CURE-INDUCED RESIDUAL STRESSES IN A NOTCHED LAMINATE

A Thesis by

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CURE-INDUCED RESIDUAL STRESS IN A NOTCHED LAMINATE

The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Aerospace Engineering.

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DEDICATION

For my father, Zainal and my mother, Yuslinar

&

for my wife, Suci, and my son, Pasya Budi Ananda

I miss you
ACKNOWLEDGEMENTS

I would like to express my gratitude to my advisor Dr. Suresh Keshavanarayana for his guidance and assistance. I would like to thank Dr. Walter J. Horn and Dr. Ramazan Asmatulu for being my committee members as well as for the encouragement. I would also want to thank all my teachers and friends at Wichita State University for being so generous to share their knowledge with me.

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ABSTRACT

The cure-induced residual stresses in the vicinity of the free edge of an open hole in IM7/977-2 carbon/epoxy laminates have been investigated. Holes in laminated structures are intended for fastener joints, access ports and as an equivalent damage size for damage tolerance evaluations. The hole in the laminate is commonly produced post cure by either drilling or grinding operations. Due to the residual thermo-mechanical and chemical strains in the laminate, a self-equilibrating free edge and in-plane stress field is generated upon drilling the hole. Use of strain gages is limited to measurement relative to the fully cured state and cannot accurately capture the strain gradients. Thus, this study was carried out using finite element model of an open-hole tension configuration.

The finite element models were developed for 16-ply unidirectional tape IM7/977-2 [$0_{4}/90_{4}]_S$ and $[0/90/45/-45]_{2S}$ laminates. The simulations were used to highlight the in-plane and through-thickness stresses along critical sections resulting from cure induced mechanisms. The results indicated significant interlaminar stresses in the vicinity of the hole due to curing. Based on rudimentary analysis, it is shown that the failure criteria must include the residual stresses for improved predictions of failure initiation in multidirectional laminates.
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<td>Full Form</td>
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<tr>
<td>3D</td>
<td>Three Dimensional</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing Material</td>
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<td>BC</td>
<td>Boundary Condition</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<td>FEM</td>
<td>Finite Element Model</td>
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<tr>
<td>MPa</td>
<td>Mega Pascal</td>
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<tr>
<td>OHT</td>
<td>Open-Hole Tension</td>
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<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Plastic</td>
</tr>
<tr>
<td>UD</td>
<td>Unidirectional</td>
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<tr>
<td>DOC</td>
<td>Degree of Cure</td>
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LIST OF SYMBOLS

\( \alpha \) \hspace{1cm} \text{Degree of cure}

\( \sigma \) \hspace{1cm} \text{Stress}

\( p \) \hspace{1cm} \text{Pressure}

\( t \) \hspace{1cm} \text{Time}

\( T \) \hspace{1cm} \text{Temperature}

\( \phi \) \hspace{1cm} \text{Diameter}

\( A_1 \) \hspace{1cm} \text{Rate constant}

\( A_2 \) \hspace{1cm} \text{Rate constant}

\( k_1 \) \hspace{1cm} \text{Rate constant}

\( k_2 \) \hspace{1cm} \text{Rate constant}

\( \Delta E_1 \) \hspace{1cm} \text{Activation Energy}

\( \Delta E_2 \) \hspace{1cm} \text{Activation Energy}

\( B_1 \) \hspace{1cm} \text{Rate constant}

\( R \) \hspace{1cm} \text{Universal gas constant}
CHAPTER 1

INTRODUCTION

In recent days, the industries are adopting composites in high proportions [1]. Among many different types of composites, continuous fiber reinforced plastics are commonly used. For example, carbon fiber reinforced plastic (CFRP) is the most common composite used in aerospace industry due to its light weight and excellent strength [2,3]. Moreover, carbon fibers also have superior fatigue strength, resistance to corrosion, as well as low coefficient of thermal expansion [1].

The applications of composites on aircraft structures can be found in [1-3].

- Interiors
- Fuselage
- Wing
- Flight control surfaces
- Fairings

The advantages of the composites are not only limited to weight savings but include production of highly integrated composite parts. Additionally, maintenance costs are reduced due to minimal corrosion during service. Moreover, the high specific mechanical strength, stiffness and better impact resistance make composite use become widespread in the industry[1].

Composite laminates with a circular hole (also referred to as notched) is a very common configuration often encountered in large assemblies [2]. The notched laminates are widely used, especially in mechanical joints where holes must be drilled to facilitate the use of fasteners, i.e.
rivets and bolts. Hallet et al. [4] mention that the analysis of open-hole configuration is very important because it can be a limiting factor in the design.

The assembly of structures containing composite materials may require the use of mechanical joints. Most polymeric composite materials used in structures are brittle, heterogeneous and anisotropic, and are not as easy to drill as metals. Accordingly, polymeric composites pose more challenges to drilling as compared to metals.

Holes must be drilled in the composite laminates to facilitate the use of fasteners. Compared to adhesive joints, fastened joints are much easier to implement because they do not need curing and if necessary, fasteners may also be removed quickly. However, each drilled hole generates stress concentration, reduces the strength of the joint and eventually, may trigger serious damage to the structure. Generally, before a particular type of composite can be used, a representative specimen must be tested. There are various types of composite tests defined in the ASTM standards [5]. One of the most important one is the open-hole tension test. The use of open-hole configuration is widespread because the plate with notch configuration is unavoidably used in many applications. The most common ones are holes for fasteners in composite parts.

New generation of wide-body aircrafts are designed with high percentages of composites [1]. In the beginning, composites were used for secondary or tertiary structures, but now the application of composite materials have expanded to primary structures such as wing and fuselage. As the usage of composites have increased, more comprehensive and in-depth knowledge related to composites is desired to establish a better understanding about the behavior of composites. One of the challenging topics in dealing with laminated composites is the residual stresses induced by the curing process.
Residual stresses in the form of tension may reduce the performance envelope or even cause failure of a composite product. They may increase the rate of delamination. About 60% of composites failure in the aviation industry is caused by delamination [6]. The residual stresses may reduce the capability of the composite structure to withstand the loads and lead to earlier failure and/or cause distortions. Moreover, the residual stresses in the form of compression may initiate buckling failure. The residual stress distributions through a composite laminate can be very complex and may vary from compressive to tensile stresses from layer to layer, depending on the material and ply orientations.

A notched composite is commonly produced using the process illustrated in Figure 1.

Figure 1. Notched laminate fabrication [3,7]
When material is removed by drilling a hole, the remaining material around the hole naturally finds a new state of equilibrium. Stress concentration will occur as a result of this. These changes of stresses may lead to a distortion of the surface around the hole. The behavior of composites laminate with stress concentration is of great interest in design because the strength as well as life will be reduced due to damage growth around these stress concentrations [1]. To determine the interlaminar residual stresses in the laminated plate, it is necessary to use a three-dimensional (3D) stress analysis. A 3D stress state appears at the free edges of the hole, mainly caused by the mismatch of in-plane shear stiffnesses and Poisson’s ratios between plies with different orientations in a composite laminate [1]. It gives rise to interlaminar shear and normal stresses at the free edge. Subsequently, a considerable amount of distortion may occur in the composite part and further repair or extra treatment may be necessary. Furthermore, the part can be rejected after the lengthy production process. Practically, prediction of the distortion is usually done by a series of trial and error processes. This is undesirable because it can be very costly and time consuming. One way to overcome this problem is to utilize finite element analysis (FEA) to predict the distortions and the residual stresses of the composite parts.

In this study, finite element models were generated to simulate the process of curing, drilling, and application of external mechanical loading to the laminate. Different sets of finite element models were developed to study the residual stresses of IM7/977-2 unidirectional composite laminates. The finite element models include 3D models of notched laminates subjected to mechanical load only (without curing thermal load) and model of notched laminates subjected to thermal curing load followed by mechanical load. 3D finite element models were developed to obtain the residual stress distributions in the thickness direction for every ply.
CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

Many studies have been performed to examine the curing of laminated composite [8-12]. During the cure process, several phenomena occur which may result in residual stresses that can cause distortion in the laminated composite part. The development of residual stresses in multidirectional laminates may be attributed to CTE mismatch between plies, resin chemical shrinkage and contact interactions between the tool surface and the part during heating and cooling cycles [10,13].

