Effects of Out-of-Plane Ply Wrinkles on the Pre and Post-buckling Behavior of Carbon Fiber Reinforced Composites Using Finite Element Analysis

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Introduction

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Introduction

Composites and their applications:

- ✓ Aerospace
- ✓ Automotive
- ✓ Civil

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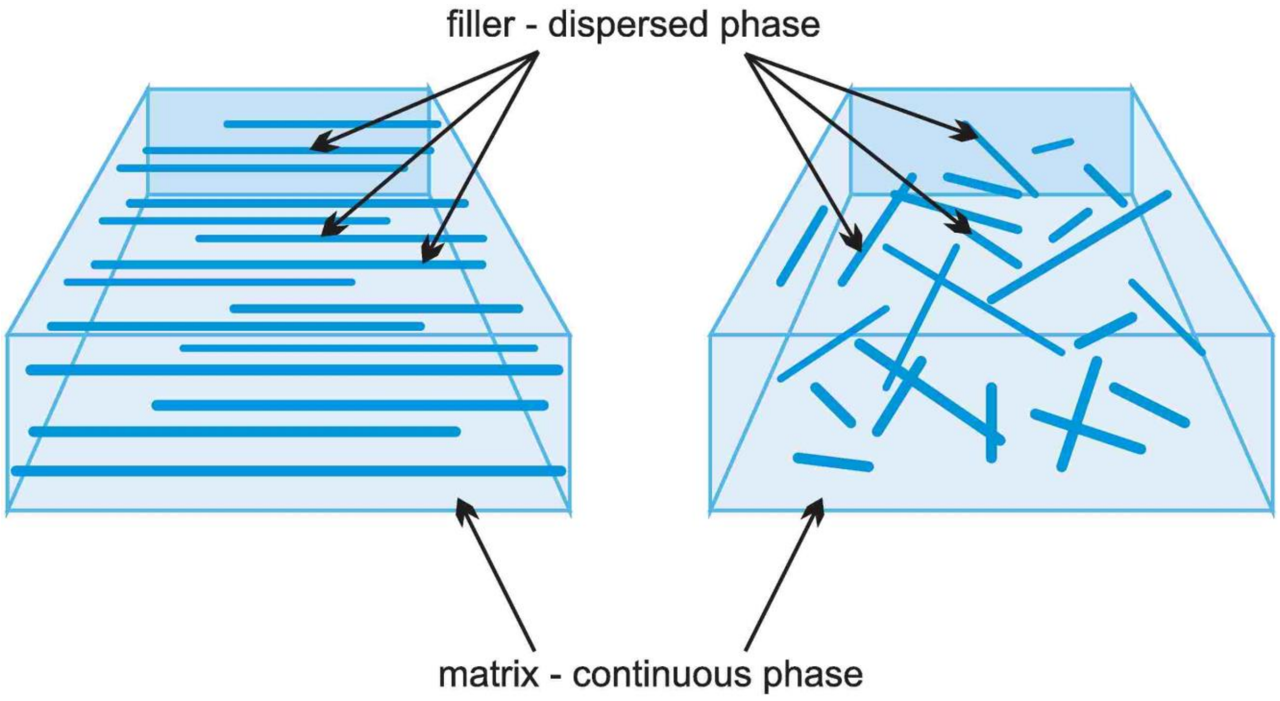
Introduction

Fiber reinforced composites:

✓ Polymer Matrix Composites

✓ Ceramic Matrix Composites

✓ Metal Matrix Composites



Introduction

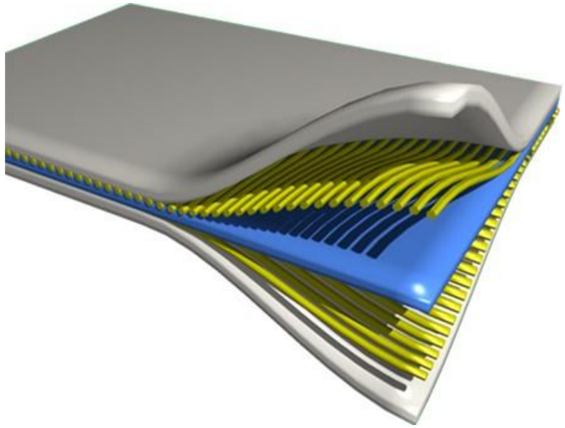
Carbon Fiber Reinforced Polymers (CFRP):

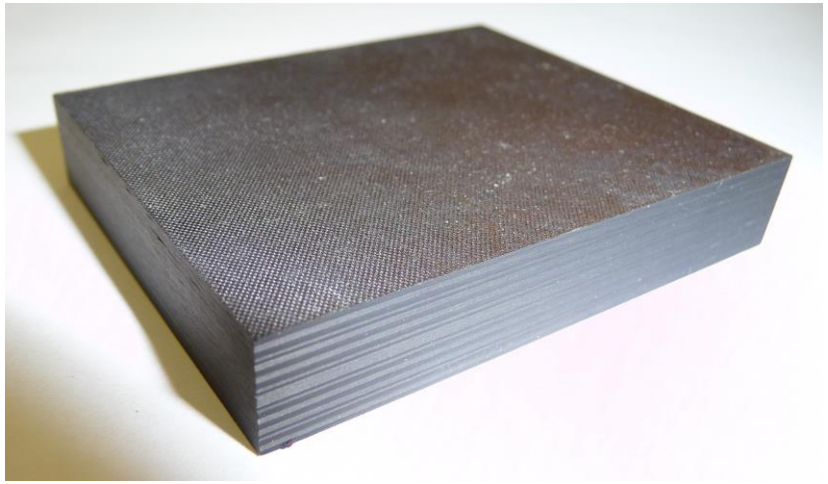
✓ Advantages:

- High Strength and Stiffness to Weight Ratio
- Attractive Appearance (in sport cars)

✓ Disadvantages:

- High Cost
- Low Electrical Conductivity
- Low Thermal Conductivity





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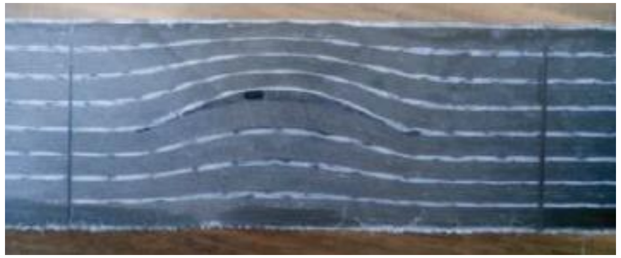
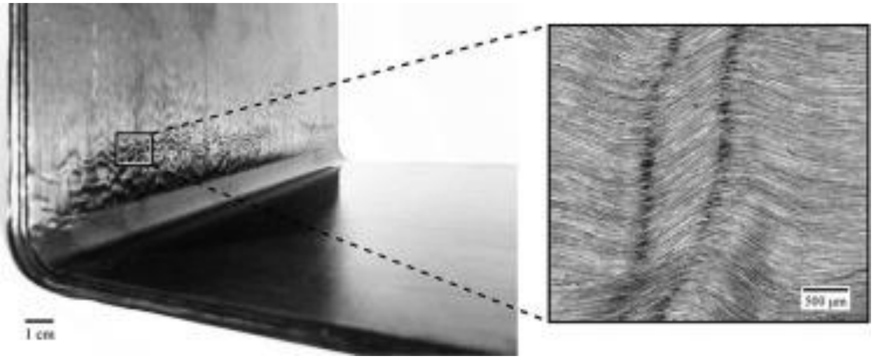
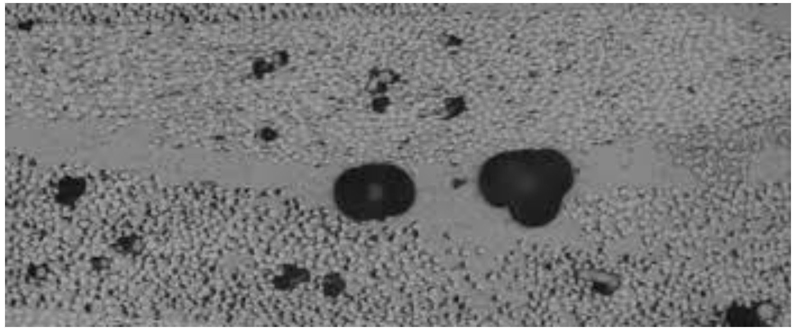
Introduction

