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# HEALTH MONITORING OF COMPOSITE CAR ROOF FAILURE UNDER EFFECT OF DIFFERENT IMPACT VELOCITY

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Abstract

During this work, the roof of the car was used as an engineering application to study and monitor the occurrence of failures under the influence of various loads. The shells are made of multilayer composite materials using epoxy resin reinforced with carbon fiber and aluminium oxide granules as reinforcing materials to increase the impact resistance that vehicles may be exposed to while driving, in addition to other loads and conditions such as vibration and constant exposure to moisture and sunlight. The simulation program was used the finite elements method through software Abaqus program in addition to the program MATLAB v.2020a to process the data obtained from the method that used in this study. The results showed that the specified failure criteria work well for predicting the overall structural response such as strain, stress, maximum force and displacement. The losses of energy of impact collision increase as an increase in impact velocity. The dissipation of energy which depend on the stress and strain distribution during elastic deformations. The effect of thickness of the lamina plays an important role in health monitoring the structure.

Keywords: failure index, Tsai-Wu, health monitoring, car roof, stress analysis

## 1. INTRODUCTION

Composites materials are being used more and more frequently to make structures lighter and more effective. As a result, even though these materials are widely used in the aerospace and construction sectors, their use in the automobile and railroad industries is also growing. Examining impact response behaviors has become necessary as the use of composite materials in daily life increases. The fundamental objective of automobiles made of composite materials is to provide passenger safety, and as a result, adequate collision protection. Tests are conducted before moving on to the production phase for this purpose. Because they are more effective and efficient than experimental tests, numerical simulation tests and finite element modelling are used [1].

When great strength, changeable stiffness, exceptional durability, and minimal weight are required, fiber reinforced composites are an ideal material. They can be processed successively into laminates to create complicated geometries with regionally distinct properties. Using this quality, the integral construction design approach integrates various jobs into a single component. The number of integral components is rising, which results in significant reductions in system maintenance costs and structural weight [2].

There are now various solution techniques, even though the damage criteria were initially created from computations of isotropic materials. Non-interactive damage criteria, interactive damage criteria, and discrete damage criteria are also the three main topics under which these damage criteria are addressed. In this study, the Tsai-Wu damage criterion one of the discrete damage criteria and the Hashin's criteria another discrete damage criterion was combined and simulated using the ABAQUS software [1, 3]. Previous works deals with the failure analysis of composite shells under the influence of vibration and buckling loading in thermal conditions [4, 5].

Many researches have focused on studying the stresses generated in composite materials with the aim of analyzing the mechanical behaviour and determining how these materials respond during loading in order to monitor the performance of engineering systems and pre-predict sudden failures. One of these researches have examined the impact of inner pressure on failure modes and the impulse, load at penetration, and performed impact analysis of pressurized cylinder. They've found that the failure mode changes and there's a chance of burst failure when there is too much interior pressure [6]. Another study, the practical results of pressure tanks were compared with the results obtained from FEM simulations [7]. in addition to the use of failure theories in health monitoring of the shells and plates

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structures for functionally graded materials [8, 9]. Also, a 16-node cylindrical super element, static and modal analyses of composite hollow cylinders under different loadings and boundary conditions are performed. The validity of the results is demonstrated by a comparison with the exact solution and conventional finite element. The element efficiently estimates the structural behavior of laminated cylinders under complicated boundary and loading conditions [10]. The Stress Analysis on rotating composite cylindrical shells under interracial stresses as surface loading had been studied, every ply as well as ply group is considered an individual thin layer of relatively homogenous and orthotropic material. The equilibrium condition is used to determine the radial stress as a function of the circumferential stress, and an average consistency condition based on the thickness of the thin layer was being used [11].

Several studies discussed a first ply failure load for composite lamination plate under in-plane loading conditions was examined for various failure criteria. First layer failure strengths were examined in this condition for various ply angles and lamina numbers. Writing a FEM code in MATLAB and computing the failure load for each lamina in composite laminate using a number of different of failure criteria, including the maximum strain and stress failure criterion and the Tsai-Hill, Tsai-Wu, and Hoffman failure theories [12, 13]. Other studies discussed the effect of some additives on the mechanical behaviour of some types of polymers such as synthetic and natural rubber [14-16]. The strength of fiber-reinforced composite laminates that have been subjected to three different forms of loading: shear load, compression load, tension load. Compared to the fully plastic behaviour of the matrix, the nonlinear hardening behaviour of the matrix has a greater impact on the transverse strength of composite lamina. For the purpose of confirming predictions of the transverse strength under tension in such a uniaxial direction [17].