Curing is performed by utilizing elevated temperature for a certain time. The existence of heat initiates chemical changes at the molecular scale. Cross-linking between the molecules of resin start to happen and the process depends on the applied temperature [14]. During the process of curing, chemical reactions take place and the resin changes from a viscous to a stiff and elastic material [10].

Typically, the process of curing is divided into three stages listed below [3].

1) A-Stage.
   In this stage, the components of resin that consist of base material and hardener are mixed, but no chemical reactions take place. Wet layup resin is considered to be in this particular stage.

2) B-Stage.
   In this stage after the components of the resin have been mixed, the chemical reaction starts to take place. The material becomes tacky and thickened during the B-Stage.

3) C-Stage.
The resin is fully cured in C-Stage. There are different ranges of temperature for resin to be fully cured depending on the type of the resin.

The mechanical properties of polymeric composites evolve with the amount of polymerization (cross-linking) [1,8-10]. It is often desirable to have a measure of the amount of cure or polymerization that has been achieved. The level of curing is usually quantified using Degree of Cure, $\alpha$. The exothermic heat associated with the polymerization is often used to quantify the cure level. The degree of cure of the resin depends on the rate at which heat is transmitted from the environment into the material [8]. The degree of cure is expressed as [8,12]

$$\alpha = \frac{H}{H_T + H_R}$$

where $\alpha$ is the degree of cure at a particular time, $H$ is the summation of reaction heat from the beginning to a certain time and $H_T$ is the total reaction for whole cure cycle and $H_R$ is the residual reaction heat. A tool called Differential Scanning Calorimeter (DSC) is utilized to measure the value of DOC of polymers/composite [8-10]. The heat flow to/from a small sample is measured under isothermal conditions to obtain the degree of cure [8-10].

While the heat flow from small samples can be used to obtain a direct measure of cure state, the same cannot be done for large composite parts. However, the temperature at different locations can be measured using thermocouples, etc. These temperature measurements are then used in cure kinetics models to estimate the degree of cure. In this thesis, the cure kinetics model of Springer, Loos and Lee [8] is used. The Springer-Loos model is expressed as [8,10,12].

$$\frac{d\alpha}{dt} = (k_1 + k_2 \alpha)(1-\alpha)(B_i - \alpha)$$

where the parameters $k_1$, $k_2$, and $B_i$ are rate constants, $\alpha$ is the degree of cure, $k_1$ and $k_2$ are defined in equations (3) and (4) [10,12] as
\[ k_1 = A_1 \exp\left(-\frac{\Delta E_1}{RT}\right) \]  \hspace{1cm} (3)

\[ k_2 = A_2 \exp\left(-\frac{\Delta E_2}{RT}\right) \]  \hspace{1cm} (4)

where \( A_1 \) and \( A_2 \) are the pre-exponential factors, \( \Delta E_1 \) and \( \Delta E_2 \) are the activation energies, \( R \) is the universal gas constant and \( T \) is the absolute temperature. The above parameters are obtained using experimental data from isothermal tests conducted at different temperatures [8].

2.1. Residual Stresses in Composites

Residual stresses can be defined as stresses remaining within a body in the absence of external loading, mechanical or thermal [15]. They are essentially self-balanced stresses due to incompatible internal strains. In laminated composites, the residual stresses are not uniform and their distributions can be very complex. Residual stresses depend on the geometry of the laminate, material properties, stacking sequence, and the process of curing involved [16]. There have been a lot of studies conducted to better understand the residual stresses in laminates especially when they are subjected to curing process [10,17,19].

According to Shohkrieh [13], the main disadvantages of residual stresses are reduction of the strength and geometrical distortion. The residual stresses are generated because of the following reasons [13].

- Mismatch of the physical and mechanical properties of the matrix and fibers.
- Matrix shrinkage after curing.
- Heat treatment after manufacturing.
- Machining.
The amount of residual stresses depends on ply orientation, stacking sequence of the laminate, fiber volume ratio, curing process and also other processing variables [1]. Experimentally, residual stresses can be measured using sensors, hole-drilling method etc. On the other hand, they also can be effectively calculated using computational approach. In order to be able to generate a good model, several main inputs are required that include combined material properties of the lamina for the fiber and matrix, stacking sequence and ply thickness, temperature gradient, chemical shrinkage distributions, and loading conditions [19].

In a finite width notched laminate, out-of-plane stresses are generated at the boundary (straight edges) as well as at the edge of the notch. The magnitudes of the stresses at the edge of the notch are much higher than at the boundary. These interlaminar stresses occur in order to maintain the force as well as moment equilibrium at the free edges.

When a laminated composite is subjected to a certain temperature change, thermal stresses are generated. In 1992, Bogetti and Gillespie [17] introduced a methodology of obtaining stresses induced by curing in laminate. This methodology is illustrated in Figure 2.
Specifically concerning unidirectional carbon fiber IM7/977-2 material, some comprehensive studies were performed at Wichita State University. Tavakol [10] investigated the distortions and residual stresses of unnotched balanced-asymmetrical laminates by generating a fully 3D coupled thermal-curing-mechanical finite element analysis on a solid rectangular-flat-composite panel. He tried to predict the residual stresses and the distortions of 430 mm × 430 mm rectangular panels and compared the finite element model with experimental results. Tavakol employed Bogetti-Gillespie models for modulus evolution as a function of degree of...
cure. However, the modulus evolution was based on measurements at the ply level which circumvented the assumptions associated with micromechanics based models. Based on his experiments, he generated cure kinetics parameters for the Springer-Loos model which was adapted in his thesis. The parameters for the models are shown in Table 1. Tavakol developed comprehensive thermal expansion and shrinkage maps as functions of both temperature and degree of cure, which were used in the simulations. The distortion predictions compared satisfactorily with the experimental measurements, in spite of ignoring the stress relaxation effects.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>$2.46 \times 10^2$</td>
<td>1/sec</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$-4.18 \times 10^{-5}$</td>
<td>1/sec</td>
</tr>
<tr>
<td>$E_1$</td>
<td>$8.26 \times 10^4$</td>
<td>J/mol</td>
</tr>
<tr>
<td>$E_2$</td>
<td>$2.65 \times 10^4$</td>
<td>J/mol</td>
</tr>
<tr>
<td>$B$</td>
<td>$6.26 \times 10^3$</td>
<td>-</td>
</tr>
</tbody>
</table>

Soltani [12] performed studies on determining mechanical properties of polymer composites cured using different staged cure cycles. He carried out several experiments to investigate the cure kinetics of unidirectional carbon fiber IM7/977-2. In these experiments, prepregs manufactured by Cytec Cycom 977-2 were used. Cycom® 977-2 is an intermediate modulus toughened epoxy resin system [20,21]. It has curing temperature of 177 °C as suggested by the manufacturer. This type of epoxy resin system is processed using autoclave or press mold and one of the benefits is it has excellent impact resistance characteristic.

Soltani performed experiments using different staged cure cycles to IM7/977-2 materials. He performed the experiments on one-stage cure cycles as well as two stage cure cycles. He also
used this material to study the possibility of using viscoelastic properties during cure and post
cure to be used as a new basis to accept or reject composite material instead of mechanical
testing. His study concluded that in one-stage cure cycle, the mechanical properties of IM7/977-
2, except SBS strength, did not vary significantly and there was no correlation between the
mechanical properties with viscoelastic properties or degree of cure.

2.2. Drilling

The most common failure due to drilling is delamination in which layers of the laminated
composite separate. Shohkrieh and Ghasemi [22] performed simulations of central hole-drilling
process for laminated carbon epoxy. The finite element models were developed using ANSYS
for two different laminates. In this modeling technique, the residual stressed material was
obtained by directly applying the initial stress and then the elements in the area of the hole were
removed. The models were given three separate loads along the longitudinal and transverse axes,
as well as shear load and then the hole drilling process was simulated by removing the elements.
Figure 3 shows the finite element model developed by Shohkrieh and Ghasemi.

![Figure 3. Stress distribution in an orthotropic material due to hole drilling under shear load [22]](image-url)
In determining the residual stresses for Carbon/Epoxy, in this study \([90_6/0_{10}]\) laminate was used. Meanwhile, for the glass/epoxy the \([0/\pm 45_3/90_5]_s\) and \([0/+45_6/90_5]_s\) were used. The results of the finite element analysis were compared to the available experimental data. They found that the residual stresses have a good correlation between the result of simulation and the experiments.

