NASA/TM–2017-219641

# Influence of Shear Stiffness Degradation on Crack paths in Uni-directional Composite Laminates

*Arunkumar Satyanarayana & Philip B. Bogert*
*Langley Research Center, Hampton, Virginia*

---

July 2017

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM–2017-219641

# Influence of Shear Stiffness Degradation on Crack paths in Uni-directional Composite Laminates

*Arunkumar Satyanarayana and Philip B. Bogert*
*Langley Research Center, Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

July 2017

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

# Abstract

*Influence of shear stiffness degradation in an element, due to damage, on crack paths in uni-directional laminates has been demonstrated. A new shear stiffness degradation approach to improve crack path prediction has been developed and implemented in an ABAQUS/Explicit frame work using VUMAT. Three progressive failure analysis models, built-in ABAQUS$^{TM}$, original COmplete STress Reduction (COSTR) and the modified COSTR damage models have been utilized in this study to simulate crack paths in five uni-directional notched laminates, 15$^o$, 30$^o$, 45$^o$, 60$^o$ and 75$^o$ under uniaxial tension load. Results such as crack paths and load vs. edge displacement curves are documented in this report. Modified COSTR damage model shows better accuracy in predicting crack paths in all the uni-directional laminates compared to the ABAQUS$^{TM}$ and the original COSTR damage models.*

## 1.0 Introduction

The use of composite materials in structural components has increased significantly in the last few years due to their inherent qualities of lower density and higher strength. Major portions of Boeing's 787 are made out of composite laminates. Also, the auto industry is rigorously working to introduce composite components in cars to reduce weight and increase fuel efficiency. In order to efficiently design structural components made from composite materials, one needs to understand their behavior thoroughly under all the design load conditions.

In this regard, progressive failure/damage analysis (PFA/PDA) methods have been developed and are still being developed by researchers to simulate failure loads and crack paths in composite structures. Most of these methods use failure criteria to identify damage initiation at an integration point in an element, accompanied by a material stiffness or stress degradation approach based on damage modes to simulate the effects of material failure. These methods have proven to be partially successful in simulating failure loads or failure stress of composite components under certain loading conditions and structural configurations by many researchers [1-11]. Using PFA methods, full scale fuselage panels and a complete barrel with a 2 bay notch was analyzed to understand the response of structures under tension and compression loading in ref [12]. Also, this study was performed to understand the interaction of a through thickness crack with stringers and frames. In order to simulate or predict crack path accurately, finite element orientation plays a huge role and its effect has been demonstrated in refs [13, 14] in greater detail. A rectangular or square mesh where the element edges are aligned along 0$^o$ and 90$^o$ ply orientation predicts the crack path more accurately in cross plies (0$^o$/90$^o$) than in off-axis plies (+θ$^o$/-θ$^o$) of a laminate. This drawback is attributed to improper load re-distribution that takes place after material damage. To develop a finite element model of a laminate where the meshes are aligned along the ply orientation is a daunting task that leads to larger finite element models and a computationally expensive task.

In this study, attention has been focused on understanding the influence of shear stiffness degradation in an element, due to matrix damage, on crack path in uni-directional laminates. A new shear stiffness degradation approach for off-axis plies will be developed to minimize the impact of improper load re-distribution that takes place in the damaged element, when its edges are aligned along 0$^o$/90$^o$ angles. To demonstrate this phenomenon, five uni-directional notched laminates of 15$^o$, 30$^o$, 45$^o$, 60$^o$ and 75$^o$ ply orientations are analyzed with ABAQUS$^{TM}$, the original COSTR and the new modified COSTR damage models. All five models are discretized with square or rectangular quadrilateral shell elements and analyzed with the ABAQUS$^{TM}$/Explicit solver. The results such as load vs. edge displacement and crack path in these laminates will be presented in the results section of this document.

## 2.0 Shear Stiffness Degradation Methodology

In general, PFA methodology consists of damage detection through failure criteria, followed by damage evolution through stiffness or stress degradation and crack path simulation by element deletion in the model using a stress or stain based criterion. As our objective in this study is to understand the influence of shear stiffness degradation on crack path in uni-directional laminates, the second step of the PFA methodology related to transverse and shear stiffness degradation of the built-in Abaqus model, the original COSTR [10] and modified COSTR damage models will be discussed briefly. Also, since uni-directional laminates under tension load are considered here, failure of these laminates are dominated by matrix damage rather than fiber damage. Hence axial stiffness degradation profiles will not be discussed here. However readers are encouraged to read references [15, 10] for complete understanding of built-in Abaqus and original COSTR damage models respectively. Graphical representation of transverse and shear stress law adopted in built-in Abaqus damage models is shown in figure-1[15] below.