Other study, was established a finite element model for eight-node isoparametric elements for the shell and three-node curved beam elements for the stiffener are used in the analysis of the stiffened panels. Several failure theories, including the Max stress criterion, Max strain criteria, Hoffman criteria, Tsai-Wu criteria, and Yeh-Stratton criteria, were applied to estimate the first ply failure load using an iterative process [18]. Also, a fatigue damage analysis was carried out utilizing Tsai-Hill failure mechanism and the material stiffening degradation process to analyze double lap joints employing continuum shell components. The mechanism of failure was also verified using fatigue damage analysis, which had a strong connection with the stress test results. Matrix failure and Fiber failure were the two main forms of failure that were seen [19]. The effect of adding nanoparticles on the mechanical properties to prevent failure in structure was examined [20, 21]. The effects of three theories of failure on carbon/epoxy composite at various angles was examined by implementing the classical laminate theory to a MATLAB program using five layers of laminates, the strength ratio calculated using the last ply failure load was obtained without duplicating layers with the same angles [22]. While, the Puck failure criterion and fiber- and matrix-dependent damage factors in laminated composite were used to evaluate the initial failure and continuous failure.

Additional tests for artificially noised modal forms were conducted that use of time-frequency distributions may be a useful substitute for the well-known signal processing techniques used in these applications and is an efficient tool for the identification and localization of structural damage [23]. And the effects of surface states on the plate's dynamic behaviour as well as the contact forces caused by surface roughness. The effect of the moving exciter speeds on the dynamic response of the plate is also discussed in this study [24]. For the purpose of measuring the contact surface tension between a ball and a flat surface, two calibration approaches are suggested, test-based and analytic results-based methodology. The measured stress behaviours support the traditional Hertz hypothesis. This enables the use of thermos-elasticity to produce the first quantitative results for contact pressure distribution [25]. Advanced industrial mechanical components may be properly sized and designed utilizing analysis employing the finite element technique in accordance with various boundary conditions, internal loads, and vibrating amplitude [26]. other study discussed the possibility of identifying a composite material problem and by using the example of a structural interruption to understand the behaviour and the performance of some of these materials [27].

In this work, the health monitoring of car roof application which made from laminated composite shell under effect of different loads. The theory of failure in composite material were used to determined Tsia-Wu failure index to monitoring the stress concentration regions to achieve the failure mechanism.

## 2. THEORY OF FAILURE FORMULATION (TSAI-HILL THEORY)

Various failure modes are not properly accounted for in the Tsai–Wu failure criterion for matrix composites, as well as the factor F12 in the formula cannot be calculated by the fundamental materials strength values. The Tsai-Wu criterion had these two drawbacks; hence a new criterion was suggested based on the probable hypothesis that composites have infinite strength when subjected to pure hydrostatic pressure. The fundamental higher strength of the material is used to reevaluate some coefficients in the nonlinear tensor expression of the Tsai-Wu failure criterion, notably the coefficient

F12, under four different stress states. Based on various coefficient values under various stress levels, the reconstructed Tsai-Wu failure criterion may differentiate between several failure mechanisms.

Instead of dilatation, the von Mises focus on the relation to distortional strain energy (change in volume). When distortional and dilatational effects cannot be distinguished in the case of orthotropic materials, this theory as implemented to composite materials does not fall under distortional energy theory. Tsai was the first to link the failure strengths of an orthotropic lamination to the failure strength parameters in Hill's theory [28]. The Tsai-Hill theory is the name given to this failure hypothesis of orthotropic lamination. The maximum work theory is another name for it. Several writers have provided experimental evidence in favor of this concept, including [29].