Defects in composites:

- ✓ Delaminations
- ✓ In-plane fiber waviness
- ✓ Out-of-plane ply wrinkles
- ✓ Foreign Object Damages (FODs)
- ✓ Porosity (Holes)

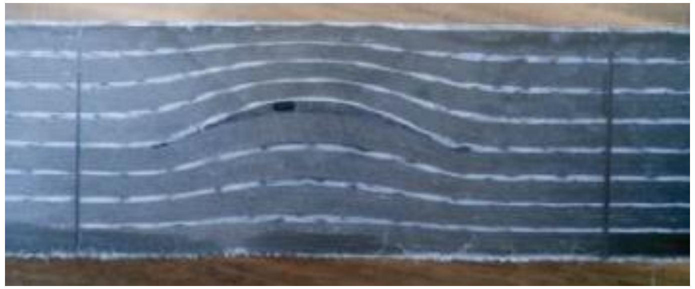


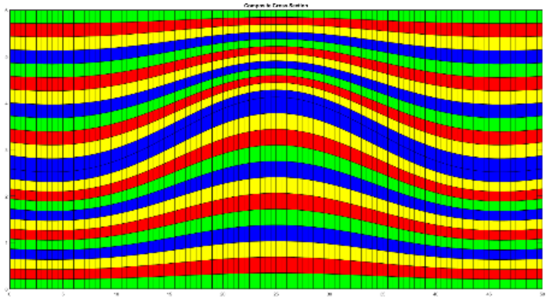


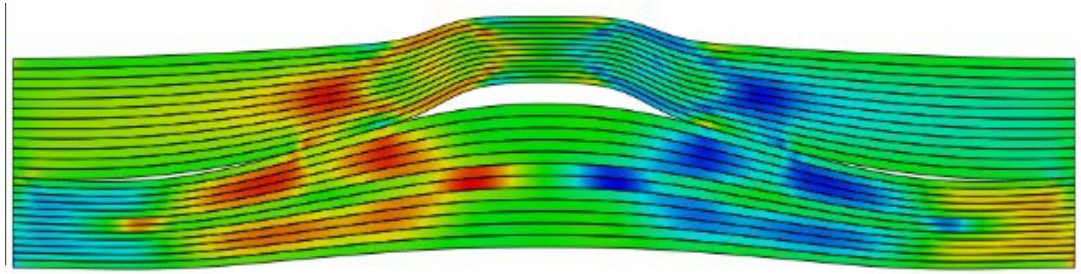


Goals

- Developing an automated approach for analyzing wrinkle problems
- Studying the effects of wrinkles on the postbuckling behavior of composites







Literature Review

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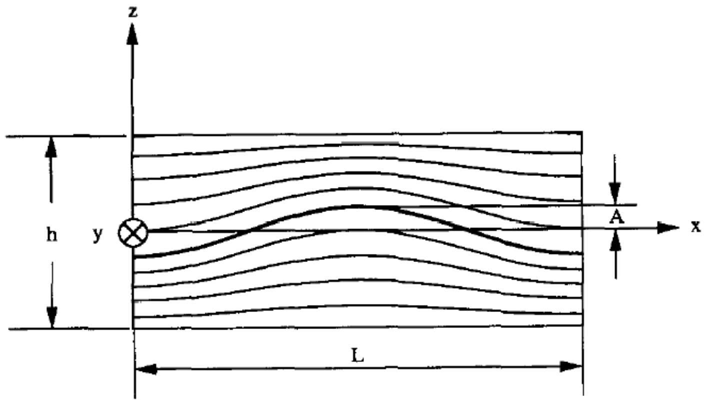
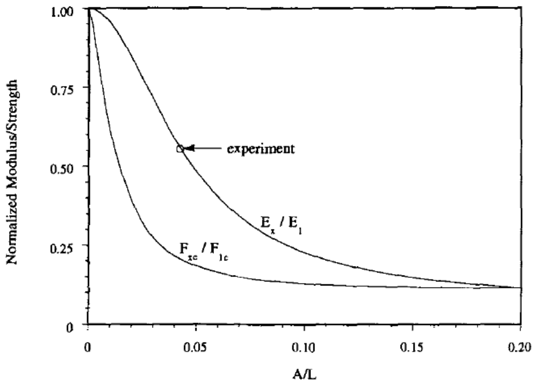
Literature Review

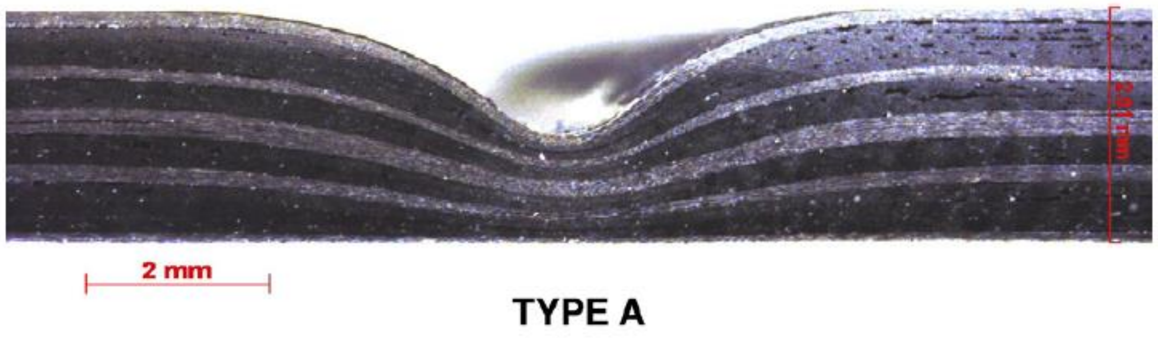
- Hsiao et al. [1,2] used analytical classical laminate theory to find a way for obtaining the effective properties such as Young's modulus and Poisson's ratio. They verified their results by fabricating unidirectional prepreg composites and performing proper mechanical tests.

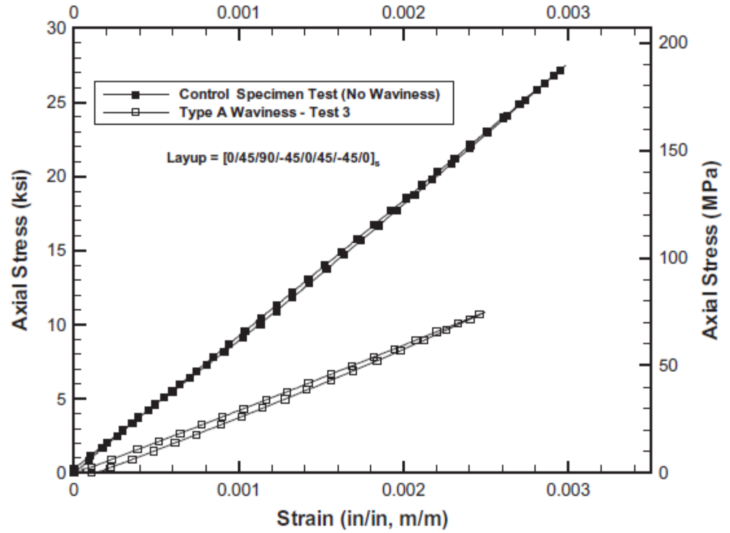




Literature Review

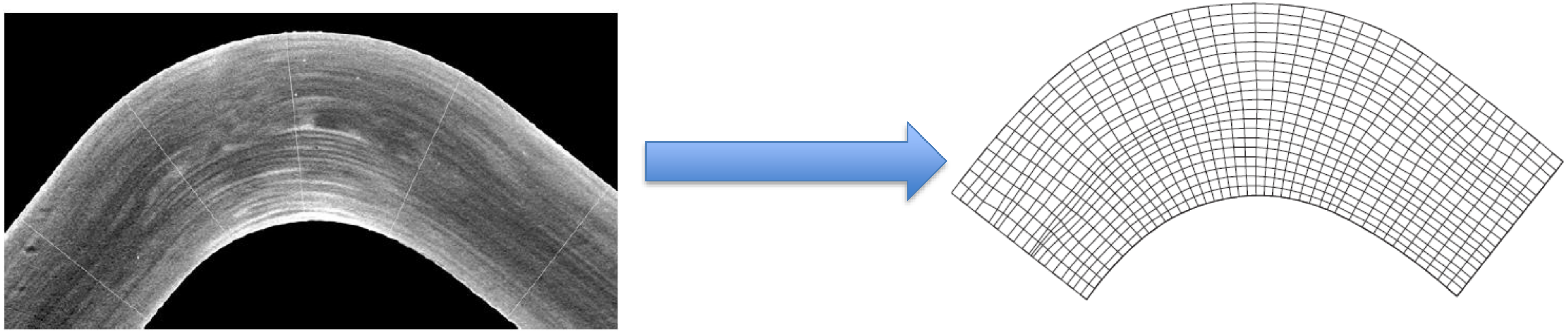
- El-Hajar [3] study presents the results of analytical and experimental efforts performed on the tension behavior of a common aerospace grade carbon fiber/epoxy material system containing out-of-plane fiber waviness. Unidirectional and multidirectional laminates were examined with different thicknesses containing three levels of waviness.