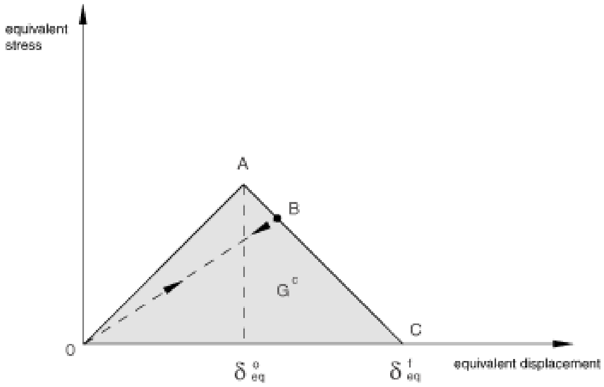


Figure-1: Transverse and Shear Stress Degradation law of built-in Abaqus damage model.

When the matrix failure criterion is satisfied due to equivalent transverse or shear stress reaching the failure limit, the corresponding stresses are gradually decreased in a linear fashion until the area under the bi-linear curves shown in figure-1 is equal to the critical fracture energy of the matrix material. However, this stress evolution law is valid when the element's characteristic length is less than or equal to 0.06 in. In case of elements whose characteristic length is greater than 0.06 in., the stresses are reduced to 0 instantaneously. In the case of the orginal COSTR damage model, transverse and shear stresses are reduced to 0 instantaneously as shown in figure-2, when the matrix failure criterion is satisfied.

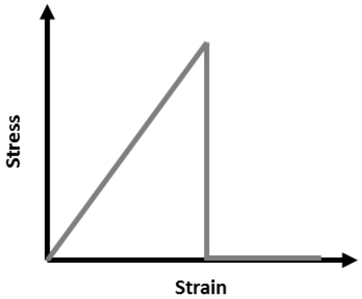


Figure-2: Transverse and Shear Stress Degradation law of original COSTR damage model.

However in the modified COSTR damage model, the transverse and shear stresses are reduced to 0 instantaneously in plies where the fibers are aligned parallel to the loading direction. In the case of plies where fibers are not parallel to the loading direction, the transverse stress is reduced to 0 instantaneously but the shear stress is reduced by the matrix volume fraction and allowed to reach max shear strength limit and maintain that level until a failure strain criterion is satisfied. The graphical representation of the stress degradation approach adopted in the modified COSTR damage model is shown in figure-3.

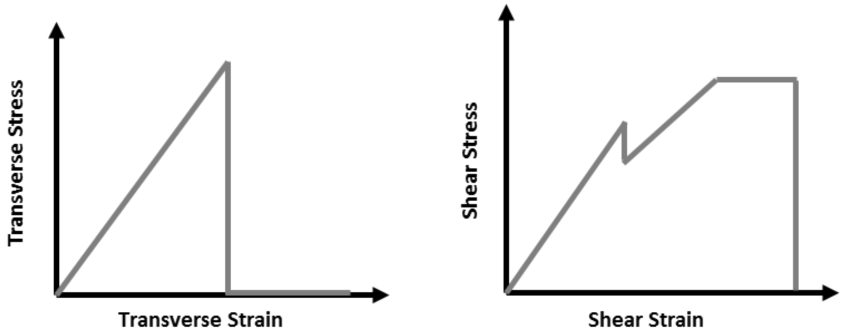
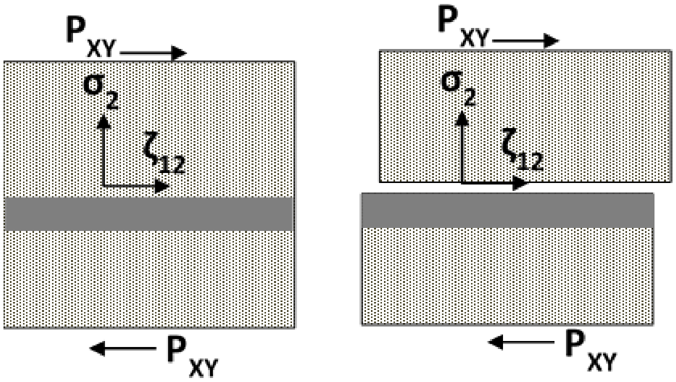
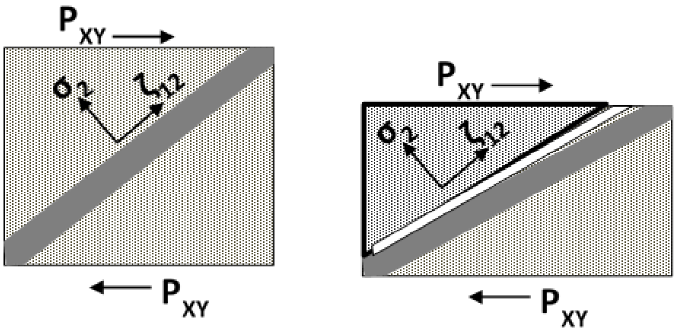


Figure-3: Transverse and Shear Stress Degradation law of modified COSTR damage model.