Hill's criterion for anisotropic material yielding has the following form:

$$(G+H)\,\sigma_L^2 + (F+H)\,\sigma_T^2 + (F+G)\,\sigma_{T'}^2 - 2H\,\sigma_L\,\sigma_T - 2G\,\sigma_L\,\sigma_{T'} - 2F\,\sigma_T\,\sigma_{T'} + 2L\,\tau_{TT'}^2 + 2M\,\tau_{LT'}^2 + 2N\,\tau_{LT}^2 < 1 \quad \text{... (1)}$$

$$2N = \frac{1}{\tau_{LTU}^2} \quad \text{... (2)}$$

If only $\sigma_L$ acts, criteria (1) give:

$$(G+H) = \frac{1}{\sigma_{LU}^2} \quad \text{... (3)}$$

when $\sigma_T$ acts alone, criteria (1) give:

$$(F+H) = \frac{1}{\sigma_{TU}^2} \quad \text{... (4)}$$

And if $\sigma_{T'}$ acts:

$$(F+G) = \frac{1}{\sigma_{T'U}^2} \quad \text{... (5)}$$

And consider simply geometrical symmetry, it is extracted that: $\sigma_{T'U} = \sigma_{TU}$

Combining the three equations previously yields the following definitions of the three strength parameters:

$$2H = \frac{1}{\sigma_{LU}^2} + \frac{1}{\sigma_{TU}^2} - \frac{1}{\sigma_{T'U}^2},\ 2G = \frac{1}{\sigma_{LU}^2} + \frac{1}{\sigma_{T'U}^2} - \frac{1}{\sigma_{TU}^2},\ 2F = \frac{1}{\sigma_{TU}^2} + \frac{1}{\sigma_{T'U}^2} - \frac{1}{\sigma_{LU}^2} \quad \text{... (6)}$$

In case of plane stress or biaxial state, might be assumed that there is basically no stress present throughout the thickness, to get: $\sigma_{T'} = \tau_{LT'} = \tau_{TT'} = 0$. Consider the cross section of a typical lamina (ply) as a unidirectional lamina including fibers with in L direction and gives:

$$2H = 2G = \frac{1}{\sigma_{LU}^2},\ 2F = \frac{2}{\sigma_{TU}^2} - \frac{1}{\sigma_{LU}^2} \quad \text{... (7)}$$

Modifying the strength parameters in (7) produces:

$$G + H = \frac{1}{\sigma_{LU}^2}, \qquad F + H = \frac{1}{\sigma_{TU}^2} \quad \text{... (8)}$$

For the case of biaxial stress, substituting the strength parameters in (1) results in the Tsai-Hill failure theory. When the discrepancy around it is broken, failure begins.

$$\left(\frac{\sigma_L}{\sigma_{LU}}\right)^2 + \left(\frac{\sigma_L\ \sigma_U}{\sigma_{LU}^2}\right) + \left(\frac{\sigma_T}{\sigma_{TU}}\right)^2 + \left(\frac{\tau_{LT}}{\tau_{LTU}}\right)^2 < 1 \quad \text{... (9)}$$

Tensile strengths are substituted out for compressive strengths when normal stresses are compressive. It is important to note that by substituting the following values, the Tsai-Hill theory may be simplified to the von Mises theory in isotropic materials.

## 3. RESULTS AND DISCUSSION

Failure criteria were used in this section to get at the results for the first ply failure analysis (failure loading) of the composite lamination. Tsai-Hill failure criteria were used as the study's failure standards to health monitoring the car roof structure. In this work, the first ply failure stress was analyzed and determined in relation to various degrees of orthotropy, ply angles, plies number, and the lamina ply thickness. A multilayer composite material made of epoxy resin reinforced with carbon fiber and aluminum oxide granules as reinforcing materials is chosen for investigation. The dimensions of the composite laminate are 1.5 m long, 1.2 m wide, and 0.001 m thick per layer, respectively. Mapped mesh type with four-node rectangular element was used to define element shape and degree of freedom as shown in the figure 1. Low and high velocity impact loading is applied to a composite car roof geometry and boundary conditions as indicated in figure 2.

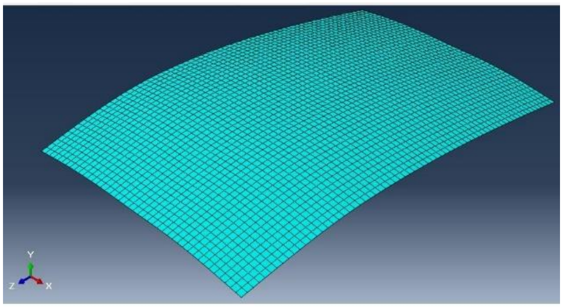

Fig. 1. Mapped mesh type

Through the results obtained from the analysis of the car roof, deformations, strain and strain (normal and shear component) under the influence of various impact forces due to different impact velocity were calculated. After extracting these variables, they are entered into the Tsai-Wu equation to calculate the failure criterion for the application used and based on the results of the mechanical properties of the materials used during the tensile and compression test.

