Evaluation of the Residual Strength of Structures Made of Composite Materials Based on a Conservative Distribution of Damage Parameters

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Evaluation of the Residual Strength of Structures Made of Composite Materials Based on a Conservative Distribution of Damage Parameters

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Abstract. The purpose of this study is to develop the method that conservatively estimates the residual strength of a composite structure with barely visible impact damage (BVID), without direct modelling of impact process. The basis of the research is in the conservative transformation of kinetic energy of impactor into damage of the material, which is associated with the system of microcracks in the matrix, fiber and interface. A special algorithm that distributes damage parameters in worst way for the composite structure provides conservative estimation of residual strength. Thus, bvid allowables can be set using fewer experiments.

1. Introduction

Barely visible impact damage (BVID) is the key factor for thick laminate composites. Commonly it is associated with the damage due to a low velocity impact as possible incidents during structure lifecycle: falling of tools, hailstones, runway debris etc. This type of damage may significantly reduce the mechanical characteristics without any visible marks on impacted surface. General certification procedure of aerospace composite structures based on demonstrating of "no growth" concept for such defects after impact under operational loads [1 - 15]. This leads to increase of safety margins and as a result to an essential reduction of weight efficiency. Compression after impact (CAI) is a common test for evaluation of damage tolerance of composite laminates. Practice indicates that prediction methods show unsatisfactory results in many cases and physical testing still prevails for evaluation of composite residual strength and damage growth in industry for today [1]. To reduce the amount of expensive physical tests, a reliable predictive method is required for engineering practice.

This work proposes the approach for estimation of the minimum possible residual strength, based on "the worst" distribution of matrix, fiber and interface damages and its accumulation after impact. The minimum possible residual strength condition is fulfilled by decreasing the stiffness of the laminate via energy absorption from the impact. It is assumed, that the portion of the kinetic energy of an impactor is transformed into microcracks of fractured matrix materials (by several damage modes) but the other portion is transformed back to the impactor or to elastic and kinetic energies of the specimen.

2. Transformation of impact energy into damage

The ratio of kinetic energy, which is transformed into the damage, can be estimated by tests or can be taken conservatively. The transformation of unit of energy into unit of damage can be derived from material damage model. For example, using composite material failure model described in [16, 17], the energy spent on degradation can be approximated as an area taken by close loop of loading curve (fig. 1).

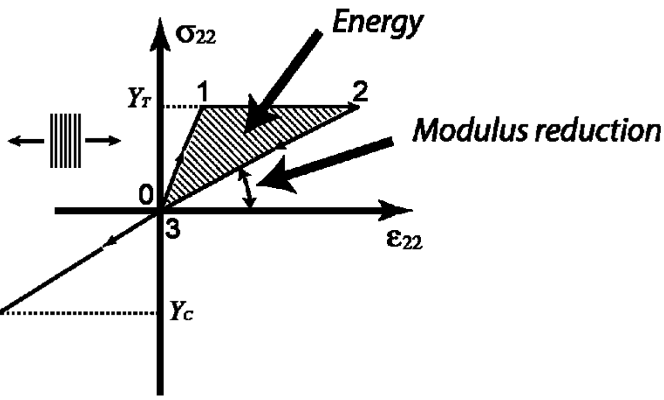

Figure 1. Transformation of damage energy into stiffness reduction.

This idea gives a formal rule for transformation of energy (En) into damage, for example, in case of transversal tension loading:

$$En = \frac{(\varepsilon_{22}^1 - \varepsilon_{22}^2)Yt}{2} = \frac{\left(\frac{Yt}{E_2^1} - \frac{Yt}{E_2^2}\right)Yt}{2} = \frac{Yt^2}{2E_2^0}\left(1 - \frac{1}{\psi}\right) \quad (1)$$

where:
ε_{22}^1 – deformation at point 1 (fig. 1)
ε_{22}^2– deformation at point 2 (fig. 1)
Yt – failure stress in case of transversal tension
E_2^1 – transversal modulus at point 1 (fig. 1)
E_2^2 – transversal modulus at point 2 (fig. 1)
E_2^0 transversal modulus of not damaged material
ψ – damage parameter, associated with stiffness reduction ($0 \le \psi \le 1$)

The equation (1) gives the relation between damage parameter ψ and required for this damage energy En.

For simplicity we can assume, that the damage of the material was obtained by a compression loading and use parameters corresponding to a compressive failure - stress Yc and transversal modulus E_2.

Another source to spend impact energy is the delamination. The energy spent on delamination can be estimated as

$$En_{delam} = SG_I \quad (2)$$

where:
S – area of delamination
G_I- fracture toughness for open type crack growth
First mode of fracture toughness G_I is chosen in (2) due to conservative fact that $G_I < G_{II}$ and $G_I < G_{III}$.