The intent for degrading shear stress as shown in figure-3 stems from the reasoning that even when matrix damage occurs at a material point, the shear stiffness of the element is not completely lost due to the fibers still being intact.



a. Load $P_{XY}$ Parallel to Fiber (Off-Axis Plies)



b. Load $P_{XY}$ Inclined to Fiber (Off-Axis Plies)

Figure-4: Hypothesis for Shear Stiffness Degradation Approach.

For example consider an element where the fiber is parallel to the load Pxy as show in figure-4a. Considering the loading direction, this element fails due to shear stress reaching the strength limit and the fiber does not offer any stiffness in the shear direction. Hence the shear stress is reduced to 0 instantaneously in plies where fibers are parallel to the loading direction. Similarly looking at the element in figure-4b, one can observe that, the fiber offers some resistance to shear deformation along the loading direction even after the matrix is damaged due to transverse or shear stresses reaching their strength limit. Hence the shear stiffness contribution due to matrix is removed by reducing shear stiffness by the matrix volume fraction (Vm) of the lamina. This reasoning is currently applied to uni-axial loading but may be easily modified and verified latter for multi-axial loading.

Another modification made to the modified COSTR damage model is in the matrix damage detection criterion. Along with the Hashin-Rotem failure criterion for the matrix material [10], the strain in the fiber direction should be positive under tension and negative under compression for a material point to be considered as damaged. This stress and strain criteria along with above mentioned shear stiffness degradation approach is found to predict cracks in uni-direction laminates with better accuracy even when the element edges are not aligned along the fiber direction.

## 3.0 Description of a Uni-directional Laminate Considered in Verification of Modified COSTR Damage model

Geometric and finite element mesh description of the notched uni-directional laminate is shown in figure-5. Fiber orientations of 15°, 30°, 45°, 60° and 75° were chosen to show the range of applicability of the hypothesis. The notch is 0.125 in. wide and 0.5 in. long. The laminates' material system is T800/3900-2 and its properties and strengths are presented in table-1. The left edge of the specimen is fixed in all degrees of freedom (DOF). The right edge is fixed in all DOF except the horizontal (X) direction. An axial displacement of 0.05 in. along X direction was applied to the right edge of the coupon. The S4R shell element size is approximately 0.06 in. by 0.06 in. PFA of the laminates were performed using the Abaqus/Explicit solver.

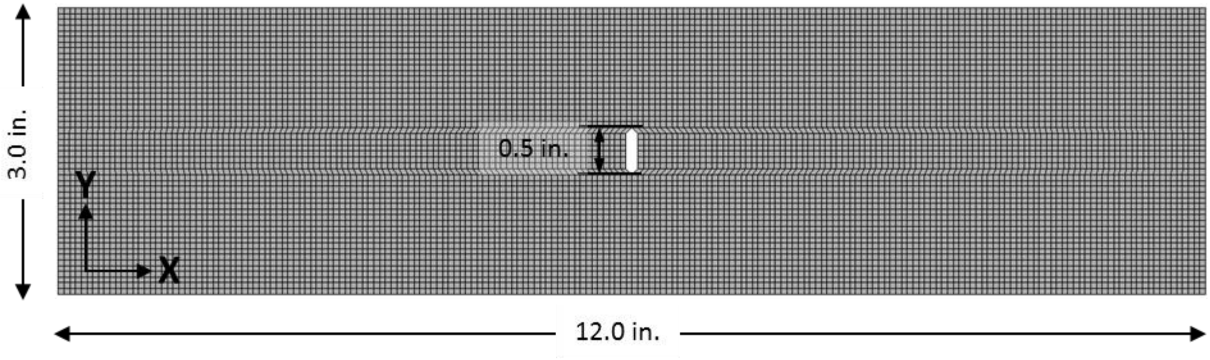


Figure-5: Geometric Description & Finite Element Mesh of Notched Uni-directional Laminate.