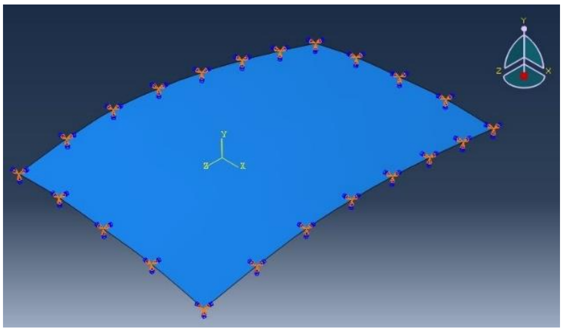

Fig. 2. Boundary conditions

Figures (3-9) show normal, shear strain and stress as well as Von Mises stress distribution on the composite laminated car roof under effect of low impact velocity (20 km/hr). The losses of energy of impact collision increase as an increase in impact velocity. The dissipation of energy which depend on

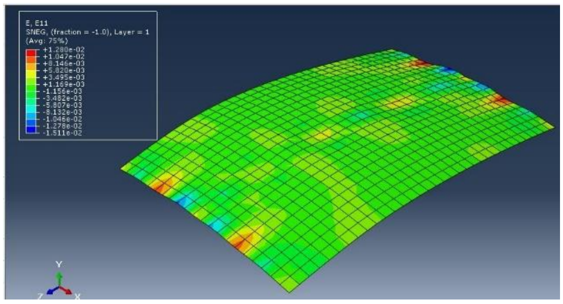

Fig. 3. Normal strain in x-direction

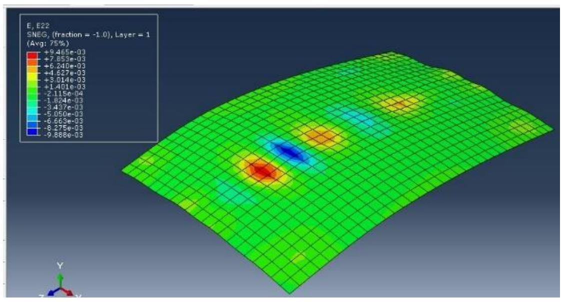

Fig. 4. Normal strain in y-direction

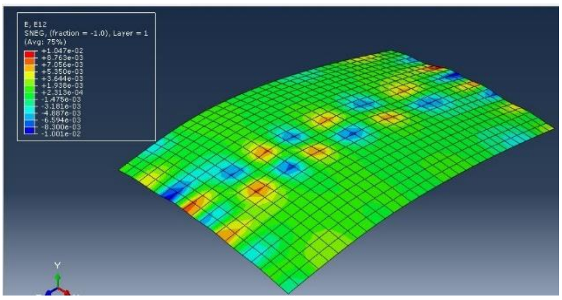

Fig. 5. Shear strain

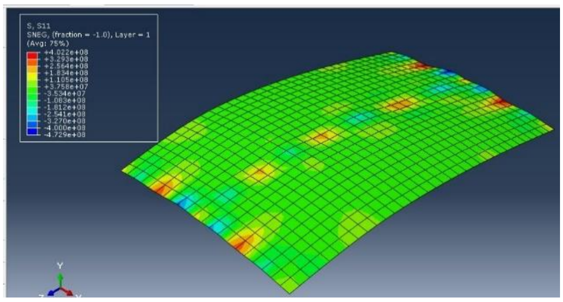

Fig. 6. Normal stress in x-direction

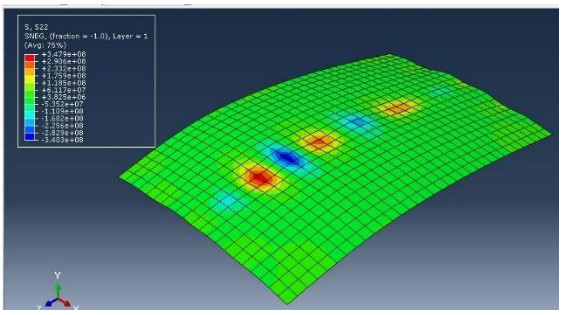

Fig. 7. Normal stress in y-direction

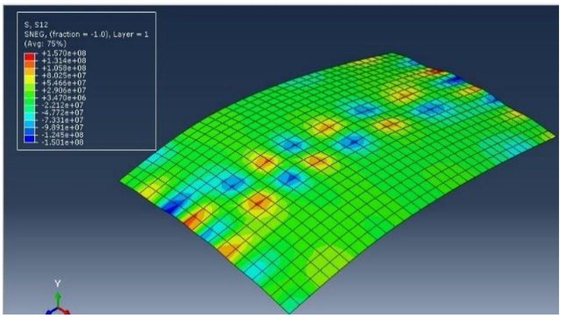

Fig. 8. Shear stress

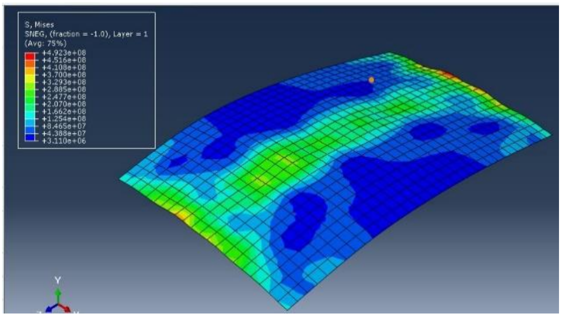

Fig. 9. Von Mises stresses

the stress and strain distribution during elastic deformations is influenced by the rate of deformation and increases with growing impact velocity. The dissipation of energy rises with deformation throughout plastic deformations and help to health monitoring of the car roof structure.

Figures 10-16 show normal, shear strain and stress as well as Von Mises stress distribution on the composite laminated car roof under effect of low impact velocity (100 km/hr). The dissipation of energy rises with distortion during plastic distortions. In high impact velocity, the material's plasticity greatly lowers rebound height due to high strain and stress. Due to significant plastic deformations, the height of rebound decreases with material ductility. Since the viscoelastic model becomes more viscous and the viscous resistance to deformations increases in comparison to the elastic resistance, in the event of an elastic impact, a reduction in elasticity results in a decrease in the rebound height. This causes the rebound height to decrease and energy losses increase. When