3. Damage distribution algorithm

Avoiding the direct impact modelling, we can analyze variants with one, two, three and so on delaminated layers with different damage distribution for corresponding energy taken from impactor (fig. 2) and choose the worst variant of them.

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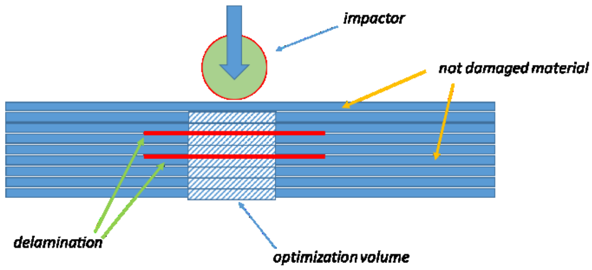

Figure 2. Delamination placement and volume with possible damage

Having estimated value of energy spent on stiffness degradation, we need to distribute damage parameters in the volume Ω, which is assumed to be affected by an impactor. Conservative distribution is the case when the structure has the lower residual strength. It is questionable point, but for the first step we can assume that the worst case is the one with maximum deformation of analyzing volume Ω. Formally, we can assume that it is deformation energy in the possible affected volume Ω. Now it is possible to formulate the problem for damage distribution:

$$Max_{\psi(x,y,z)}\left(1/2\int_{\Omega} E_{ijkl}\,\varepsilon_{ij}\varepsilon_{kl}d\Omega\right), \tag{3}$$

where following [16]

$$E_{ijkl}=\begin{bmatrix} \frac{1}{E_{11}} & -\frac{\psi\nu_{21}}{E_{22}} & -\frac{\psi\nu_{31}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\psi\nu_{12}}{E_{11}} & \frac{1}{\psi E_{22}} & -\frac{\psi\nu_{32}}{E_{33}} & 0 & 0 & 0 \\ -\frac{\psi\nu_{13}}{E_{11}} & -\frac{\psi\nu_{23}}{E_{22}} & \frac{1}{\psi E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\psi G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\psi G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\psi G_{23}} \end{bmatrix}^{-1} \tag{4}$$

subjected to constrains:

$$0<\psi\le 1$$
$$En=\int_{\Omega} e_n d\Omega=\int_{\Omega}\frac{Yc^2}{2E_2^0}(1-1/\psi)d\Omega=Const. \tag{5}$$

Consider gradient of the objective function for finite volume used in topology optimization method:

$$\frac{\partial\int_{\Omega} E_{ijkl}\,\varepsilon_{ij}\varepsilon_{kl}d\Omega}{\partial\psi_e}=\int_{\Omega_e}\frac{\partial E_{ijkl}}{\partial\psi_e}\varepsilon_{ij}\varepsilon_{kl}d\Omega \tag{6}$$

where ψ_e- damage of the material at volume Ω_e (undamaged material corresponds to $\psi = 1$), index e is associated with volume and damage of one element in FEM analysis. Each tensor component $\frac{\partial E_{ijkl}}{\partial \psi_e}$ can be calculated directly using matrix of (4).

The SIMP optimization algorithm described in [18] has been implemented into Abaqus software using special user subroutines. The iterative procedure for finding of element damage value ψ_e^K at step K has the form

$$\psi_e^{K+1} = \begin{cases} max\{(1-\zeta)\psi_e^K, \psi_{min}\} \; if \; \psi_e^K B_K^{-\eta} \leq max\{(1-\zeta)\psi_e^K, \psi_{min}\} \\ min\{(1+\zeta)\psi_e^K, 1\} \; if \; min\{(1+\zeta)\psi_e^K, 1\} \leq \psi_e^K B_K^{-\eta} \\ \psi_e^K B_K^{-\eta} \;\; otherwise, \end{cases} \tag{7}$$

where $B_K = \Lambda_K^{-1} \int_{\Omega_e} \frac{\partial E_{ijkl}}{\partial \psi_e} \varepsilon_{ij} \varepsilon_{kl} d\Omega$, and Λ_K is a multiplier that satisfies the total damage energy constraint and is found by a bi-sectioning algorithm. The variable η is a tuning parameter with typical value of 0.5 and ζ is a move limit with reasonable value of 0.2.

4. Example problem

To demonstrate the algorithm of damage parameters distribution to get the worst case, let us consider the compression problem of composite plate with dimensions 200mm×200mm and total thickness of 8mm formed by 40 layers of quasi-isotropic layup [0°/45°/-45°/90°]$_{5S}$. Fig. 3 shows the placement of optimizing volume, which is a cylinder of diameter 50mm with one non-damaged, and consequently, not optimized layer at the side of impact. The loading was applied through displacement to get better convergence of numerical analysis. Displacements were chosen to get deformation of the layup to be 2%, which is near the failure one. The direction of compression loading is 0° degree. Solid elements with incompatible modes (perform close to second-order elements for regular element shape) were used with grid density of one element per layer.