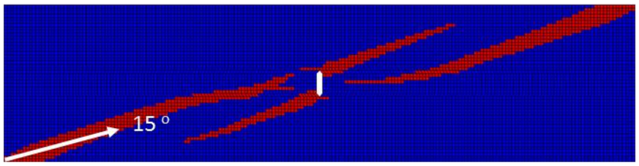
Table 1: Properties and Strengths of T800/3900-2 Material System.

| **Properties** | **Values** |
|---|---|
| $E_1$ (Msi) | 23.2 |
| $E_2$ (Msi) | 1.3 |
| $G_{12}$ (Msi) | 0.9 |
| Nue12 | 0.28 |
| $X_T$ (Ksi) | 412.0 |
| $X_C$ (Ksi) | 225.0 |
| $Y_T$ (Ksi) | 8.72 |
| $Y_C$ (Ksi) | 24.3 |
| $S_{XY}$ (Ksi) | 13.76 |
| $Gc^{FT}$ (in-lbs/in$^2$) | 232.5 |
| $Gc^{FC}$ (in-lbs/in$^2$) | 303.5 |
| $Gc^{MT}$ (in-lbs/in$^2$) | 1.58 |
| $Gc^{MC}$ (in-lbs/in$^2$) | 4.49 |

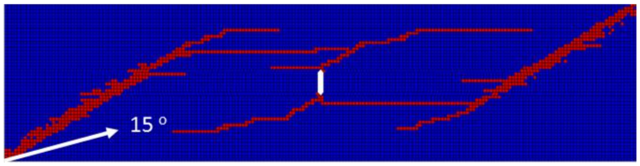
## 4.0 Progressive Failure Analysis Results

Results such as crack paths obtained from progressive failure analysis of uni-directional laminates are presented in figures 6-10. In figure-6 one can notice that the crack paths (red colored elements) predicted by the modified COSTR damage model are inclined very closely along the $15^o$ fiber angle. The Abaqus built-in damage model predicts crack paths also close to $15^o$ angle. However the original COSTR damage model predicts crack paths along a $45^o$ angle. For the $15^o$ uni-directional laminate, due to its geometric configuration and fiber orientation, the stress concentration is higher at bottom left hand and top right hand corners than at the notch tips. Hence the cracks initiate and propagate from these two corners firsts and then from the notch tips. A similar phenomenon was also noticed in the $30^o$ uni-directional laminate as shown in figure-7. Even in this laminate, the stress concentration is higher at bottom left hand and top right hand corners and hence the cracks initiates from these two corners first as predicted by the modified COSTR damage model. The crack originating from the right hand corner is more closely aligned along the $30^o$ angle than the one that originated from the left hand corner. In the case of crack paths predicted by built-in

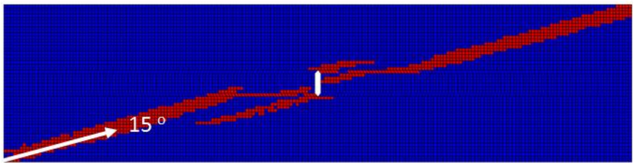
Abaqus and the original COSTR damage model, the crack paths are not as well aligned along the 30° angle but the damage initiation points are similar to the modified COSTR damage model.



**Built-in Abaqus Damage Model**

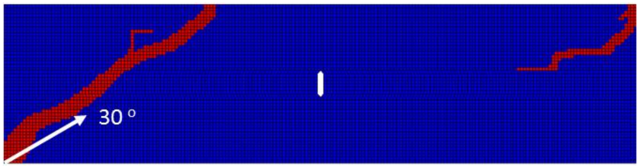


**Original COSTR Damage Model**

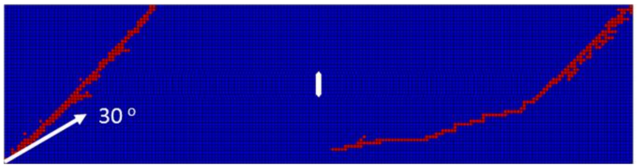


**Modified COSTR Damage Model**

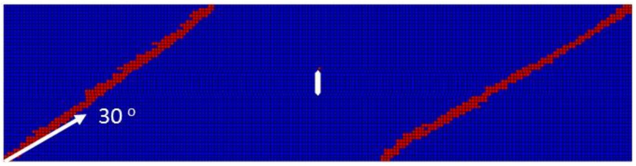
Figure-6: Crack Paths in a Notched 15° Uni-directional Laminate.



**Built-in Abaqus Damage Model**

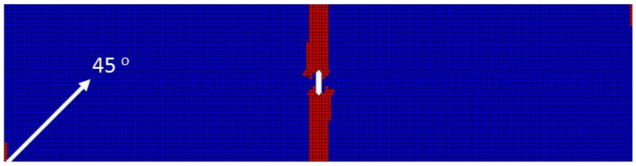


**Original COSTR Damage Model**

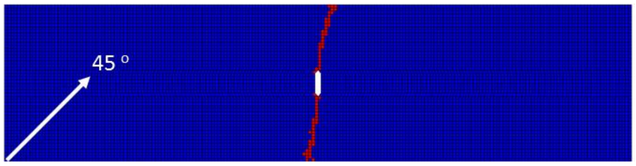


**Modified COSTR Damage Model**

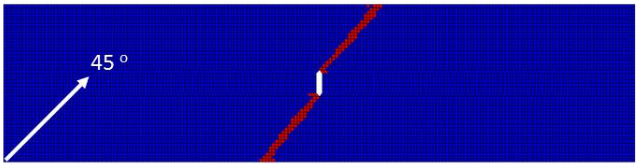
Figure-7: Crack Paths in a Notched 30° Uni-directional Laminate.



