12}^2}{S_{12}^2} \right)^{\frac{1}{2}} \geq 1 \tag{4}$$

Fiber breakage:

$$\sigma_{11} > 0 \quad \left(\frac{\sigma_{11}^2}{X_T^2} \right)^{\frac{1}{2}} \geq 1 \tag{5}$$

$$\sigma_{11} < 0 \quad \left(\frac{\sigma_{11}^2}{X_C^2} \right)^{\frac{1}{2}} \geq 1 \tag{6}$$

Implementation of the Progressive Failure Subroutine in Abaqus

The use of a failure criterion provides the identification of the first failed areas but does not allow following the damage evolution because no material degradation is considered.

To implement a strength reduction procedure in ABAQUS where the stiffness properties of the material are removed in the failed areas, and to simulate the damage growth accurately, the failure analysis must be able to predict the failure mode in each ply, and then apply the corresponding reduction in material stiffness as the loading level is increased.

The developed procedure works evaluating, at each increment of the analysis and in each integration point, the failure index. If the failure index is detected, then the properties of the integration point are degraded according to the proposed criteria. In this way a progressive material failure is reached.

In particular, the idea is that material in the failed area can be substituted by an equivalent material with degraded properties. These properties are not easily determined as there are several factors that influence the failure mode and make difficult to represent correctly the behavior in the finite element models.

The model here adopted implements the following. When the failure index indicates matrix cracking, tensile or compression, the fiber stiffness in the fiber direction and the transverse stiffness are kept constant, but the stiffness in the matrix direction are put equal to zero. Instead when the failure index indicates fiber breakage, the fibers can not work any more but the matrix can still contribute. The only transverse stiffness is equal to zero when there is fiber-matrix shearing.

The procedure has been preliminarily tested by validation cases as characterization coupons tests, and then used for stringer stiffened fiber composite panels.

Finite Element Model

The application of the subroutine implemented in ABAQUS with the Hashin criterion is then validated by means of a NASA panel, investigated at NASA Langley Research Center, which experimental and numerical results can be found in literature [9]. The panel is a stiffened composite panel, constituted of unidirectional carbon fibers AS4/3501-6 with 8 layers [45°/-45°/0°/90°]s and of stringers with L section of 24 layers and stringers with T section of 48 layers, respectively.

The material properties are reported in Table 1, where M1 is the material for the layers at +/-45° having a thickness of 0.15 mm, M2 is the material for the layers at 0° having a thickness of 0.315 mm, and M3 is the material for the layers at 90° having a thickness of 0.085 mm.

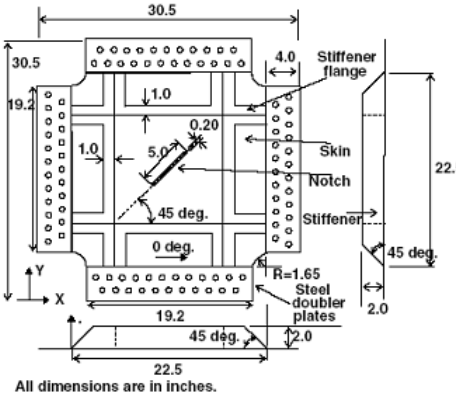
The geometry and the dimension of the panel are reported in Figure 1, while the finite element model obtained in ABAQUS, based on 7428 nodes and 7352 elements, S4R and S3R types, is shown in Figure 2. During the model development, particular attention is given to the definition of the stringers lay-up using the offset parameter, and to the stringers lamina orientation using different reference systems.

Mechanical characteristics				Maximum stress			
	Material type				Material type		
	M1	M2	M3		M1	M2	M3
E_{11}[*MPa*]	111350	113280	110109	X_T[*MPa*]	1350	1506	1241
E_{22}[*MPa*]	11031	11031	11031	X_C[*MPa*]	1034	1034	1034
G_{12}[*MPa*]	5516	5516	5516	Y_T[*MPa*]	34.47	34.47	34.47
G_{13}[*MPa*]	5516	5516	5516	Y_C[*MPa*]	213.74	213.74	213.74
G_{23}[*MPa*]	2758	2758	2758	S_{12}[*MPa*]	120.66	120.66	120.66
ν_{12}	0.34	0.34	0.34	S_{13}[*MPa*]	33.09	33.09	33.09
Density g[kg/m^3]	1510	1510	1510	S_{23}[*MPa*]	33.09	33.09	33.09

Table 1: Material characteristics of the NASA panel

Validation

The results of the analyses are here reported. In particular, Figure 3 reports the comparison between the load-displacement curve obtained by the ABAQUS analysis with the implemented user subroutine, and the experimental and numerical results obtained by NASA [9], where FV1, FV2 and FV3 correspond to the matrix



All dimensions are in inches.