Palani [23] developed 3D finite element model using Arbitrary Lagrangian Eulerian (ALE) capability in LS-DYNA to simulate the drilling process. The model had dimensions of \(155 \times 155 \times 20\) mm and utilized a total of 30,000 solid elements. The material used was unidirectional carbon epoxy composite. The finite element model developed by Palani is shown in Figure 4. In his work, Palani used MSC Patran as the preprocessor and LS DYNA as the solver. LS POST was used in the post processing to see the results. Firstly, he generated the drill bit geometry using Pro/Engineer and then exported it (in IGES file) to Patran where the mesh was then performed. He also generated a rectangular workpiece and created very fine mesh in the contact area between drill bit and workpiece. The drill bit was considered as rigid body and modeled as shell elements instead of 3D elements to reduce the analysis time. In LS DYNA, the drill was capable of traveling down as well as rotating and getting in to contact with the work piece elements. When the drill moved through the work piece, the hole was generated. The main focus of this study is about the cutting force generated during drilling forces. It was found that the thrust force in the finite element simulation is very close to the experimental result in both trend and magnitude.
Sicot et al. [24] used incremental layer removal method to simulate hole-drilling to estimate the cure induced global (not free edge) residual stresses in, [0]s and [0\textdegree/90\textdegree]s laminates made from T300/914 unidirectional carbon/epoxy prepreg. The simulations were done using ABAQUS and utilized standard two-step cure cycle but with three different cooling rates as shown in Figure 5. The authors reported that the residual stresses decreased when the cooling rates were reduced. The authors did not report any results about the stress fields that develop in the vicinity of the hole boundary.

**Figure 5. Two stage cure cycle with different cooling rate [24]**

### 2.3. Stresses in Open Hole Configuration

Stress concentration is a very important issue to deal with in laminated composite materials with the main consideration that failure is usually started at or near the location of
maximum stress concentration. There are several factors that have been proven to be the causes of stress concentration [26], for example, cutouts, joints, discontinuous geometry, etc. The estimation of stress concentration factors for different notches and laminates has been accomplished using complex stress function approach, finite element analysis and modification of isotropic solutions using appropriate correction factors [26]. A typical comparison of stress distributions across the net-section as reported by Tan [26] is shown in Figure 6.

![Figure 6. Comparison of predicted and experimental stress concentrations of the \([0_2/45/-45]_{2S}\) laminate containing a hole with \(2a = 5.1\) mm and \(2a/w = 0.136\) [26]](image)

Currently, there are several stresses based failure criteria available to predict the strength of notched laminate[26]. One of the criteria is the point stress criterion developed by Whitney and Nuismer [25]. This criterion is established based on the stress fields around a hole. According to this criterion, failure occurs in an open-hole tension configuration when the stress at some distance away from the hole edge is equal to or greater than the strength of the laminate.
without a hole. For an isotropic plate with a hole, the stress distribution can be expressed in the following equation (5) [26]

\[
\frac{\sigma_x}{\sigma} = 1 + \frac{1}{2}\left(\frac{R}{x}\right)^2 + \frac{3}{2}\left(\frac{R}{x}\right)^4
\]

(5)

where \(\sigma\) is the applied stress parallel to the y-axis at infinity and \(R\) is the radius of the hole.

Figure 7. Graphical presentation of point stress criterion [26]

For orthotropic plate containing a circular hole case, the point stress criterion is obtained by substituting Equation (7) to (6) [26].

\[
\sigma_y(x,0)\bigg|_{x=R+d_o} = \sigma_o
\]

(6)

The stress distribution along the axis perpendicular to the loading direction can be approximated as [26]
\[ \sigma_y(x,0) = \frac{\sigma}{2} \left\{ 2 + \left( \frac{R}{x} \right)^2 + 3 \left( \frac{R}{x} \right)^4 - \left( K_T^{\infty} - 3 \right) \left[ 5 \left( \frac{R}{x} \right)^6 - 7 \left( \frac{R}{x} \right)^8 \right] \right\} \quad (x > R) \]

(7)

with [26]

\[ K_T^{\infty} = 1 + \frac{2}{A_{22}} \sqrt{A_{11}A_{22} - A_{12}^2 + \frac{A_{11}A_{22} - A_{12}^2}{2A_{66}}} \]

(8)

where \( K_T^{\infty} \) in equation (8) is the stress concentration factor at the edge of the hole in an infinite plate, \( A_{i,j} \) (\( i,j = 1, 2, 6 \)) are the components of the in-plane stiffness matrix with 1 and 2 parallel and transverse to the loading directions respectively [26].

Another version of this criterion uses the average stress over some characteristic distance to predict failure. The characteristic distances capture the presence of a process zone prior to failure of the notched laminate. Both these criterion employ the average laminate stress along the loading direction across the net section. One may also use these approaches in conjunction with a ply failure criterion (e.g., Tsai-Wu) and apply it at the ply level and also capture interaction effects through the effective stress based on the failure function. In most practical applications reported in literature, average stress across the net section is typically used.

S. Ding et al. [27] studied the 3D interlaminar stresses in thermoplastic composite laminates with a circular hole. The study used AS4/PEEK material with \([0/+45/-45/90]_{2S}\) laminate orientation. Finite element models were developed with dimensions of 6.92 mm in length, 3.46 mm in width and a radius of the circular hole \( r = 1.09 \) mm.
The finite element model utilized 54,912 elements and 81,668 nodes using 10-noded tetrahedral elements. It was assumed that the layers are bonded perfectly to each other and the mesh close to the hole was set to be finer as shown in Figure 8. Quasi-static remote loading was applied in 50 increments.

![Figure 8. Mesh of 16-ply composite laminate with circular hole [27]](image)

S. Ding et al. [27] generated comprehensive plots particularly related to interlaminar stresses for notched composite with [0/45/-45/90]_{2S} orientation. The typical interlaminar stresses in the vicinity of the hole as predicted by this model are shown in Figure 9.
Rybicki and Schmueser [28] investigated the effect of stacking sequence on free edge stresses around a circular hole in a laminated plate under in-plane tension. Their study was performed using earlier finite element model as well as an experimental study. In this study, they investigated the stress distributions around a notch using a 3D finite element model. They computed tangential strain distribution around a circular hole for [0/±45/0]s laminate subjected to remote in-plane tension loading and compared the results with experimental test data. This study also investigated the interlaminar normal stress distribution around the notch. The type of laminate used was graphite/epoxy with different stacking sequences. A typical result from this study can be seen in Figure 10.
In 1983, Carlsson [29] studied the interlaminar stresses in 28 ply graphite-epoxy laminate. The dimensions of the model had the same length and width of 24 mm. The circular hole at the center had a diameter 6 mm. The stacking sequence used was \([\pm 45/0_2/\pm 45/90/0_3/\pm 45/0_2]_S\). The model was subjected to in-plane compression applied as negative displacement along the longitudinal direction of the laminate. The finite element model was developed using 3D solid elements with 20 nodes. In this study because of the symmetrical lay-up as well as the geometry, only one-eighth of the laminate was modeled. Finite element model developed by Carlsson is shown in Figure 11.
Figure 12. Distribution of $\sigma_z (\sigma_z / \sigma_{x,0})$ through the thickness at the hole boundary [29]

From this study, it was concluded that high interlaminar stresses occur especially at the ply interface and also at the free edge. The largest interlaminar normal stress occurs at the hole edge perpendicular to the loading direction. The FEM was too coarse to capture the steep stress gradient precisely but still the results obtained have a good correlation at a short distance away from the interface. The results of this study are shown in Figures 12 and 13.

Figure 13. Distribution of $\sigma_z (\sigma_z / \sigma_{x,0})$ along the y-axis at $x = 0$ for 2/3 ply interface [29]
Goonetilleke [30] investigated free-edge effect around holes in composite laminates. He used earlier finite element code to approximate interlaminar stresses for graphite/epoxy notched laminate. He applied a remote tensile load to an open-hole model and compared the resulting interlaminar stresses with those from an earlier study reported by Whitcomb (1981). Figure 14 shows the configuration of the model used in this study and the comparison of interlaminar stresses across the laminate thickness is shown in Figure 15.