**Built-in Abaqus Damage Model**

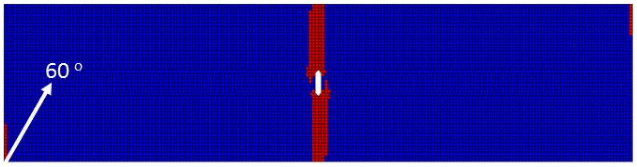


**Original COSTR Damage Model**

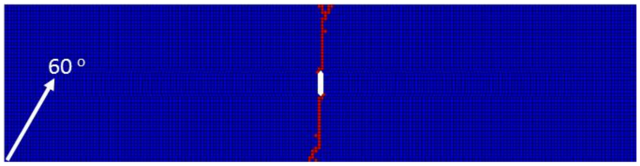


**Modified COSTR Damage Model**

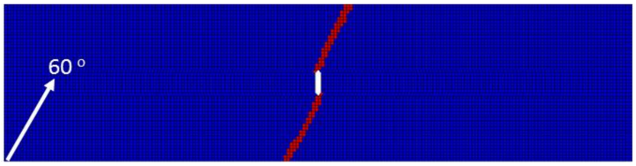
Figure-8: Crack Paths in a Notched 45° Uni-directional Laminate.



**Built-in Abaqus Damage Model**

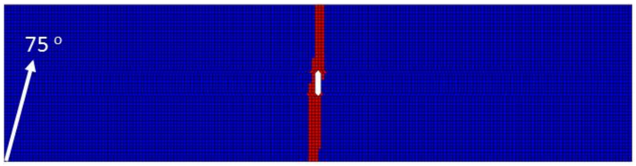


**Original COSTR Damage Model**

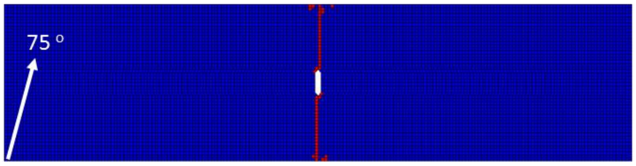


**Modified COSTR Damage Model**

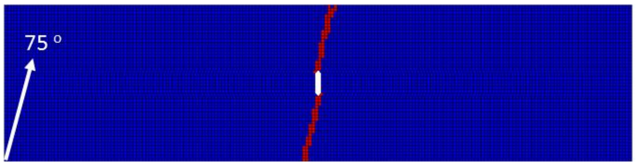
Figure-9: Crack Paths in a Notched 60° Uni-directional Laminate.