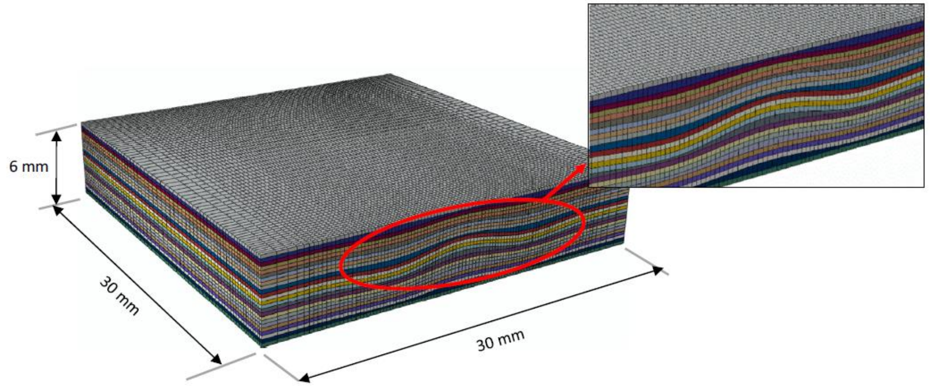
Literature Review

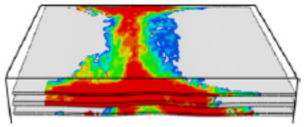
- A method for automated generation of finite element meshes for unidirectional composites with waviness defects is proposed by Nikishkov et al [4]. Images used as input for mesh generation are recorded with X-ray computed micro-tomography.

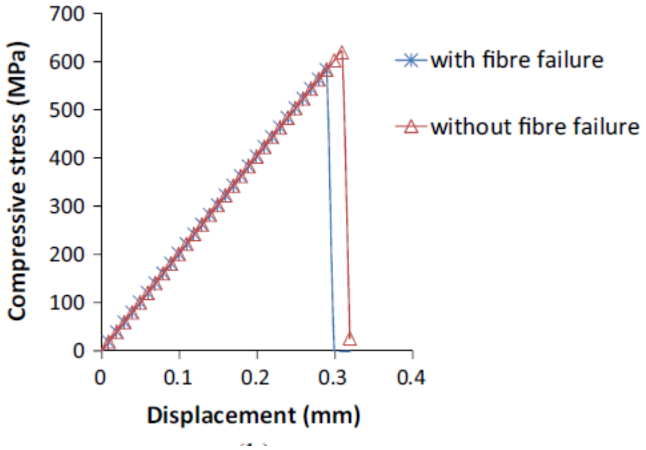


Literature Review

- An experimental and numerical study has been carried out by Hallet et al. [5] to understand and predict the compressive failure performance of quasi-isotropic carbon–epoxy laminates with out-of-plane wrinkle defects. The wrinkles were seen to significantly reduce the pristine compressive strength of the laminates.





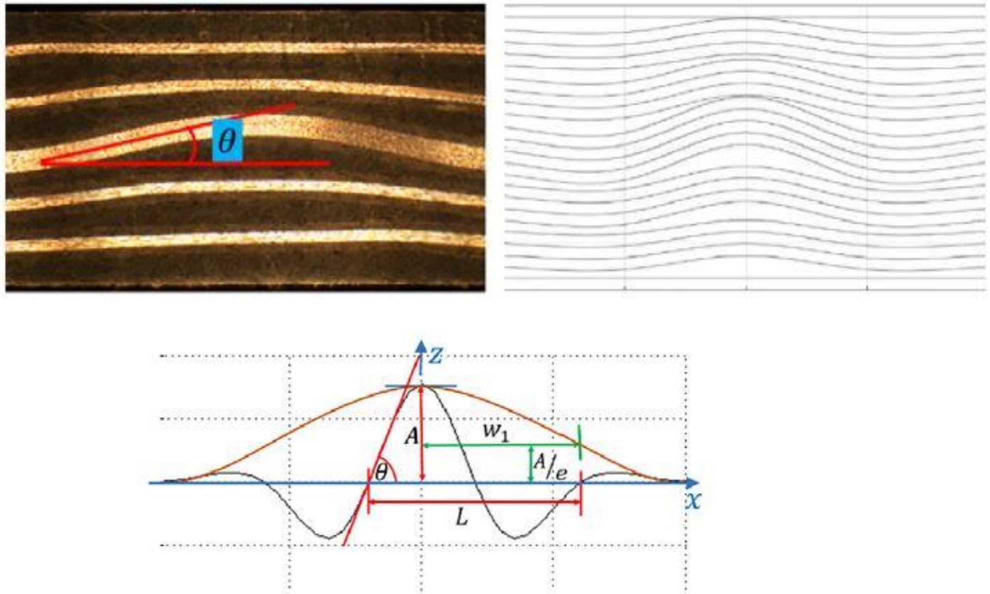


Computational Methodology

Problem Definition

✓ The inputs are:

- Number of layers
- Layup orientations
- Location of the wrinkles
- Shape of the wrinkles
- Geometry of the structure



$$d = A_i e^{-x^2/w_1^2} \cos\left(\frac{2\pi x}{L}\right)$$

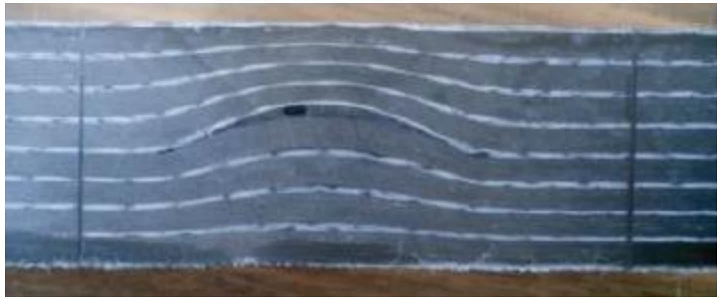
Figure 1. Geometry of the problem and wrinkle definition

Automation

Main.m | Initial_Calculations.m | Mesh_Generation.m | Making_inp_3D.m

```
clear all;close all;fclose all;clc
tic
%==========================================================================
%============================ Inputs ====================================
LayUp = [45/90/-45/0,3]; SetUp = "sym"; Dimension = "3D"; %OR 2D!
Orient =                 "ON" ;
Interface_Elements = "OFF";
Interface_Surfaces = "ON" ;
CZM =                    "OFF";
Loading = "TensileX"; WrinkleType = "Normal";
Thickness = 0.25; Cohesive_Thickness = 0.00;
E1   = 161000; E2 = 11380; E3  = E2  ;
G12  = 5170;  G13 = G12;   G23 = 3980;
nu12 = 0.32; nu13 = 0.32; nu23 = 0.43;

nz = 1 ; % Number of elements in each layer in thickness direction
Lx = 150; Ly = 25; % Lz = N*th; % Dimensions in X and Y directions
ElemX = 200; ElemY = 10; % ElemZ = N*nz;% Numberof elements in X, Y and Z dir
%======================== Wrinkle Properties ============================
Amax = 4.0*Thickness;
L = 0.4*Lx; W1 = 0.7*Lx; X0 = 0.5*Lx; % X0 is the center of the wave with max amplitude
ZFormula = "Linear";  % or gaussian
%==========================================================================
```