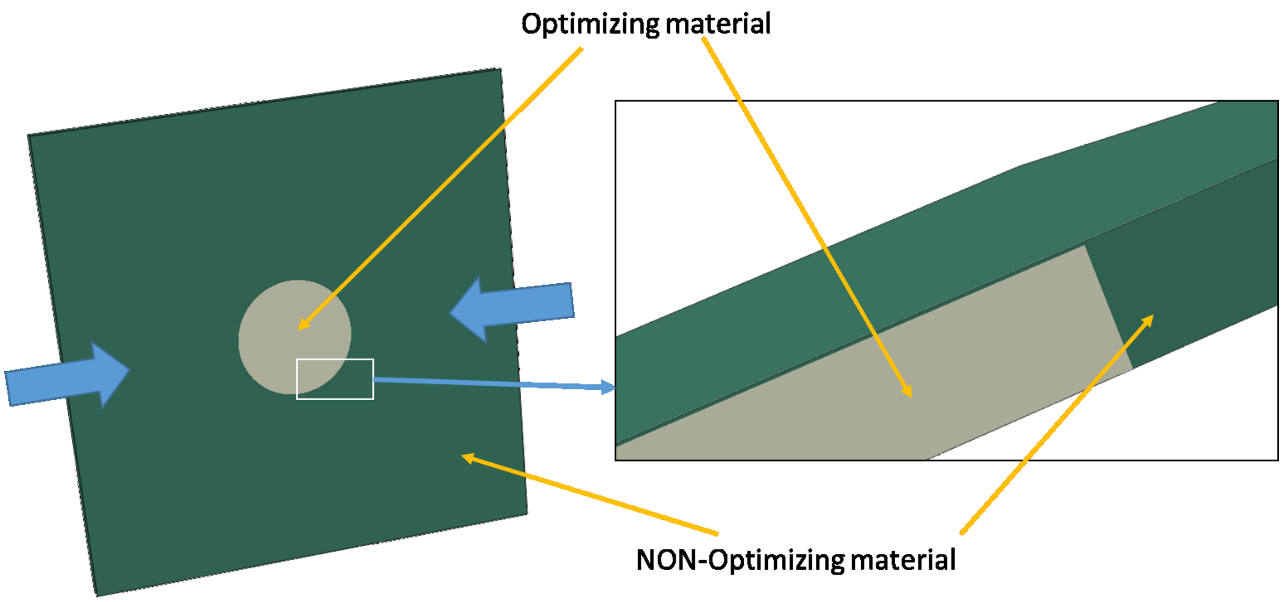

Figure 3. Problem statement scheme

Model has two materials. First one represents optimizing volume, and second one has no influence from damage variation. Nonlinear geometry changes during deformations were taken into account. Material properties used in the analysis are shown in Table 1 and 2.

Table 1 Mechanical properties [16]

E_{11} (GPa)	E_{22}(GPa)	G_{12}(GPa)	ν_{12}	ν_{23}
126	11	6.6	0.28	0.4

Table 2 Strength properties [16]

X_t(MPa)	X_c(MPa)	Y_t(MPa)	Y_c(MPa)	S_{12}(MPa)
1950	1480	48	200	79

Having done few program runs it was found, that the algorithm tries to spend all energy to the most imperfect elements. This led to idea to restrict minimum damage value to 0.5 what looks reasonable for physical meaning. Thus, in this study further models have a constraint for damage parameter:

$$0.5 < \psi \leq 1$$

Using new restriction, after 20 iterations damage has been distributed by program only into ±45 layers and completely removed from layers with 0° and 90° degree (Fig.4).