**Built-in Abaqus Damage Model**



**Original COSTR Damage Model**

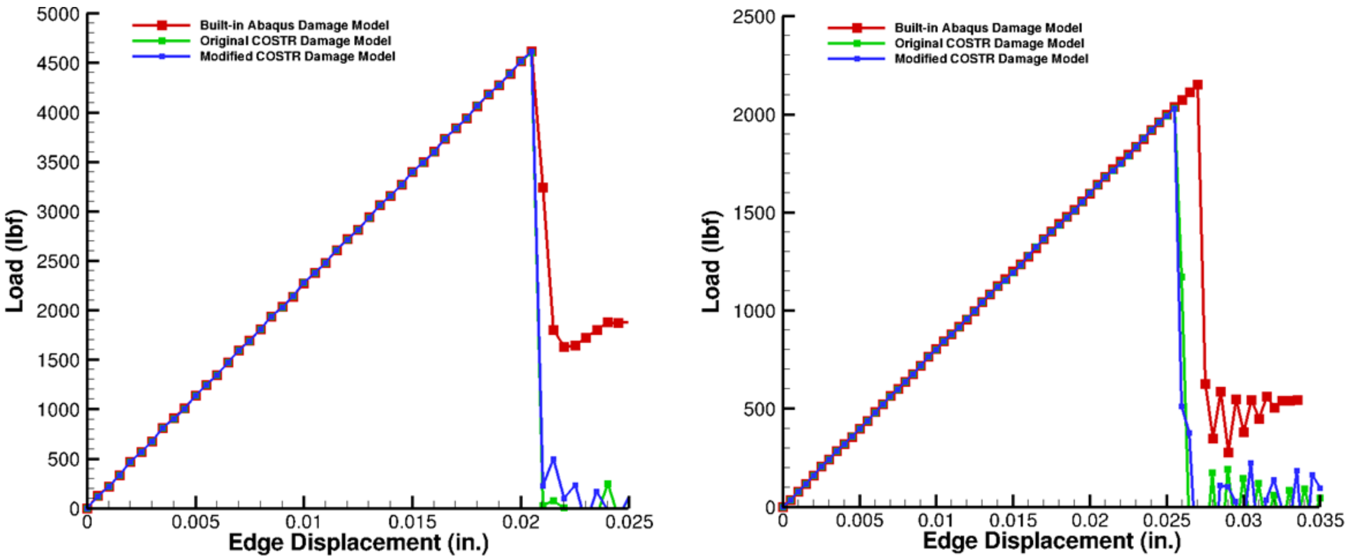


**Modified COSTR Damage Model**

Figure-10: Crack Paths in a Notched 75$^{o}$ Uni-directional Laminate.

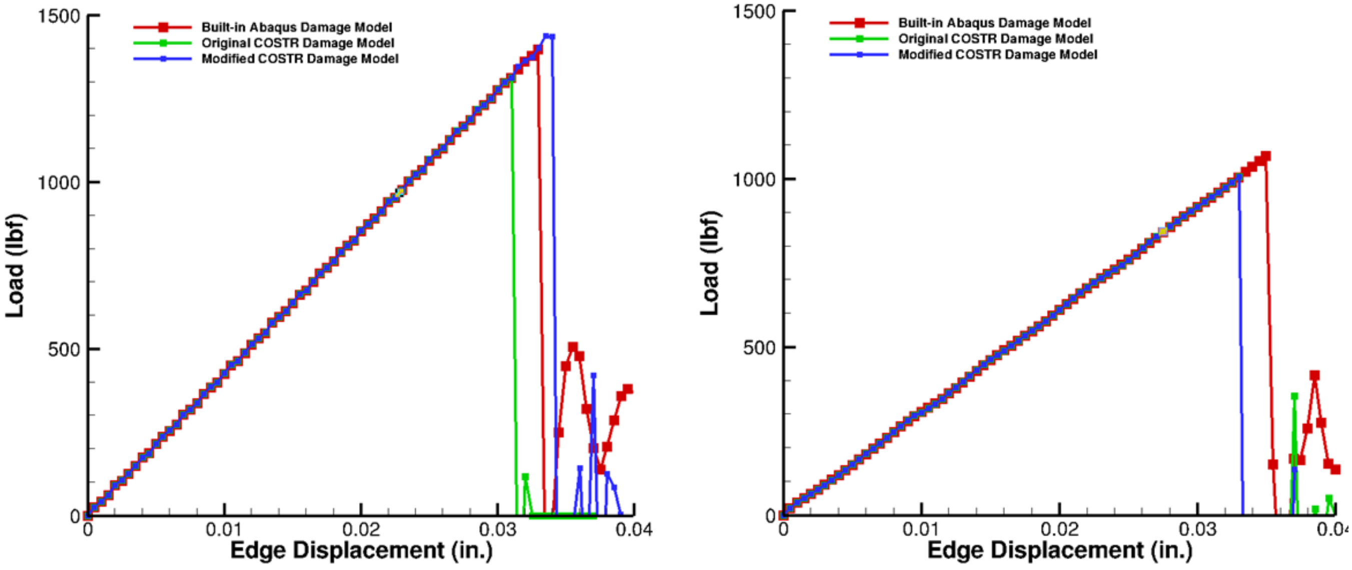
In figures 8-10, the crack paths predictions in the 45$^{o}$, 60$^{o}$ and 75$^{o}$ laminates are presented respectively. The crack path orientations in these (45$^{o}$, 60$^{o}$ and 75$^{o}$) laminates as predicted by built-in Abaqus damage model are perpendicular to the loading direction where the crack paths are self-similar in nature originating from the notch tips. Similar trend was noticed in the crack path orientation predictions by original COSTR damage model except that the crack paths are very well defined and tend to propagate at an angle as they reached the free longitudinal edges. However the modified COSTR damage model predicts crack paths more aligned along the fiber direction.