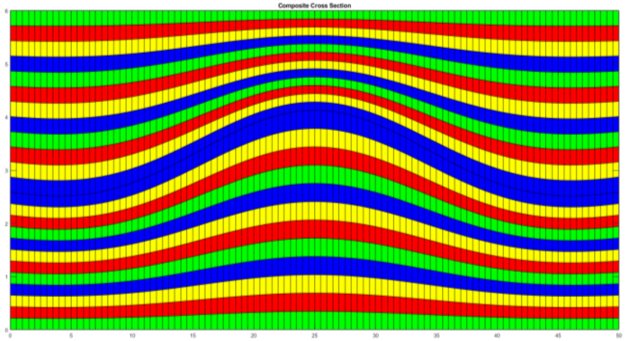


Figure 2. Constructing the FEA mesh

Zero-thickness cohesive elements

✓ No physical gaps between eleme

✓ Closer to the physics of the probl

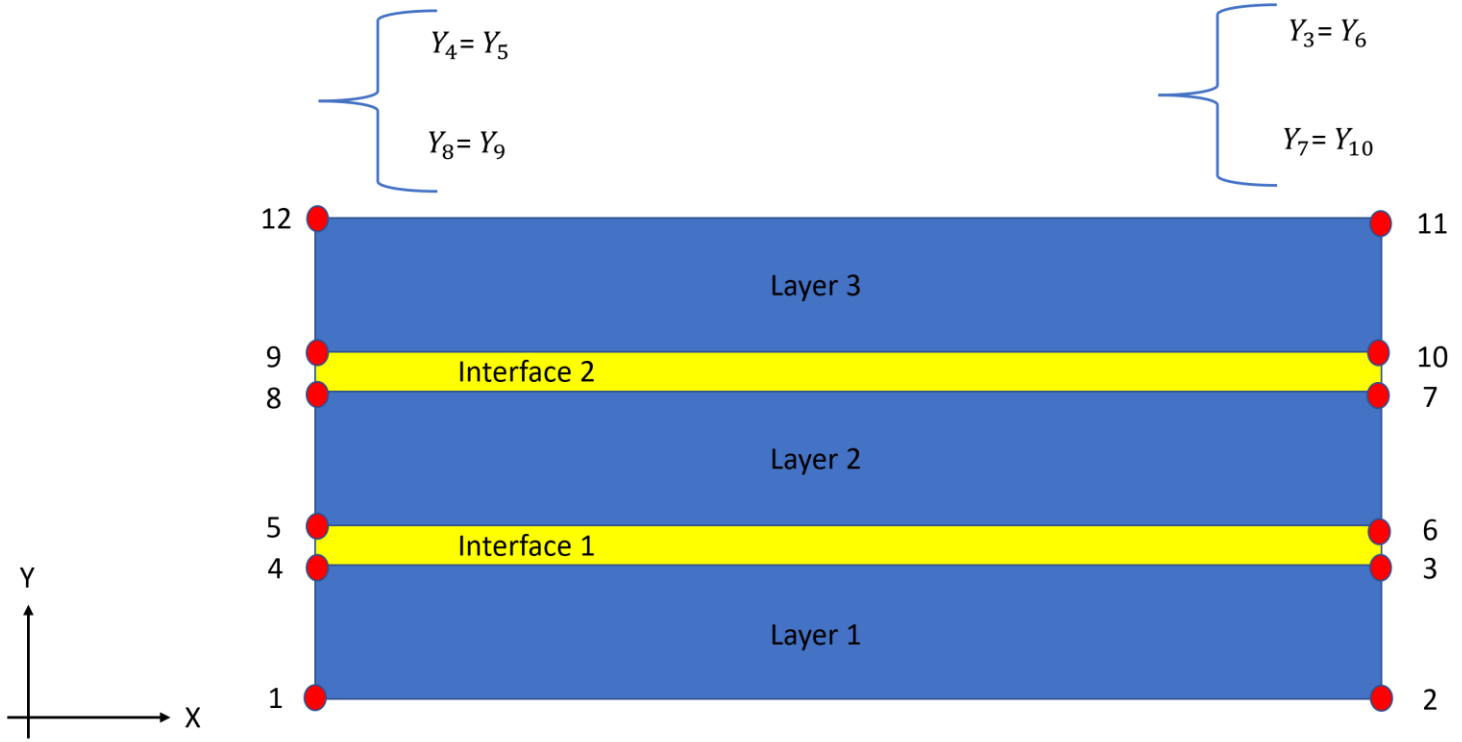


Figure 3. Zero-thickness cohesive elements

Traction-separation law

✓ Material property for cohesive elements

K_{I} (N/mm^3)	K_{II} (N/mm^3)	σ_{Imax} (MPa)	σ_{IImax} (MPa)	G_{Ic} (N/mm)	G_{IIc} (N/mm)	α
10^5	10^5	60	90	0.26	1.002	1

✓ Damage initiation and progression:

$$f_{mt} = \left(\frac{\sigma_N}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 \qquad \left(\frac{G_I}{G_{Ic}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\alpha} = 1$$

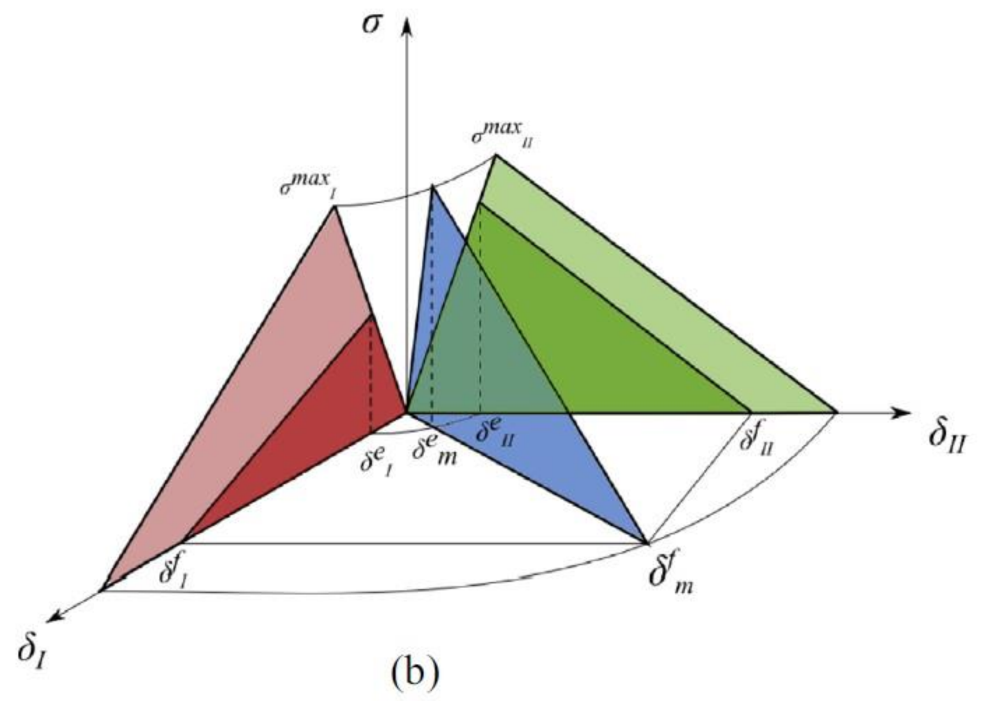
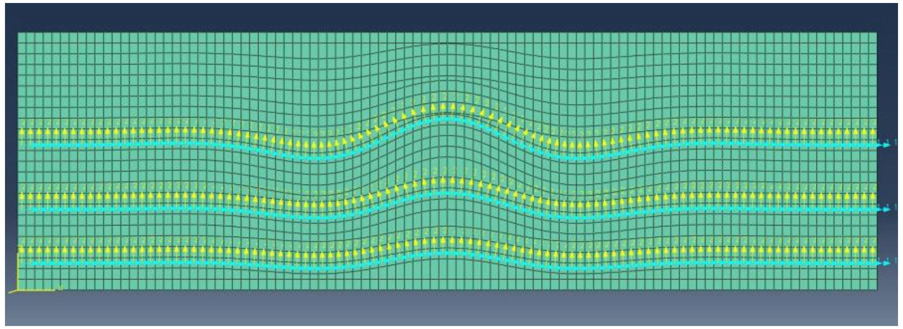


Figure 4. Mixed-mode traction-separation

Abaqus user subroutines

Three Abaqus user subroutines have been developed:

✓ UEXTERNALDB
✓ ORIENT
✓ UMAT



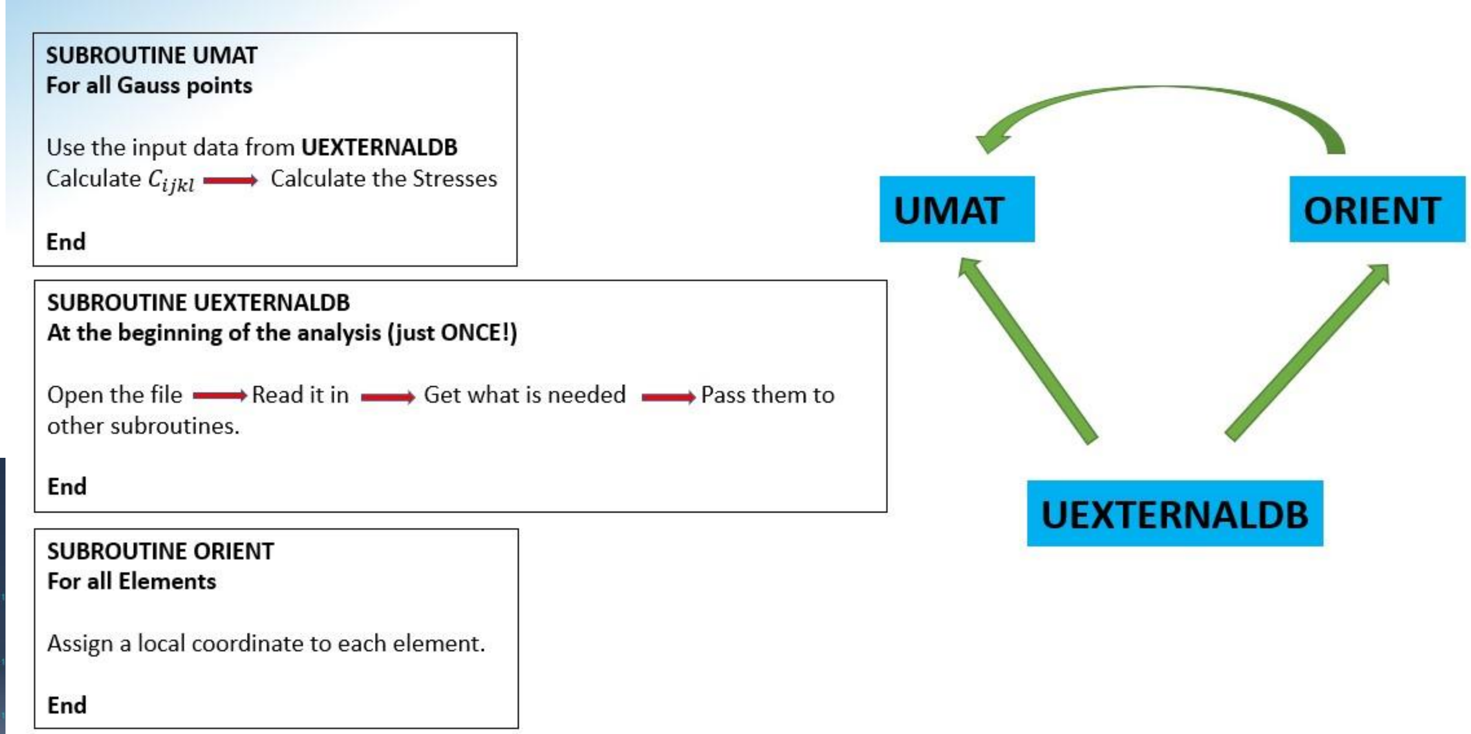


Figure 5. Passing information between Abaqus user subroutines

Postbuckling analysis

Steps for a postbuckling analysis:

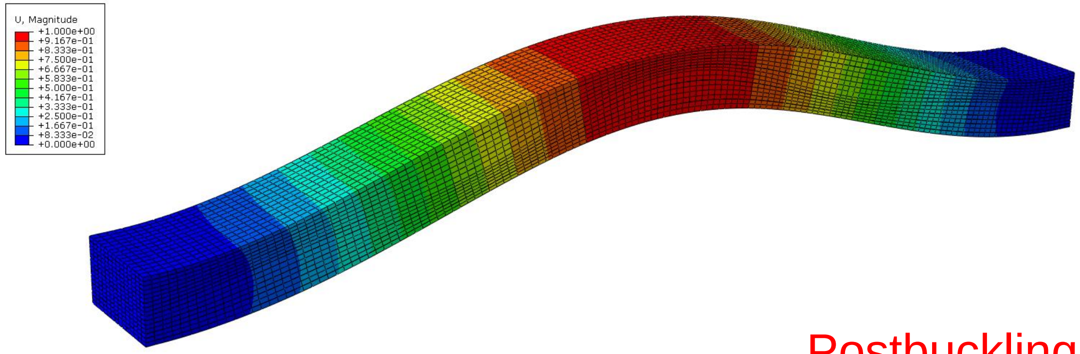
1. An Eigenvalue analysis

- Buckling modes (Just a shape!)
- An estimation of buckling loads

2. A large deformation analysis

- Real behavior of the structure
- Delaminations

Mode shape



Postbuckling configuration

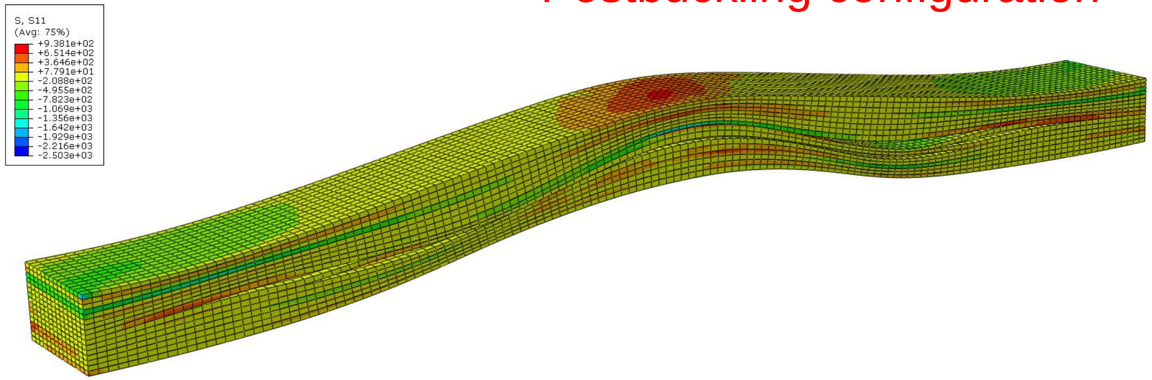


Figure 6. Eigenvalue and postbuckling analysis

Results and Discussion

Tensile Test:

A 24-layer $[45\backslash 90\backslash -45\backslash 0]_{3s}$ composite under tensile load:

- ✓ S11 axial stress is **12%** higher for the perfect case
- ✓ S13 shear stresses are significantly higher for the wrinkled case