Figure 1: Geometry and dimension of the NASA panel [9]

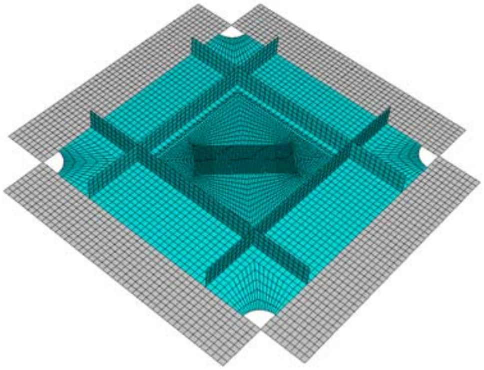


Figure 2: Mesh of the NASA panel

failure, shear failure and fiber breakage, respectively. Figure 4 shows the deformed shape obtained by the analysis with an amplitude factor equal to 2, while Figure 5 reports the comparison of the failure mode obtained from the analysis and that one observed during the experimental tests performed by NASA.

It is possible to note that the numerical analyses are able to reproduce the experimental behavior with good accuracy.

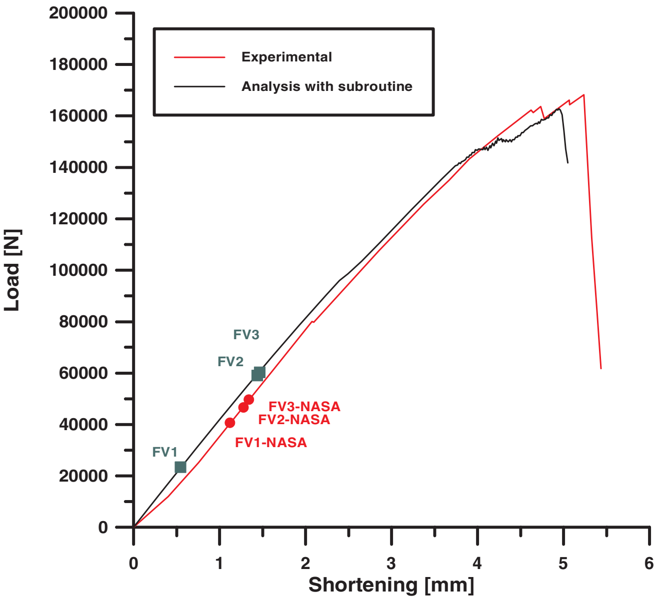


Figure 3: Analysis results compared with NASA data

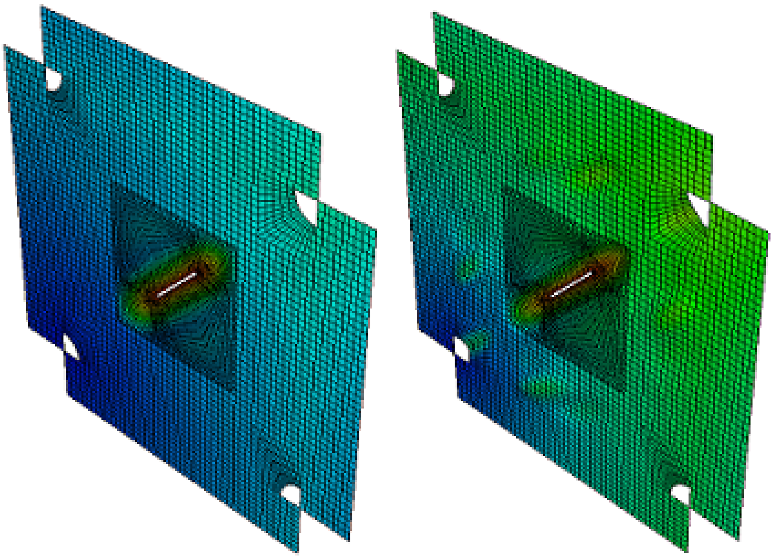


Figure 4: Deformed buckling shape, at 1.70 mm and at 4.41 mm

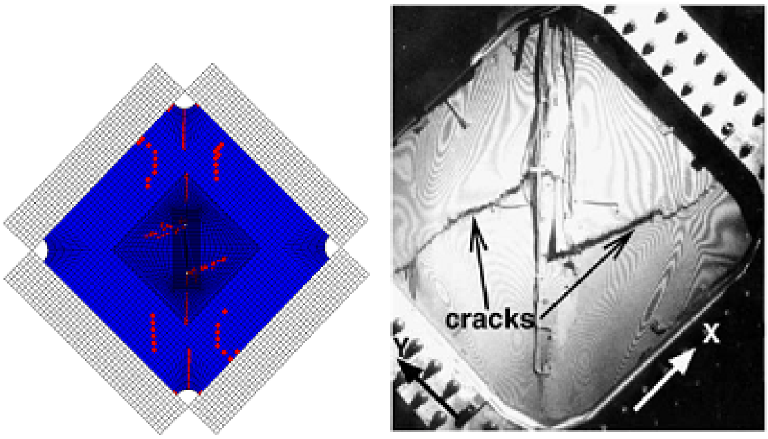


Figure 5: Comparison of the failure mode

Conclusions

The paper describes a tool based on the Hashin failure criterion, and implemented as user defined subroutine in ABAQUS, allowing to follow progressive damage in composite panels in the post-buckling field.

The procedure, previously validated using simple test cases, has been successfully applied to a reference test case, whose experimental results are available in literature.

Acknowledgement

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