Figure 14. Laminate configuration used by Goonetileke [30]
Figure 15. Comparison of interlaminar stress across laminate thickness in [45/90/-45/0]s specimen [30]

The interlaminar stresses in the vicinity of the hole edge as reported by the previous investigators are results of remote in-plane loads post cure. These stress distributions do not include the contributions of residual stresses emanating from the curing process. While the presence of residual stresses and resulting distortions in unnotched laminates have been reported widely, the same cannot be said about notched laminates. The notched strength predictions are
often based on the use of some characteristic distance obtained semi-empirically using a combination of experimental data and elastic analysis. While these predictive models can incorporate both in-plane and interlaminar stresses through an appropriate failure criteria, the cure induced stresses are often neglected. The present study is a first step at bridging this gap by investigating the magnitude and distribution of the cure induced stress field. Most experimental methods of estimating residual stresses are based on surface strain measurements. While good correlation between experiments and finite element models have been reported for open-hole configurations, these measurements are strictly for post cure and hole formation. These measurements/predictions do not include the residual strains due to the cure process.
CHAPTER 3

PROBLEM STATEMENT AND OBJECTIVES

3.1 Problem Statement

In the present investigation, the stress distributions around the edge of a circular hole arising from the curing process followed by a remote tensile loading, was investigated. An open-hole tension specimen with geometry in accordance with ASTM D5766 was used. According to ASTM D 5766 [31], the width of the open hole tension specimen was $36 \pm 1$ mm ($1.50 \pm 0.05$ in.) and the length was in the range of 200 to 300 mm (8.0 to 12 in.). The diameter of the centrally located hole was $6 \pm 0.006$ mm ($0.250 \pm 0.003$ in). The geometry of the specimen is illustrated in Figure 16.

The laminates used in this study were balanced and symmetric, made of IM7/977-2 UD tape carbon fiber epoxy material. This material system was chosen due to the availability of comprehensive data which included cure kinetics, thermal expansion and shrinkage, and modulus evolution as a function of degree of cure [10,11]. The laminates used were made of 16 plies with a stacking sequence of $[0_4/90_4]_S$ crossply laminate and $[0/90/45/-45]_{2S}$ quasi-isotropic laminate. Each ply in the laminate had a nominal thickness of $127 \mu$m (0.127 mm) and therefore the total thickness was equal to $2,032 \mu$m (2.032 mm).

Figure 16. The dimensions of rectangular plate with circular notch at the center
3.2 Objectives and Scope

The main objective of this research was to study the residual stresses developed in the IM7/977-2 carbon/epoxy notched laminated composite that was induced by the curing process. The study was conducted by performing finite element analysis using MSC Marc non-linear finite element program [32]. The specific goals of this research were.

1. Generate 3D FEM of notched laminated composite using MSC Marc
2. Simulate the curing process followed by remote loading
3. Simulate the drilling process using layerwise material removal by employing the element deactivation feature in MSC Marc
4. Obtain interlaminar residual stresses distributions in the vicinity of the notch
5. Analyze the interlaminar stresses for the laminates

In this thesis, the scope of the work was limited to 3D solid element finite element simulation. The material properties, cure kinetics models, cure dependent thermal expansion and cure shrinkage for IM7/977-2 material were adapted from Tavakol’s work[10].
CHAPTER 4

FINITE ELEMENT MODEL DEVELOPMENT

4.1. Model Description

A 3D solid finite element model of the laminated open-hole tension specimen was assembled using MSC Marc (version 2011) finite element program. Each ply had a thickness of 127µm (0.127 mm) so that the overall thickness for 16 plies was 2,032 µm (2.032 mm). Each layer in the model represented a single ply of IM7/977-2 unitape material. In the model, the circumference of the notch was divided into 72 mesh seeds. The mesh was finer around the notch in comparison with the region that was far away from the hole to capture stress gradients in the vicinity of the hole. For the model without a notch, there were a total of 35,712 elements, whereas for the model with a notch there were 28,800 elements. The different meshes used in the model with and without notch are shown in the Figures 17 and 18.

Figure 17. Full finite element model of the laminate without notch

Figure 18. Full finite element model with notch at the center
In developing the finite element model, a coordinate system was defined such that the origin was located at the center of the notch at the bottom surface. The positive x-direction was to the right along the length and the positive y-direction was defined to be in the in-plane transverse direction (width). The positive z-direction was defined upward from the bottom surface through the thickness. The coordinate system used in this study is illustrated in Figures 19 and 20.

Figure 19. Coordinate system

Figure 20. 16-ply laminate in thickness direction
The laminate was modeled with 16 layers of 20-noded isoparametric solid elements (element type 21 in MSC Marc [33]). The element employs \textit{tri-quadratic} interpolations functions for coordinates and displacements [33]. The geometry of an element is illustrated in Figure 21. The use of one element across each ply thickness allowed for capturing linear strain distributions across the ply thickness.

![Figure 21. A 20-Node brick element [33]](image)

4.2 Boundary Conditions

The following boundary conditions were used for all load cases. All of the nodes at the left end were constrained in the x-direction while those of the right end were free to move in the x-direction. In y-direction, all nodes at half of the width on left and right ends were constrained. Meanwhile, all nodes at half of the thickness on the left and right end were constrained in z-direction. For a better understanding, the boundary conditions used in the finite element models are illustrated in Figure 22 and the dimensions of the model are summarized in Table 2.
Figure 22. Applied boundary conditions

Table 2. Dimensions of the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (2L)</td>
<td>200</td>
</tr>
<tr>
<td>Width (2w)</td>
<td>36</td>
</tr>
<tr>
<td>Diameter of notch (d)</td>
<td>6</td>
</tr>
<tr>
<td>Thickness (h)</td>
<td>2.032</td>
</tr>
</tbody>
</table>

The applied boundary conditions can be written as

\[
\begin{align*}
    u(-L, y, z) &= 0 \\
    v(-L, 0, z) &= 0 \\
    w(-L, y, \frac{h}{2}) &= 0 \\
    u(L, y, z) &= 0 \\
    v(L, 0, z) &= 0 \\
    w(L, y, \frac{h}{2}) &= 0
\end{align*}
\]  

(9)

4.3 Material Properties

The ply properties for the fully cured IM7/977-2 material[10] used in this model are summarized in the Table 3.
Table 3. IM7/977-2 Carbon/Epoxy material properties [10]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density ($\rho$)</td>
<td>1,700 kg/m$^3$</td>
</tr>
<tr>
<td>Longitudinal modulus ($E_1$)</td>
<td>150 GPa</td>
</tr>
<tr>
<td>Transverse modulus ($E_2 = E_3$)</td>
<td>8.2 GPa</td>
</tr>
<tr>
<td>Shear modulus ($G_{12} = G_{13}$)</td>
<td>4.15 GPa</td>
</tr>
<tr>
<td>Shear modulus ($G_{23}$)</td>
<td>2.5 GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio ($\nu_{12}$)</td>
<td>0.13</td>
</tr>
<tr>
<td>Poisson’s Ratio ($\nu_{23}$)</td>
<td>0.4</td>
</tr>
<tr>
<td>Poisson’s Ratio ($\nu_{13}$)</td>
<td>0.011</td>
</tr>
<tr>
<td>Thermal conductivity ($\kappa_1$)</td>
<td>6.7 W/m/C</td>
</tr>
<tr>
<td>Thermal conductivity ($\kappa_2 = \kappa_3$)</td>
<td>0.7 W/m/C</td>
</tr>
<tr>
<td>Specific Heat ($C_p$)</td>
<td>1400 J/kg/C</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion ($\alpha_1$)</td>
<td>-1.6 $\mu$m/m/C</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion ($\alpha_2 = \alpha_3$)</td>
<td>175 $\mu$m/m/C</td>
</tr>
</tbody>
</table>

The properties such as the Young’s and shear moduli, transverse thermal expansion coefficient and cure shrinkage are known to be functions of temperature and degree of cure [10]. The Bogetti-Gillespie model based on the experimental data reported by Tavakol [10], was employed to simulate the cure dependence of these properties. The cure shrinkage and thermal expansion coefficient measurements, from thermal ramp experiment at different rates reported by Tavakol [10], were used to define the thermal expansions as functions of temperature and degree of cure. The transverse thermal expansion coefficients extracted from these data sets [10] are plotted in Figure 23. These data were input into MSC Marc in the form of tables at specific
combinations of temperature and degree of cure. Linear interpolations was used to extract values at other intermediate combinations of temperature and degree of cure.