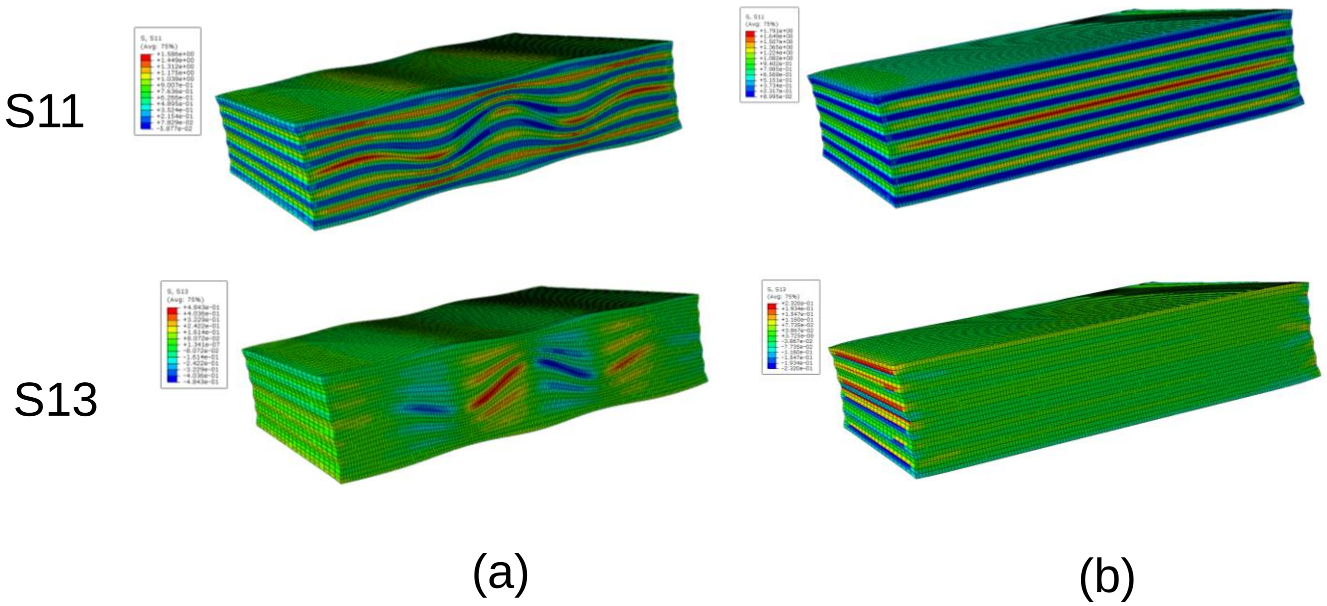
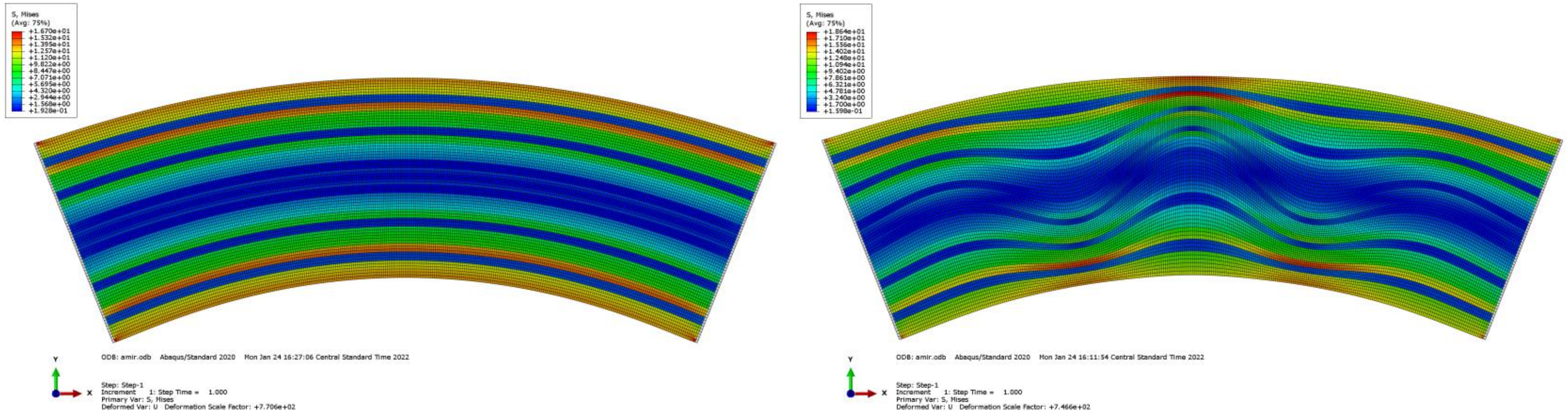


Figure 7. Stress distributions for a (a) wrinkled and (b) perfect composite

Bending Test:

A 24-layer composite $[0]_{24}$ under bending load:

- ✓ Maximum Von Mises stress is 11% higher for the wrinkled composite



(a) (b)

Figure 8. Von Mises stress distributions for a (a) perfect and (b) wrinkled composite

Penetration of elements after fracture:

- ✓ Works reasonably in a simple mode-I fracture

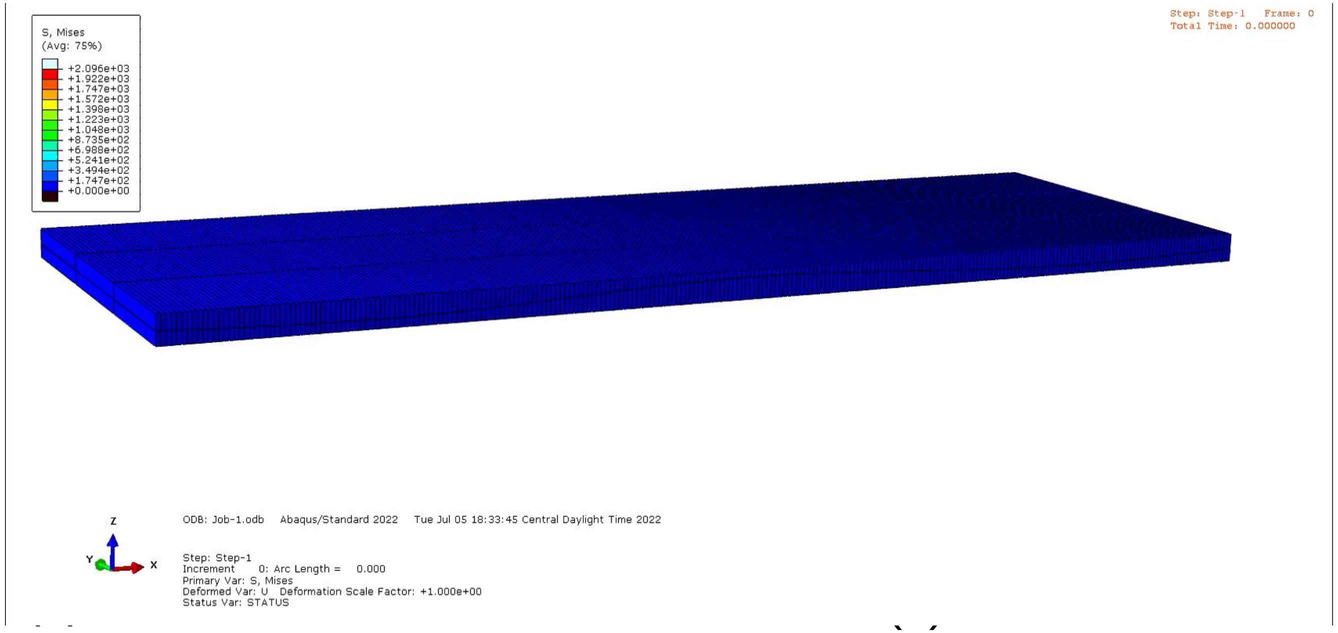


Figure 9. Mode-I fracture in a double cantilever beam test

Penetration of elements after fracture:

- ✓ Prevention of Layers penetration after initial fracture
- ✓ Proper contacts used between every two adjacent layers