Even though the intention of this study was to develop and verify a shear stiffness degradation procedure that predicts crack paths aligned along the fiber direction in a uni-direction laminates, load vs. edge displacement curves for all of the above 5 laminates are presented in figures 11 for the sake of completeness. The failure load predicted by all 3 damage models is same for a 15$^{o}$ uni-directional laminate as presented in figure 11a. In case of the built-in Abaqus damage model, the load drops to around 1500 lbf and oscillates around this load level. This phenomenon could be due to artificial damping energy applied by the solver to avoid rapid deformation associated with the rotation of a node related to a failed element or to a rapid reduction in stiffness. However the original and modified COSTR damage models predict the load to drop and oscillate around 0 lbf load level. Also, similar phenomenon was noticed in the 30$^{o}$ laminate except that the load dropped and oscillated around 500 lbf load level as predicted by the built-in Abaqus damage model as presented in figure-11b. For this laminate, the peak load predictions by the original and modified COSTR damage models are slightly lower than the load predicted by built-in Abaqus damage model. In case of the 45$^{o}$, 60$^{o}$ and 75$^{o}$ uni-directional laminates, the peak load predictions by all the three damage models are within 10% of each other. For these laminates, the load drops to zero lbf and oscillates around this load level as shown in figures11c-e. For the 75$^{o}$ laminate, the drilling degree of freedom (dof) was fixed for all the nodes in the finite element models that were analyzed using the modified and original COSTR damage models. This was done to prevent, excessive rotation with respect to the normal direction of the plate, in one of the nodes of a failed element.



a. 15° Uni-directional Laminate

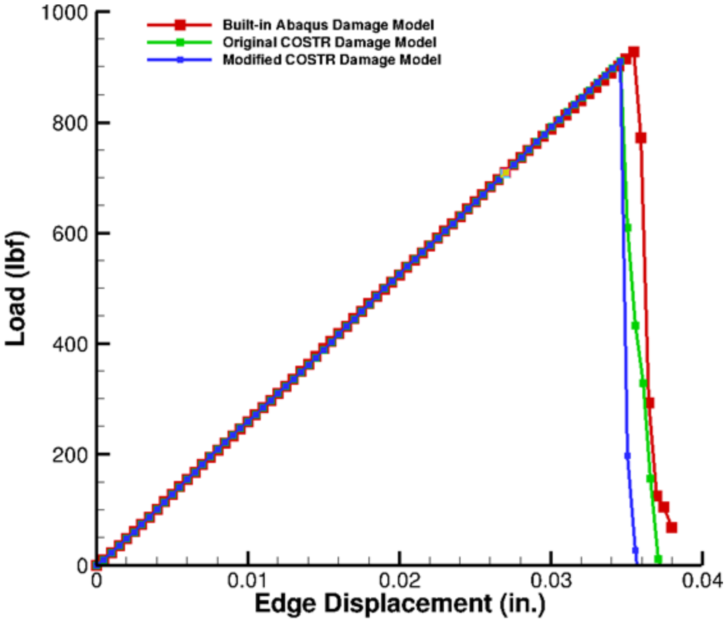
b. 30° Uni-directional Laminate



c. 45° Uni-directional Laminate

d. 60° Uni-directional Laminate

Figure-11: Load vs. Edge Displacement of Notched Uni-directional Laminate.



e. 75° Uni-directional Laminate

Figure-11: Load vs. Edge Displacement of Notched Uni-directional Laminate - Con't.

## 5. Conclusion

Progressive failure analyses of 5 uni-directional laminates with the built-in Abaqus, original and modified COSTR damage models were performed using the Abaqus/Explicit solver. Results such as crack path predictions and load vs. edge displacement curves, predicted by all the three models are presented. The new shear stress stiffness degradation procedure coupled with a slightly modified fiber strain criterion, implemented in modified COSTR damage model, seems to predict crack paths that are aligned along the fiber orientation angle for all 5 laminates. However with the built-in Abaqus and original damage models, the crack path predictions are away from the fiber orientation angles. The built-in Abaqus damage model predicts crack path close to the fiber orientation angle in case of a 15° laminate. Verification of the new shear stiffness degradation procedure was performed on uni-directional laminates under a uni-axial tension loading condition. However the influence of the shear stiffness degradation procedure in a failed element, on crack path predictions, when the element edges are not aligned along the fiber direction is demonstrated adequately using the built-in Abaqus, original COSTR and modified COSTR damage models. The modified COSTR damage model, minimizes the extent of improper load distribution that occurs in a failed element due to the matrix damage mode to a great extent and hence simulates crack paths which are aligned along the fiber orientation angle.

# References

1. Chang, F. K.; and Chang, K. Y.: "A Progressive Damage Model for Laminated Composites Containing Stress Concentrations." *Journal of Composite Materials*, Vol. 21, September 1987.

2. Coats, T.W., and Harris, C.E., "A Progressive Damage Methodology for Residual Strength Predictions of Notched Composite Panels," NASA/ TM-1988-207646.

3. Chang, F. K.; and Lessard, L.: "Damage Tolerance of Laminated Composites Containing an Open Hole and Subjected to Compressive Loadings: Part I – Analysis." *Journal of Composite Materials*, Vol. 25, January 1991.