Figure 23. Cure dependent transverse thermal expansion coefficients of IM7/977-2 material [10, 34]

4.4 Load Cases

Different load cases were used to study and compare the stress distributions in the vicinity of the hole. Firstly, the fully cured notched laminate model was subjected to mechanical load only. This load case served as a basis for comparisons with the cure induced stresses. In MSC Marc, the mechanical load was applied as face load (pressure) in the positive x-direction that was applied to the right surface of plate as shown in Figure 24. This pressure basically
represented a remote stress to the laminate. The amount of applied stress was 136.7 kPa, which was equivalent to a resultant force of 10 N for this particular dimension of the laminate used in this study. The loading was applied in 10 equal increments and the results were extracted using MSC MENTAT pre/post processor.

![Diagram of mechanical loading application](image)

**Figure 24. Mechanical loading application**

In the second loading case, a thermal load was applied to the uncured and unnotched model in the form of the nominal thermal cure cycle recommended by the manufacturer (MRCC). The temperature was applied to the external surfaces of the unnotched test specimen. The curing of the specimens was carried out in three stages. The curing process was initiated at room temperature of approximately $25^\circ$ C. In the next stage, the temperature was ramped up to $177^\circ$ C in 60 minutes. After reaching $177^\circ$ C, the laminate dwelled at this temperature for three hours. After that, the temperature was cooled down to room temperature at a cooling rate of approximately 2.85 $^\circ$C/min. The whole process of curing was simulated using 200 increments in MARC for a total of 22,000 seconds. The profile for the cure cycle in the simulation was taken from the previous experiments performed by Tavakol [10]. The profile of the cure cycle is shown in the Figure 25.
In the subsequent analysis, the fully cured unnotched laminate was subjected to a process where layers of elements were removed to generate the hole. This process is described in the following section. After the formation of the hole, a remote tensile load was applied. The whole cure cycle was completed in 168 increments, followed by 32 increments of element removal to create the hole. In the final 10 increments, the remote tensile load was applied. Therefore for the coupled mechanical-thermal curing analysis, a total of 210 increments were used.

4.5 Drilling Simulations

In this study, the simulation of drilling used the *uactive* user subroutine[35]. This user supplied subroutine, written in FORTRAN language, was accessed by the MSC Marc program during each increment of the element removal portion of the analysis. The program listing may be found in Appendix-A. This subroutine facilitates layerwise removal of elements at user described time steps. Even though this process does not simulate the drilling forces and resulting damage due to the brittle nature of the polymeric matrix, it represents a way of creating the hole.
It was started when the curing process was completed and the temperature returned to the initial room temperature. In this model, the process was started at the increment 168. At that increment number, elements in the center of the notch region were removed layer by layer. In order to simplify the process, elements corresponding to each ply (of the hole region) were predefined as a set. Every time one set was removed, the remaining elements around the hole assumed a new state of equilibrium. This process was repeated for each layer until all of the elements of the hole were completely removed.

The process of element removal is illustrated in the Figures 26 and 27.

![Drilling simulation of $[0_4/90_4]_S$ laminate](image)

Figure 26. Drilling simulation of $[0_4/90_4]_S$ laminate
Figure 27. Drilling simulation of $[0/90/+45/-45]_{2S}$ laminate
CHAPTER 5

RESULTS AND ANALYSES

The results from the finite element analyses described in the previous sections were post processed using MSC MENTAT. The stress distributions along predefined segments were obtained by defining ‘node paths’ along the same. The stress distributions along these paths were used to compare and highlight the cure-induced stresses.

Based on the simulations for fully cured notched laminates subjected to remote tension loading, there were some interesting results. The laminates subjected to tensile remote stress definitely demonstrated stress concentration because of the existence of the notch. For \([0/90]_S\) laminate subjected to mechanical tension load only, the maximum stress in the longitudinal direction, \(\sigma_{xx}\) for \(0^\circ\) ply was approximately 1.55 MPa. For the \([0/90/+45/-45]_{2S}\) laminate, the maximum \(\sigma_{xx}\) was 1.55 MPa which was the same in \([0/90]_S\) laminate. For both types of laminate, maximum \(\sigma_{xx}\) occurred in \(0^\circ\) ply, which was in fiber direction. This was logical, considering that the \(0^\circ\) ply carries majority of the applied load.

Figures 28(a) and 28(b) highlight the stress concentration at the hole edge of \([0/90]_S\) and \([0/90/+45/-45]_{2S}\) laminates. In Figure 28(a) stress concentrations were observed at the four outer plies from the bottom and top surface where the \(0^\circ\) plies are located. Meanwhile, in Figure 28(b) the stress concentration also occurred in the \(0^\circ\) plies. The stress distribution is symmetric about the mid-plane and the maximum stresses occurred in the \(0^\circ\) plies at the bottom and top surface.
The in-plane stress profiles across the thickness for the two laminates are shown in Figures 29 (a) and 29(b). The stress distributions and stress levels for elastic loading were consistent with the trends reported in literature [32]. A stress concentration factor of approximately 11 was generated in the 0° plies. The comparison of in-plane stress, $\sigma_{xx}$ for both laminates along the minimum section is illustrated in Figure 30.

![Figure 29. In-plane stress $\sigma_{xx}$ due to remote tension along the hole edge (x = 0, y = r) in (a) $[0/90]_S$ and (b) $[0/90/+45/-45]_{2S}$ laminate without curing thermal load (mechanical load only)]
Figure 30. Comparison of $\sigma_{xx}$ in $0^\circ$ ply in $[0\!/90\!\!/4\!/90\!]_S$ and $[0\!/90\!\!/+45\!\!/-45\!]_{2S}$ laminates along the minimum section

5.1. **Interlaminar Stresses at the Hole Edge** ($x = 0$, $y = r$)

The curing process induced residual stresses in the laminate. Drilling process redistributed the stresses in the laminate. Every time a layer was removed, the remaining elements assumed a new equilibrium configuration and the interlaminar stresses were increased. Figure 31 illustrates the development of interlaminar stresses during the process of elements removal. The free-edge effect produced stresses in the thickness direction.
In the model associated with mechanical loading only (without curing thermal load), the distribution of interlaminar normal stress $\sigma_{zz}$ is presented in Figure 32. Starting from close to zero, $\sigma_{zz}$ in $[0_4/90_4]_S$ notched laminate increased and reached a maximum at the interface of ply 2 and ply 3. The maximum $\sigma_{zz}$ in this location was relatively small approximately 0.0055 MPa. After reaching a peak, then $\sigma_{zz}$ decreased significantly. In ply 4 the sign reversed from positive to negative and it continued to drop. The decrease took a turn after in the interface of ply 5 and 6. The minimum value was -0.0098 MPa. Small increase in the distribution was detected from ply 6 to the middle of the laminate and the stress distribution then flipped with respect to the mid-plane.

On the contrary, for notched $[0_4/90_4]_S$ laminate subjected to curing thermal load, the stress distribution was in the opposite direction. It was related to the fact that curing shrinkage induced longitudinal compressive strains in the laminate. Therefore, the plot of stress $\sigma_{zz}$ was
flipped from the model without curing thermal load. Figure 32.(a) and 32.(b) provide a clear comparison of $\sigma_{zz}$ between the laminate with curing and without curing thermal load (mechanical load only). It is interesting to note the magnitude of interlaminar stresses with and without curing induced stresses differ by orders of magnitude.