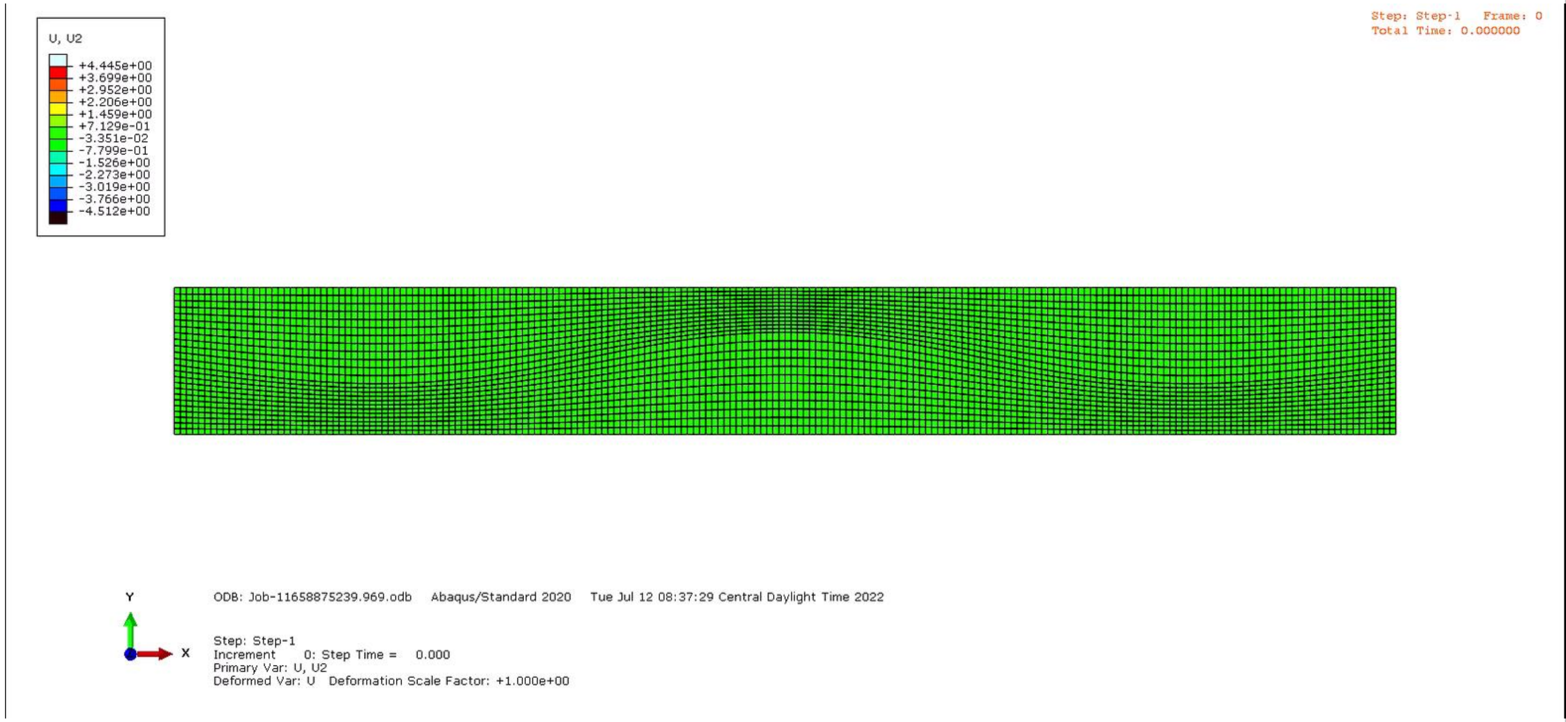
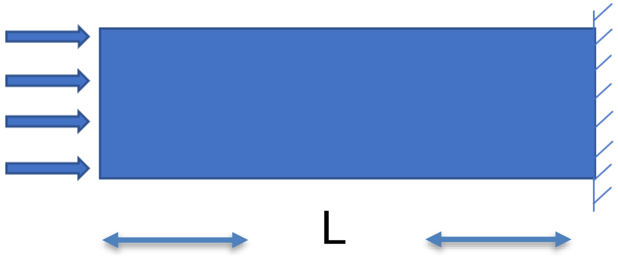


Figure 10. Von Mises stress distributions for a (a) perfect and (b) wrinkled composite

Postbuckling Analysis:

A series of postbuckling analysis have been performed on the $[0\backslash 90]_{6s}$ following composites

- ✓ Perfect
- ✓ Wide wrinkle
- ✓ Local Wrinkle



(a)

(b)

(c)

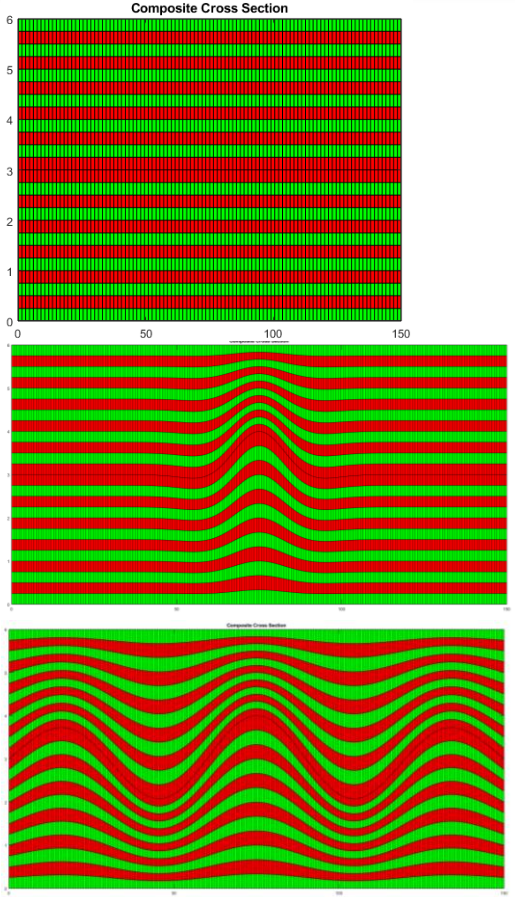


Figure 11. A (a) perfect (b) locally wrinkled (c) widely wrinkled $[0\backslash 90]_{6s}$ composite

Postbuckling Analysis:

For a composite with
L=100mm:

- ✓ 39% reduction of buckling load for locally wrinkled
- ✓ Crack starts to grow right at the wrinkle location
- ✓ 25% reduction of buckling load for widely wrinkled

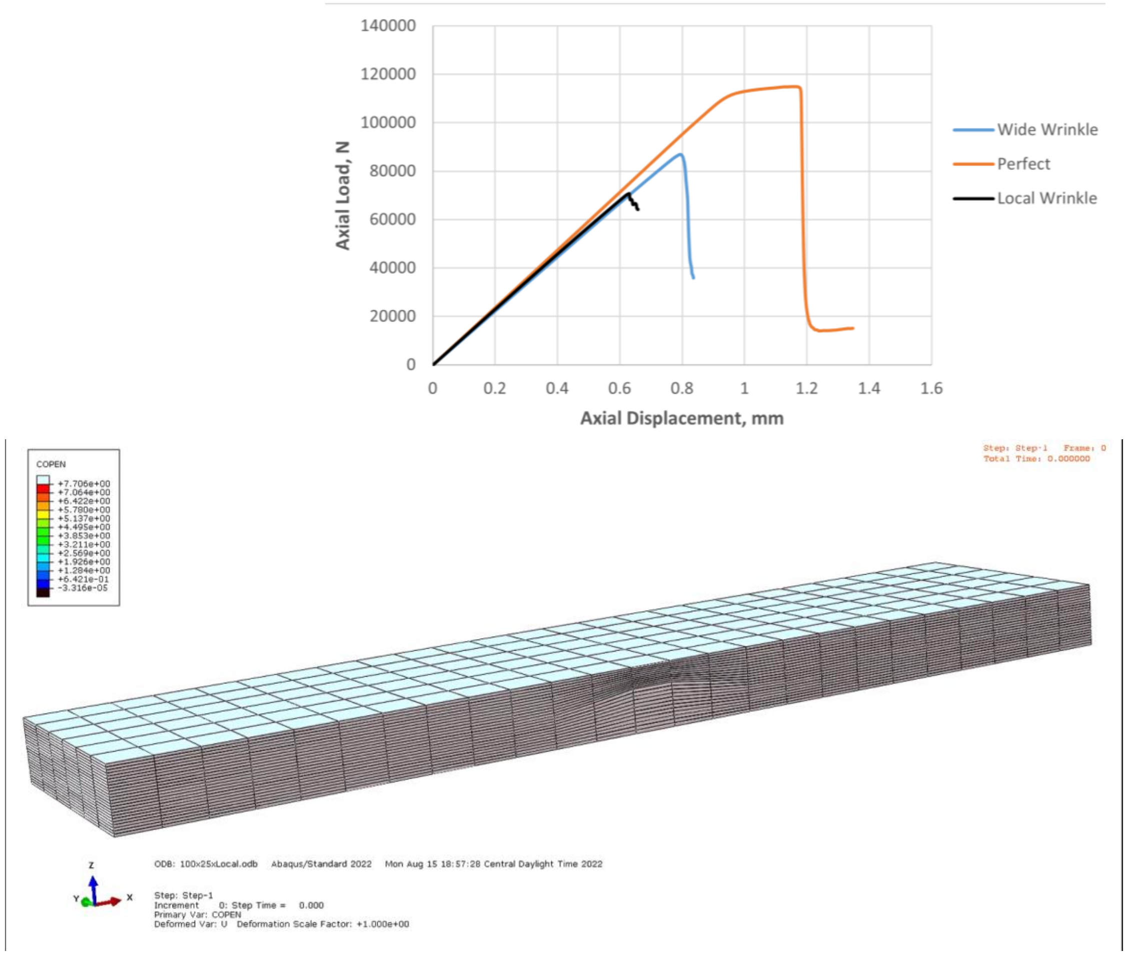


Figure 12. Postbuckling (a) load-displacement plots and (b) behavior of locally wrinkled composite for L=100mm