4. Tan, S.: "A Progressive Failure Model for Composite Laminates Containing Openings." *Journal of Composite Materials*, Vol. 25, May 1991.

5. Qing, X; Chang, F. K.; and Starnes, J.: "Damage Tolerance of Notched Composite Laminates with Reinforcing Strips." *Journal of Composite Materials*, Vol. 37, No. 2, 2003.

6. Ambur, D. R.; Jaunky, N.; and Dávila, C. G.: "Progressive Failure of Composites' Laminates using LaRC02 Failure Criteria." *Proceedings of the 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, April 2004, AIAA 2004-1595-CP.

7. Bogert, B. P.; Satyanarayana, A.; and Chunchu, B. P.: "Comparison of Damage Path Predictions for Composite Laminates by Explicit and Standard Finite Element Analysis Tools," *Proceedings of the 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Newport, Rhode Island, May 2006, AIAA 2006-1750.

8. Camanho, P. P.; Maimi, P.; and Dávila, C. G.: "Prediction of Size Effects in Notched Laminates Using Continuum Damage Mechanics." *Composite Science and Technology 67*, 2007, pp. 2715-2727.

9. Satyanarayana, A., Przekop, A., "Predicting Failure Progression and Failure Loads in Composite Open-hole Tension Coupons," NASA/CR-2010-216700.

10. Satyanarayana, A., Bogert, P., Karayev, Z. K., Nordman, S. P., Hamid, "Influence of Finite Element Size in Residual Strength Prediction of Composite Structures," *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Honolulu, Hawaii, April 2012, AIAA-2012-1619.

11. Pineda, J. E., Waas, M. A., "A Thermodynamically-Based Mesh Objective Work Potential Theory for Predicting Intralaminar Progressive Damage and Failure in Fiber-Reinforced Laminates," *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Honolulu, Hawaii, April 2012, AIAA-2012-1612.

12. Gould, K., Satyanarayana, A., Bogert, P., "Progressive Damage Analysis Tools Employed in the Investigation of Panel versus Fuselage Response Behavior," *Proceedings of the American Society for Composites 31st Technical Conference and ASTM Committee D30 Meeting*, Williamsburg, Virginia, September 2016.

13. Song, K., Li, Y., and Rose, C. A., "Continuum Damage Mechanics Models fro the Analysis of Progressive Failure in Open-Hole Tension Laminates," *Proceedings of the 52rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Denver, Colorado, April 2011, AIAA-2011-1861.

14. Dalgarno, R., and Robbins, D., "Fiber-Aligned, Discrete-Layer Modeling Aproaches for Progressive Failure Simulation of Open Hole Composite Panels," *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Honolulu, Hawaii, April 2012, AIAA-2012-1695.

15. ©Dassault Systems, 2013. "Damage and Failure for Fiber Reinforced Composites: Overview," in *ABAQUS Analysis User's Guide*, Version 6.13, Section 24.3

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

**1. REPORT DATE** *(DD-MM-YYYY)*
01-07-2017

**2. REPORT TYPE**
Technical Memorandum

**3. DATES COVERED** *(From - To)*

**4. TITLE AND SUBTITLE**
Influence of Shear Stiffness Degradation on Crack paths in Uni-directional Composite Laminates

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Satyanarayana, Arunkumar; Bogert Phil B.

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**
826611.04.07.01

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

NASA Langley Research Center
Hampton, VA 23681-2199

**8. PERFORMING ORGANIZATION REPORT NUMBER**
L-20823

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSOR/MONITOR'S ACRONYM(S)**
NASA

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
NASA-TM-2017-219641

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

Unclassified
Subject Category 24
Availability: NASA STI Program (757) 864-9658

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Influence of shear stiffness degradation in an element, due to damage, on crack paths in uni-directional laminates has been demonstrated. A new shear stiffness degradation approach to improve crack path prediction has been developed and implemented in an BAQUS/Explicit frame work using VUMAT. Three progressive failure analysis models, built-in ABAQUSTM, original COmplete STress Reduction (COSTR) and the modified COSTR damage models have been utilized in this study to simulate crack paths in five uni-directional notched laminates, 15o, 30o, 45o, 60o and 75o under uniaxial tension load. Results such as crack paths and load vs. edge displacement curves are documented in this report. Modified COSTR damage model shows better accuracy in predicting crack paths in all the uni-directional laminates compared to the ABAQUSTM and the original COSTR damage models.

**15. SUBJECT TERMS**

ABAQUS; Complete stress reduction; Laminates; Uni-directional

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | STI Help Desk (email: help@sti.nasa.gov) |
| U | U | U | UU | 16 | **19b. TELEPHONE NUMBER** *(Include area code)*<br>(757) 864-9658 |