![Graph of $\sigma_{zz}$ at the hole edge (x = 0, y = r) in [0/90]S laminate (a) after curing followed by mechanical load and (b) without curing (mechanical load only)](image)

Figure 32. Comparison of $\sigma_{zz}$ at the hole edge (x = 0, y = r) in [0/90]S laminate (a) after curing followed by mechanical load and (b) without curing (mechanical load only)

Figures 33 and 34 display the fringes of interlaminar stresses near the boundary of the notch in [0/90]S laminate. It is shown in the Figure 33 that the maximum $\sigma_{zz}$ generated in [0/90]S laminate is approximately 48 MPa. This critical value of $\sigma_{zz}$ was observed to occur in plies 5 and 12 that had 90° orientation. At the hole edge (x = 0, y = 3 mm, 0 ≤ z ≤ 2.032 mm) where the interlaminar stresses were obtained, the maximum shear stress $\tau_{xz}$ was 0.51 MPa and it occurred in the boundary of ply 4 (0°) and ply 5 (90°). Starting from a value close to zero in ply 1 at the bottom surface, the shear stress $\tau_{xz}$ kept increasing in the first four 0° plies until it reached the interface between plies 4 and 5. In the next four 90° ply, the shear stress $\tau_{xz}$ decreased until it
finally changed direction at the mid-plane of the laminate. The drop continued until the interface of ply 12 and 13 where the value started to increase again until finally close to zero.

Based on the results, the maximum shear stresses $\tau_{xz}$ and $\tau_{yz}$ for this type of notched laminate subjected to tensile loading were 41 MPa and 45 MPa respectively. It can be concluded that among the interlaminar residual stresses in $[0_4/90_4]_S$ notched laminate, $\sigma_{zz}$ was the largest one.

![Figure 33. $\sigma_{zz}$ stress distribution around the notch in $[0_4/90_4]_S$ laminate after curing followed by mechanical load](image)

Figure 33. $\sigma_{zz}$ stress distribution around the notch in $[0_4/90_4]_S$ laminate after curing followed by mechanical load
Figure 34. (a) Shear stress $\tau_{yz}$ and (b) $\tau_{xz}$ distribution around the notch in $[0_4/90_4]_S$ laminate after curing followed by mechanical load

When the results were compared, the maximum $\sigma_{zz}$ generated in $[0/90/+45/-45]_{2S}$ laminate was approximately 52% lower than in the $[0_4/90_4]_S$ laminate. In Figure 35, the maximum $\sigma_{zz}$ in this $[0/90/+45/-45]_{2S}$ notched laminate is only around 23.2 MPa. These results were along expected lines since the $[0_4/90_4]_S$ had strong groupings of 0 and 90 plies, whereas these plies were dispersed in the $[0/90/+45/-45]_{2S}$ laminate.

It can be observed that at the hole edge ($x = 0, y = 3$ mm, $0 \leq z \leq 2.032$ mm) where the through-thickness stresses were taken, $\sigma_{zz}$ in $[0_4/90_4]_S$ was predominantly in tension. The result showed that in this type of laminate, the maximum $\sigma_{zz}$ was higher than other interlaminar residual stresses. Meanwhile, Figures 36 (a) and 36 (b) present the fringe plots of interlaminar shear stress $\tau_{yz}$ and $\tau_{xz}$. 
Figures 35 and 36 show the fringe plots of interlaminar residual stresses in the quasi-isotropic $[0/90/+45/-45]_{2S}$ laminate. It can be observed that shear stress was strongly developed between adjacent plies which were oriented in different directions, especially when they were oriented 90° from each other. In contrast, the shear stress was a minimum between adjacent plies that had the same orientations.
Efforts had been made to further study the interlaminar stresses for both types of laminate. In order to get a better understanding of the interlaminar stress distributions, all three interlaminar residual stresses along $x = 0$, $y = 3$ mm, $0 \leq z \leq 2.032$ mm in $[0_4/90_4]_S$ notched laminate were plotted together in Figure 37. Meanwhile, Figure 38 presents the interlaminar stresses of quasi-isotropic $[0/90/+45/-45]_{2S}$ notched laminate. It can be quickly observed from these figures that the critical interlaminar stress in crossply $[0_4/90_4]_S$ laminate was the out-of-plane normal stress $\sigma_{zz}$. Whereas, in $[0/90/+45/-45]_{2S}$ notched laminate the maximum interlaminar stress generated was shear stress. It may also be observed that stress $\sigma_{zz}$ was symmetric with respect to the interface $z = 0.5h$, while the shear stresses $\tau_{xz}$ and $\tau_{yz}$ showed antisymmetric distributions.

Figure 37. Interlaminar stresses at the hole edge ($x = 0, y = r$) in $[0_4/90_4]_S$ laminate after curing followed by mechanical load.
The development of the interlaminar stress $\sigma_{zz}$ in $[0/90/4/90/4]$ laminate was clearly observed. Its cause was mainly the significant difference of Poisson’s ratios between longitudinal and transverse direction (Poisson’s effect). The orthogonal plies had significant difference in deformation. In the $[0/90/4]$ laminate subjected to mechanical load, the interlaminar stresses sharply changed at the boundary between $0^\circ$ with $90^\circ$ ply. Meanwhile, for the plies with the same orientation, the interlaminar stresses developed were the minimum.

The maximum $\sigma_{zz}$ occurring in $[0/90/4/45/-45]_{2S}$ laminate due to only the remote stress (no cure induced stresses) was approximately 0.0365 MPa. It was relatively very small in comparison with the result of the $[0/90/4]_{S}$ laminate with curing. For the quasi-isotropic laminate $[0/90/4/45/-45]_{2S}$ the maximum stress $\sigma_{zz}$ was 23 MPa. Hence, this maximum $\sigma_{zz}$ was only around

Figure 38. Interlaminar stresses at hole edge ($x = 0, y = r$) in $[0/90/4/45/-45]_{2S}$ laminate after curing followed by mechanical load
48% of the \([0_4/90_4]_S\) laminate. Thus, delamination is expected to easily occur in the \([0_4/90_4]_S\) laminate.

The results of \(\sigma_{zz}\) distribution were observed to be symmetric to the half of the thickness. This behavior occurred for both \([0_4/90_4]_S\) and \([0/90/+45/-45]_2S\). In contrast, for the interlaminar shear stresses \(\tau_{xz}\) and \(\tau_{yz}\) the patterns were anti-symmetric. The anti-symmetric stress distribution occurs for both types of laminate. The plots of the interlaminar stresses versus thickness of the laminate were compared between the models with and without curing subjected to the same amount of remote stress in Figure 39. The results showed that the interlaminar stresses were highly developed when the laminate was subjected to the curing thermal load. The applied mechanical load contributed to only very small interlaminar stresses while the thermal load generated large magnitude of stresses.

![Figure 39. Comparison of interlaminar stress \(\sigma_{zz}\) at hole edge \((x = 0, y = r)\) in \([0_4/90_4]_S\) laminate without curing (mechanical load only) and with curing followed by mechanical load](image-url)
As observed in the Figure 39, it is shown that the $\sigma_{zz}$ of the laminate due to given remote stress is close to zero. It happened because the stress resulting from mechanical load was much smaller than stress induced by curing process. For $[0_4/90_4]_S$ laminate subjected to mechanical load, the first three $0^\circ$ outer plies at bottom surface (plies 1, 2, 3) and top surface (plies 14, 15, 16) developed positive $\sigma_{zz}$ that indicated they were under tensile loading. However, starting from the fourth ply, $\sigma_{zz}$ switched direction indicating that the plies underwent compression. The results of $\sigma_{zz}$ distribution were observed to be in symmetrical pattern to the half of the total thickness. This pattern occurred for both $[0_4/90_4]_S$ and $[0/90/+45/-45]_{2S}$. In contrast, for the interlaminar stresses $\tau_{xz}$ and $\tau_{yz}$, the patterns were anti-symmetric. The anti-symmetric stress distributions occurred for both types of laminate.

The plots of the interlaminar stresses were compared between the models with and without curing using the same amount of remote stress. The results showed that the interlaminar stresses generated were large because of the curing thermal load. The magnitudes of interlaminar stresses due to the applied mechanical load were close to zero, while the thermal load generated large amount of stresses. They varied from compression and tension depending on the applied loads as well as the orientation of the plies.