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Postbuckling Analysis:

For a composite with L=130mm:

- ✓ **13%** reduction of buckling load for locally wrinkled
- ✓ Load drops are associated with evolution of delamination cracks
- ✓ **7%** reduction of buckling load for widely wrinkled

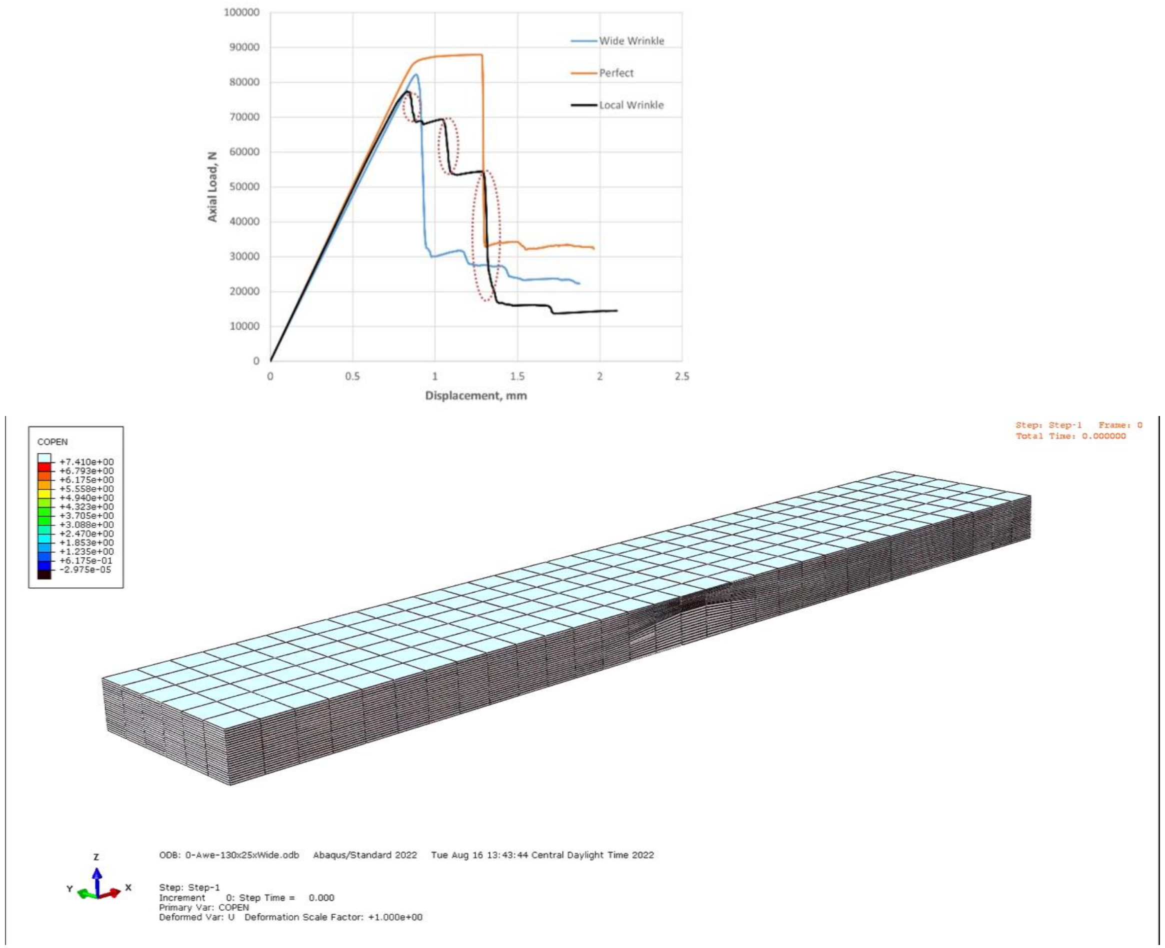

Figure 13. Postbuckling (a) load-displacement plots and (b) behavior of locally wrinkled composite for L=130mm

Postbuckling Analysis:

Effect of the length of the composite (Slenderness)

- ✓ By increasing L, the difference of widely wrinkled and perfect will be diminished (global behavior)
- ✓ Local wrinkles have more detrimental effects

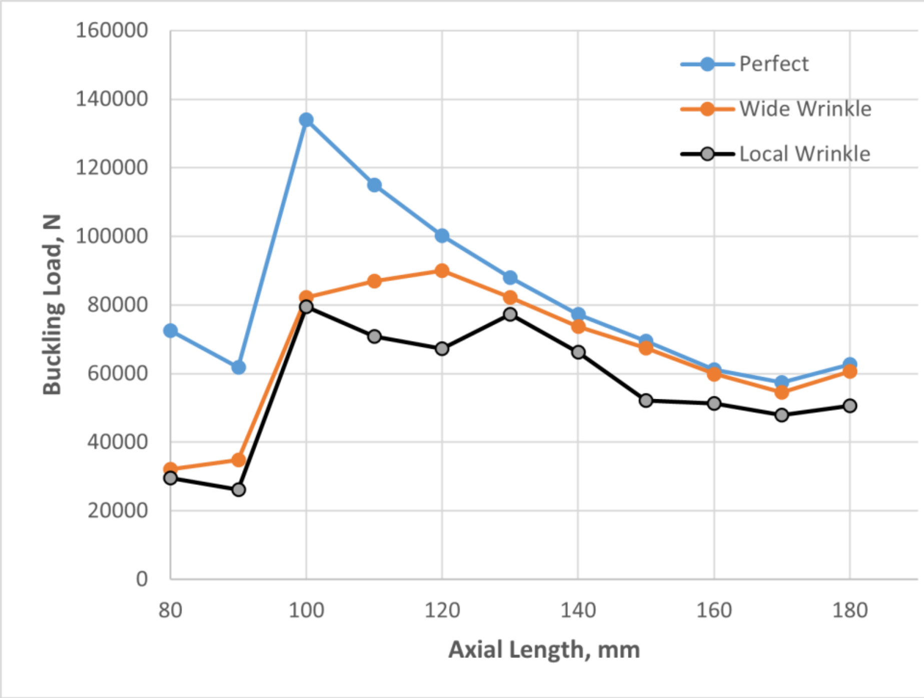

Figure 14. Postbuckling load-displacement plots for different length of the composite

Conclusions

Conclusions and Summary

- ✓ A fully automated MATLAB code has been developed to build the computational model based on the user input geometrical and material properties of the wrinkled problem.
- ✓ Three user subroutines (UEXTERNALDB, ORIENT and UMAT) have been developed for Abaqus simulations.
- ✓ It was observed that presence of wrinkle can considerably affect the shear stresses in a tensile test.
- ✓ Under bending, maximum Von Mises stress for a wrinkled problem was 11% higher than the perfect case with no wrinkle.
- ✓ Zero-thickness elements accompanying with proper contact definitions between the plies can capture the delamination behavior of a composite having wrinkles.
- ✓ It was observed that the presence of wrinkles affect the postbuckling behavior of the composites significantly, up to 40% reduction in buckling loads in some cases.
- ✓ Local wrinkles has more pronounced effects on the postbuckling behavior and delamination growth in the composites.

References:

1. Hsiao, H. M[illegible], and I. M. Daniel. "Effect of fiber waviness on stiffness and strength reduction of unidirectional composites under compressive loading." *Composites science and technology* 56, no. 5 (1996): 581-593.

2. Hsiao, H. M., and I. M. Daniel. "Elastic properties of composites with fiber waviness." *Composites Part A: Applied Science and Manufacturing* 27, no. 10 (1996): 931-941.

3. El-Hajjar, Rani F., and Derek R. Petersen. "Gaussian function characterization of unnotched tension behavior in a carbon/epoxy composite containing localized fiber waviness." *Composite structures* 93, no. 9 (2011): 2400-2408.

4. Nikishkov, Gennadiy, Yuri Nikishkov, and Andrew Makeev. "Finite element mesh generation for composites with ply waviness based on X-ray computed tomography." *Advances in Engineering Software* 58 (2013): 35-44.

5. Mukhopadhyay, Supratik, Mike I. Jones, and Stephen R. Hallett. "Compressive failure of laminates containing an embedded wrinkle; experimental and numerical study." *Composites Part A: Applied Science and Manufacturing* 73 (2015): 132-142.

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