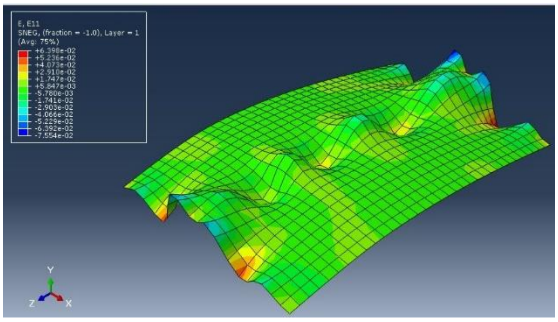

Fig. 10. Normal strain in x-direction

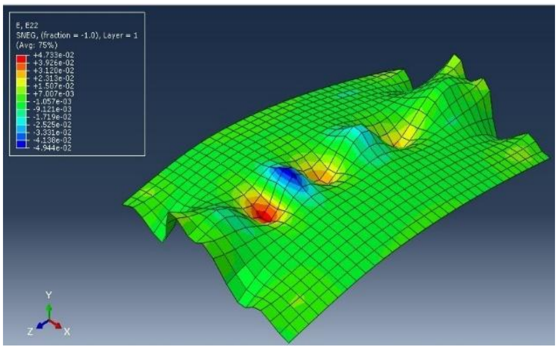

Fig. 11. Normal strain in y-direction

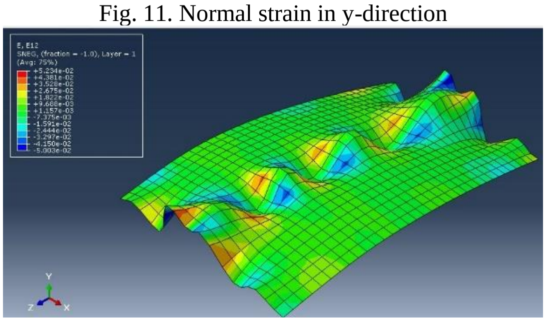

Fig. 12. Shear strain

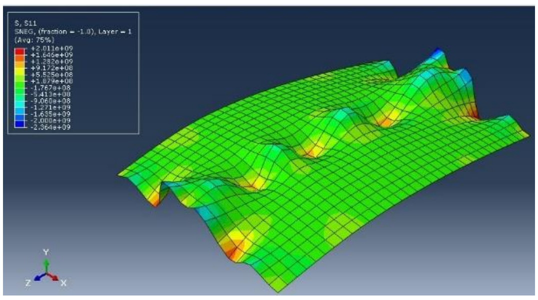

Fig. 13. Normal stress in x-direction

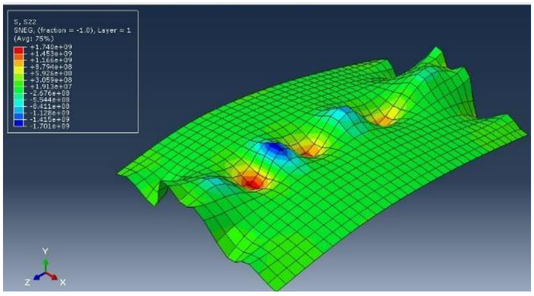

Fig. 14. Normal stress in y-direction

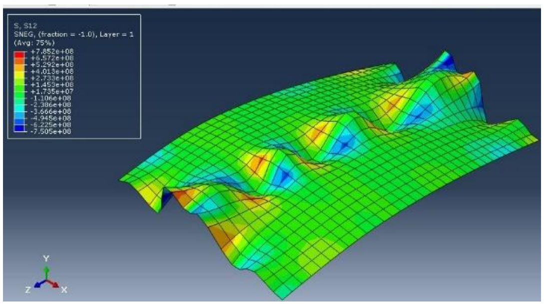

Fig. 15. Shear stress

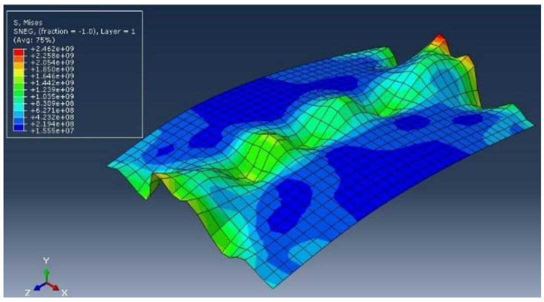

Fig. 16. Von Mises stresses

investigating the failure theories of car roof structure under the conditions of impact action, it is essential to take into consideration these parameters in order to increase the reliability of the health monitoring for the dynamic process.

Table 1 show normal, shear strain and stress as well as Von Mises stress values of the composite laminated car roof under effect of different impact velocity (20 km/hr, 40 km/hr, 50 km/hr, 80 km/hr, 100 km/hr). All of the specified failure criteria work well for predicting the overall structural response. When compared to experimental data from tests, failure criteria that exhibit less error in predicting the amount of dissipated energy typically tend to yield larger derivations in the prediction of maximum force, peak displacement, as well as impact time during contact. The Tsai-Wu criteria demonstrates the highest permanent displacement caused by poor tensile and compression damage separation.