In $[0/90/+45/-45]_{2S}$ laminate, the interlaminar stresses also showed significant difference between notched laminates with and without curing thermal load. For laminate without curing thermal load, the stress components $\sigma_{zz}$, $\tau_{xz}$, and $\tau_{yz}$ components were observed really small in comparison with laminate with curing thermal load. The stress difference was not as severe as $[0_4/90_4]_S$ laminate. It happened because the orientation of the fibers did not change as great as the $[0_4/90_4]_S$ laminate. Both types of laminate showed a symmetrical stress distribution for $\sigma_{zz}$ while for $\tau_{xz}$ and $\tau_{yz}$ an anti-symmetric pattern.
As can be seen in Figure 41, $\sigma_{zz}$ in notched laminate with curing is obviously has greater value than the laminate without curing thermal load. In this case, the maximum stress $\sigma_{zz}$ occurred in ply 2 and ply 15. The stress in plies 5 and 12 had the minimum value -13.4 MPa which meant this plies underwent a compression. The shear stress distribution $\tau_{xz}$ in Figure 42 below definitely shows an anti-symmetric distribution plot. By comparison, the interlaminar shear stress $\tau_{xz}$ without curing thermal load was less significant than the portion of with curing one. In laminate with curing, started from close to zero, $\tau_{xz}$ kept increasing in plies 1 to 4. The maximum value was 0.002 MPa at the boundary of plies 4 and 5. Shortly after reaching this peak, $\tau_{xz}$ decreased until it switched direction at the mid-plane. The decrease continued up to the interface of 90° and 0° where the values became a minimum and started to increase again. At the top of the thickness, $\tau_{xz}$ returned to close to zero again.
Figure 41. Comparison of shear stress $\sigma_{zz}$ at hole edge ($x = 0$, $y = r$) in $[0/90/\pm 45/\pm 45]_{2S}$ laminate without curing (mechanical load only) and with curing followed by mechanical load.

Figure 42. Comparison of shear stress $\tau_{xz}$ at hole edge ($x = 0$, $y = r$) in $[0_4/90_4]_S$ laminate without curing (mechanical load only) and with curing followed by mechanical load.
In Figure 43, anti-symmetric distribution was also noticed in shear stress $\tau_{xz}$ in quasi-isotropic laminate. However, in this laminate, the stress distribution had more variations. It happened because in $[0/90/+45/-45]_{2S}$ the orientations kept changing from one ply to another. The maximum $\tau_{xz}$ was observed at the interface of $45^\circ/-45^\circ$. It because the shear mismatch was the highest at the interface of $45^\circ/-45^\circ$ plies.

![Figure 43. Comparison of shear stress $\tau_{xz}$ at hole edge (x = 0, y = r) in $[0/90/+45/-45]_{2S}$ laminate without curing (mechanical load only) and with curing followed by mechanical load](image)

Comparison of shear stress $\tau_{yz}$ in $[0_4/90_4]_S$ and $[0/90/+45/-45]_{2S}$ laminates are shown in Figures 44 and 45. In both laminates the stress distributions were anti-symmetric about the mid-plane. In $[0_4/90_4]_S$ laminate, the maximum $\tau_{yz}$ generated at the interface between $0^\circ$ and $90^\circ$ plies. Meanwhile, In $[0/90/+45/-45]_{2S}$ laminate, the maximum $\tau_{yz}$ generated at the interface between $+45^\circ$ and $-45^\circ$ plies.
Figure 44. Comparison of shear stress $\tau_{yz}$ at hole edge ($x = 0, y = r$) in $[0/90]_S$ laminate without curing (mechanical load only) and with curing followed by mechanical load.

Figure 45. Comparison of shear stress $\tau_{yz}$ at hole edge ($x = 0, y = r$) in $[0/90/+45/-45]_{2S}$ laminate without curing (mechanical load only) and with curing followed by mechanical load.
5.2. Net-Section Stresses in Notched Laminate

In this thesis, net-section stresses are defined to be the stresses across the minimum section along the y-axis from the hole edge to the free edge. Figure 46 gives an illustration of the section. The average ply stress values were obtained from the mid-side nodes of each ply of the laminate.

![Figure 46. Net-section used for obtaining stress distributions](image)

All six stresses of IM7-977-2 notched laminate were plotted together at the nodes in this particular section A-A. From a careful observation of all the stresses plots in Figures 47 to 49 that includes the stress distribution for each ply, the overall plots can be grouped into three typical plots. The first group was the stress distribution that had significantly positive $\sigma_{yy}$ and significantly negative $\sigma_{xx}$. Meanwhile, the other stresses $\sigma_{zz}$, $\tau_{xy}$, $\tau_{xz}$, and $\tau_{yz}$ were of very small magnitudes so they looked very close to zero when plotted together. Some small magnitudes of stress occurred in the vicinity of the free edges, both at the hole edge and at the free-edge of the laminate in transverse direction.
The second group was the crossply transition in plies 4 and 5 (0°/90° interface), where the stresses close to the middle of the cross section A-A had relatively small, but much higher at both free-edges.

The third typical group consisted of the 90° plies located at the middle of the laminate (plies 6 to 12). In these plies, the stress distributions were the opposite of the group 1 that mainly consisted of 0° plies. Such appearance occurred simply because the loading that worked on each ply were different. In 90° ply, the load was in the form of compression. On the contrary, in 0° ply the load was in the form of tension.

Figure 47. Stress distributions in ply 1 along the minimum section (z = 0.0635) in [0/90]s laminate after curing followed by mechanical load.
Figure 48. Stresses distributions in ply 4 along the minimum section (z = 0.4445 mm) in $[0_4/90_4]_S$ laminate after curing followed by mechanical load.

Figure 49. Stresses distributions in ply 8 along the minimum section (z = 0.9525 mm) in $[0_4/90_4]_S$ laminate after curing followed by mechanical load.

Unlike the $[0_4/90_4]_S$ laminate, results of net-section stresses in $[0/90/+45/-45]_{2S}$ quasi-isotropic laminate (see Appendix B) cannot easily be grouped into plies with typical stress plots.
It was because the orientation of the ply changes from one ply to the next ply. In this quasi-isotropic, each ply interface acted as ply transition, except at the middle one where −45° ply was adjacent to another −45°.

One of the rudimentary observations in [0/90/+45/-45]_2S was that the significant amount of normal stresses σ_{xx} and σ_{yy} compared to other state of stresses. In six middle plies in the middle of cross section away from the free edges, it was observed that the longitudinal stress, σ_{xx} as well as transverse stress, σ_{yy} maintained consistent sign of stress distributions: σ_{xx} was positive whereas σ_{yy} was negative. Close to the free edges, the sign might reverse. Whereas in outer plies from the top and bottom surface, these σ_{xx} and σ_{yy} changed from compression to tension and vice versa after two plies. It also can be seen how τ_{xz}, in some plies developed significant values while other stresses than these three stresses were relatively very small.

![Figure 50. Stress distributions in ply 1 along the minimum section (x = 0, z = 0.0635) in [0/90/+45/-45]_2S after curing followed by mechanical load](image)
Figure 51. Stress distributions in ply 4 along the minimum section (x = 0, z = 0.4445 mm) in 
$[0/90/+45/-45]_{2S}$ laminate after curing followed by mechanical load

Figure 52. Stress distribution in ply 8 along the minimum section (x = 0, z = 0.9525 mm) in 
$[0/90/+45/-45]_{2S}$ laminate after curing followed by mechanical load
In Figure 53, the average normal stress $\sigma_{xx}$ for all 16 plies are plotted with respect to the distance from hole edge. It can be seen that in the load case without curing (mechanical load only) the average stress was relatively very small. In this case, all nodes in the minimum section underwent tension. However, for the load case after curing followed by mechanical load, at the hole edge, the average stress was approximately -16 MPa which means the laminate underwent compression. The maximum average stress was approximately 7.5 MPa. It can be observed that along the minimum section, the stress was predominantly in compression.

![Graph showing average stress $\sigma_{xx}$](image)

Figure 53. Comparison of average stress $\sigma_{xx}$ in notched laminate without curing (mechanical load only) and after curing followed by mechanical load

Distortion happened at the edge of the notch because of the applied loads. Even though the value of distortion was relatively small, it caused the horizontal and vertical diameter of the hole to change. The diameter lengths of the notch for different load cases after deformation are presented in the Table 4.
Table 4. Diameter changes of the notch subjected to different load cases

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Diameter after deformation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Curing</td>
<td>After curing followed by mechanical load</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(mechanical load only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal (mm)</td>
<td>Horizontal (mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical (mm)</td>
<td>Vertical (mm)</td>
<td></td>
</tr>
<tr>
<td>[0/90\textdegree]_S</td>
<td>6.00006</td>
<td>5.99998</td>
<td></td>
</tr>
<tr>
<td>[0/90/45/-45]_2S</td>
<td>6.00005</td>
<td>5.99998</td>
<td></td>
</tr>
</tbody>
</table>

As a brief summary, it is concluded from this study that [0/90\textdegree]_S notched laminate generated the highest interlaminar residual stress. The most critical interlaminar stress was normal stress, \( \sigma_{zz} \) at the interface of 0\textdegree and 90\textdegree plies. Meanwhile, for the quasi-isotropic [0/90/45/-45]_2S notched laminate, the critical one was shear stress \( \tau_{xz} \) at the interface of at the interface of 45\textdegree and -45\textdegree plies. The results of interlaminar stress caused by different load cases are tabulated in Table 5.