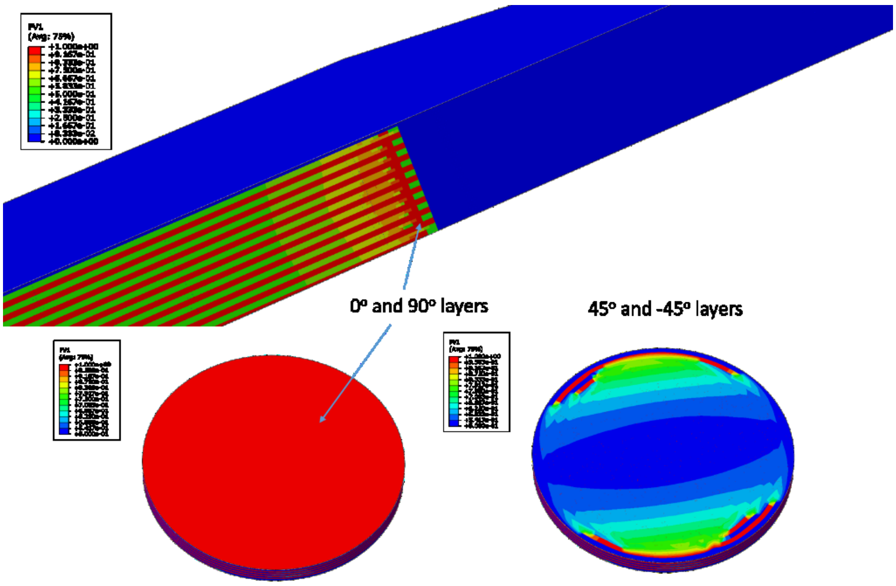

Figure 4. Damage parameter distribution

The same result was obtained for values 10, 20, 40 and 60 Joules spent on damage energy. Thus, we can state that for pure damage defect the worst case for uniaxial compression load is the reduction of matrix stiffness in ±45° layers.

5. Conclusions

The algorithm to estimate residual strength of the composite part subjected to the low velocity impact was performed. The advantage is that the approach avoids direct modelling of the impact process. The core idea of the method is the search of the worst damage distribution inside the area of the material affected by impact stresses. It was shown that the problem is identical to the topology optimization one but with opposite purpose to minimize stiffness of the structure. Example with pure damage was analyzed and result showed that for compression load degradation of ±45° layers is the most critical case. The corresponding damage parameter distribution was shown. The proposed modular formulation of the performed approach lets us to take into account more knowledge about defects from experimental statistics and reduce conservatism systematically, and eventually build a perfect BVID defect for design and development purposes in structural engineering.

6. Acknowledgement
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References
[1] Composite Materials Handbook – 17 CMH-17-3G Volume 3 2012
[2] AC 20-107B - Composite Aircraft Structure 2009
[3] Abrate S. Impact on composite structures. Aeronaut J 1998;108:541–63.
[4] Richardson M.O.W., Wisheart M.J. Review of low-velocity impact properties of composite materials. Compos Part A Appl Sci Manuf 1996; 27:1123-1131
[5] Seltzer R, González C, Muñoz R, Llorca J, Blanco-Varela T. X-ray microtomography analysis of the damage micromechanisms in 3D woven composites under low-velocity impact. Compos Part A Appl Sci Manuf 2013;45:49–60.
[6] Rivallant S, Bouvet C, Abi Abdallah E, Broll B, Barrau JJ. Experimental analysis of CFRP laminates subjected to compression after impact: The role of impact-induced cracks in failure. Compos Struct 2014;111:147–57.
[7] González E V., Maimí P, Camanho PP, Turon A, Mayugo JA. Simulation of drop-weight impact and compression after impact tests on composite laminates. Compos Struct 2012;94:3364–78.
[8] Menna C, Asprone D, Caprino G, Lopresto V, Prota A. Numerical simulation of impact tests on GFRP composite laminates. Int J Impact Eng 2011;38:677–85.
[9] Elias A, Laurin F, Kaminski M, Gornet L. Experimental and numerical investigations of low energy/velocity impact damage generated in 3D woven composite with polymer matrix. Compos Struct 2017;159:228–39.
[10] Burlayenko VN, Sadowski T. A numerical study of the dynamic response of sandwich plates initially damaged by low-velocity impact. Comput Mater Sci 2012;52:212–6.
[11] Ullah H, Harland AR, Lucas T, Price D, Silberschmidt V V. Finite-element modelling of bending of CFRP laminates : Multiple delaminations. Comput Mater Sci 2012;52:147–56.
[12] Rivallant S, Bouvet C, Hongkarnjanakul N. Failure analysis of CFRP laminates subjected to compression after impact: FE simulation using discrete interface elements. Compos Part A Appl Sci Manuf 2013;55:83–93.
[13] Hongkarnjanakul N, Bouvet C, Rivallant S. Validation of low velocity impact modelling on different stacking sequences of CFRP laminates and influence of fibre failure. Compos Struct 2013;106:549–59.
[14] Bouvet C, Rivallant S, Barrau JJ. Low velocity impact modeling in composite laminates capturing permanent indentation. Compos Sci Technol 2012;72:1977–88.
[15] Yang L, Wu Z, Gao D, Liu X. Microscopic damage mechanisms of fibre reinforced composite laminates subjected to low velocity impact. Comput Mater Sci 2016;111:148–56.
[16] Fedulov B. N., Fedorenko A. N., Kantor M. M. and Lomakin E. V.. Failure analysis of laminated composites based on degradation parameters. Meccanica, 2017;53:359–372.
[17] Fedulov B. N., Fedorenko A.N., Safonov A.A. and Lomakin E.V., Nonlinear shear behavior and failure of composite materials under plane stress conditions. Acta Mechanica. 2017 Jun 1;228(6):2033-40.
[18] Bendsoe, Martin Philip, and Ole Sigmund. Topology optimization: theory, methods, and applications. Springer Science & Business Media, 2013.