Table 5. Summary of maximum values of interlaminar stress in the vicinity of the notch

<table>
<thead>
<tr>
<th>Load case</th>
<th>([0/90\textdegree]_S)</th>
<th>([0/90/\pm 45/-45]_2S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\sigma_{zz}) (MPa)</td>
<td>(\tau_{yz}) (MPa)</td>
</tr>
<tr>
<td>Without curing (Mechanical load only)</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>After curing followed by mechanical load</td>
<td>47.9</td>
<td>20.7</td>
</tr>
<tr>
<td>Material strength [1]</td>
<td>62</td>
<td>75</td>
</tr>
</tbody>
</table>
In Table 5, it can be seen that the curing process contributes to significant stress levels in the notched laminate. Among the interlaminar stresses, $\sigma_{zz}$ was the most critical one with the maximum stress was approximately 48 MPa. The assumed material strength mentioned in the Table 5. was taken from Engineering Mechanics of Composite Material book [1]. Actually, the data mentioned were for IM7/977-3, but because of a very limited data available from references, these strength properties were assumed to be similar to facilitate a rudimentary comparison of the stress levels. It was observed that in the critical case, the curing process generates residual stress around 77% of the limit of the composite. This amount of stress is significant and drastically affects the actual limit of the laminated composites in the design.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From the results of the simulations, it can be observed that the curing process generates significant amount of residual stresses in the 16-ply IM7/977-2 UD laminates. It is common practice to assume that the interlaminar residual stresses are negligible in thin laminated composite. However, from this study, it is shown that the interlaminar stresses are not negligible and they have the potential to initiate failure, especially delamination.

Based on the results of the finite element simulations, the following points can be concluded:

1. The residual stresses induced by the curing process in unidirectional IM7/977-2 notched laminate were greater than those for the given mechanical load of 10 N.
2. Greater interlaminar residual stresses were generated in the [0/90]s notched laminate than the [0/90/+45/-45]2S and is attributed to ply grouping effects.
3. The critical interlaminar stress was normal stress $\sigma_{zz}$ in [0/90]s, whereas in [0/90/45/-45]2S, the shear stress $\tau_{xz}$ was the critical interlaminar stress.
4. The interlaminar tensile stress reached its maximum value at the interface between 0° and 90° plies because the differences in Poisson’s coefficient were the most severe. The maximum interlaminar shear stress occurred in the interface of +45° and -45° plies in [0/90/+45/-45]2S laminate.

None of the notched failure criteria currently used for laminated composite accounts for the effect of residual stresses. From this study, the critical interlaminar stress was calculated to
be approximately 77% of the material strength. Therefore, it is suggested to take into account the residual stresses in the design of composite structures. If the residual stresses are regarded, the actual margin of safety of the laminate can be significantly lower than the one calculated without residual stress.

Finally, there is a great chance to develop an improved failure criteria that include the effect of residual stresses in the future. However, in order to be able to establish a new failure theory that account for cure-induced residual stresses, more advanced, comprehensive and thorough analyses and experiments should be conducted.

6.2 Recommendations

The following recommendations are made based on the present study.

1. The residual stresses induced by curing in any design process should be considered.

2. Experimental tests using optical methods should be performed in the future to verify the residual stress induced by curing process.

3. Finite element analyses should include the effects of stress relaxation during cure and post cure.

4. In order to have a more detailed study on the cure-induced residual stresses in notched laminate, further studies should be done for a variety of stack-up sequences, material and dimensions.

5. Finer mesh should be used across the thickness to better capture the stress variations across the thickness.
REFERENCES
REFERENCES


APPENDICES
APPENDICES
Appendix A: Subroutine for deactivating elements to simulate drilling process

uactive.f

subroutine uactive(m,n,mode,irststr,irststn,inc,time,timinc)

#ifdef _IMPLICITNONE
implicit none
#else
implicit logical (a-z)
#endif

** Start of generated type statements **
integer inc, irststn, irststr, m, mode, n, j,m1
real*8 time, timinc
** End of generated type statements **

dimension m(2),mode(3)

user routine to activate or deactivate an element

m(1) - user element number
m(2) - master element number for local adaptivity
n - internal elsto number

mode(1)=-1 - deactivate element and remove element from post file
mode(1)=-11 - deactivate element and keep element on post file
mode(2)=2 - leave in current status
mode(1)=1 - activate element and add element to post file
mode(1)=11 - activate element and keep status on post file

mode(2)=0 - activate/deactivate element in all physics passes
mode(2)=1 - only activate/deactivate mechanical part in coupled
mode(2)=2 - only activate/deactivate thermal part in coupled

mode(3)=0 - activation/deactivation at the end of increment
mode(3)=1 - activation/deactivation at the beginning of increment

irststr - reset stresses to zero
irststn - reset strains to zero
inc - increment number
time - time at beginning of increment
timinc - incremental time

if(inc.eq.168) then
    do 100 j=1,432
        m1=44641+4*(j-1)
        if(m(1).eq.m1)then
            mode(1)=-1
            mode(2)=0
            mode(3)=1
        end if
    continue
100 end if

if(inc.eq.170) then
    do 200 j=1,432
        m1=44642+4*(j-1)
    end do
200
if(m(1).eq.m1) then
  mode(1)=-1
  mode(2)=0
  mode(3)=1
end if
200 continue
end if

if(inc.eq.172) then
  do 300 j=1,432
    m1=44643+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  300 continue
end if

if(inc.eq.174) then
  do 400 j=1,432
    m1=44644+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  400 continue
end if

if(inc.eq.176) then
  do 500 j=1,432
    m1=53569+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  500 continue
end if

if(inc.eq.178) then
  do 600 j=1,432
    m1=53570+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  600 continue
end if

if(inc.eq.180) then
  do 700 j=1,432
    m1=53571+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  700 continue
end if
end if
continue
end if

if(inc.eq.182) then
  do 800 j=1,432
    m1=53572+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if(inc.eq.184) then
  do 900 j=1,432
    m1=62497+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if(inc.eq.186) then
  do 101 j=1,432
    m1=62498+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if(inc.eq.188) then
  do 102 j=1,432
    m1=62499+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if(inc.eq.190) then
  do 103 j=1,432
    m1=62500+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if
if (inc.eq.192) then
  do 104 j=1,432
    m1=71425+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if (inc.eq.194) then
  do 105 j=1,432
    m1=71426+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if (inc.eq.196) then
  do 106 j=1,432
    m1=71427+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

if (inc.eq.198) then
  do 107 j=1,432
    m1=71428+4*(j-1)
    if(m(1).eq.m1) then
      mode(1)=-1
      mode(2)=0
      mode(3)=1
    end if
  continue
end if

return
end
Appendix B
Results of $[0/90/+45/-45]_{2S}$ laminate after curing followed by mechanical load.

Figure B1. Stress distributions in ply 2 along the minimum section ($x = 0, z = 0.1905$ mm) in $[0/90/+45/-45]_{2S}$ after curing followed by mechanical load

Figure B2. Stress distributions in ply 3 along the minimum section ($x = 0, z = 0.3175$ mm) in $[0/90/+45/-45]_{2S}$ laminate after curing followed by mechanical load
Figure B3. Stress distributions in ply 5 along the minimum section (x = 0, z = 0.5715 mm) in [0/90/+45/-45]$_{2S}$ laminate after curing followed by mechanical load

Figure B4. Stress distributions in ply 6 (x = 0, z = 0.6985 mm) in [0/90/+45/-45]$_{2S}$ laminate after curing followed by mechanical load
Figure B5. Stress distributions in ply 7 along minimum section (x =0, z = 0.8255 mm) in $[0/90/+45/-45]_{2\text{s}}$ laminate after curing followed by mechanical load.