Table.1. Normal, shear strain and stress

| Stress-strain | Velocity (km/hr) | | | | |
|---|---|---|---|---|---|
| | 20 | 40 | 60 | 80 | 100 |
| $\varepsilon_x$ | 0.0128 | 0.0256 | 0.0383 | 0.0511 | 0.0639 |
| $\varepsilon_y$ | 0.00946 | 0.0189 | 0.0284 | 0.0378 | 0.0473 |
| $\varepsilon_{xy}$ | 0.01047 | 0.0209 | 0.0314 | 0.0418 | 0.0523 |
| $\sigma_x$ (MPa) | 402 | 804 | 1207 | 1609 | 2011 |
| $\sigma_y$ (MPa) | 347 | 695 | 1044 | 1392 | 1740 |
| $\sigma_{xy}$ (MPa) | 157 | 314 | 471 | 628 | 785 |
| $\sigma_{Von}$ (MPa) | 492 | 984.7 | 1477 | 1969 | 2462 |

The MATLAB program was used to calculate the failure parameter depending on the resulting of strain failure criteria. A mathematical model was used with the MATLAB v.2020a program using the numerical analysis method, in addition, the influence of design variable was studied, such as on the Tsai-Wu failure criterion in three directions (longitudinal 11, transverse 22, shear 12). The effect of thickness of the lamina was drawn on this criterion to find out the parameters that most affect the resulting failure and to health monitoring the structure with the change of this parameter, in addition to the areas that are under the influence of a large load and can be treated to avoid the failure. The flow chart in figure 17 illustrates the procedures in the estimate process for the Tsai-Wu failure criterion in three directions for the suggested model.

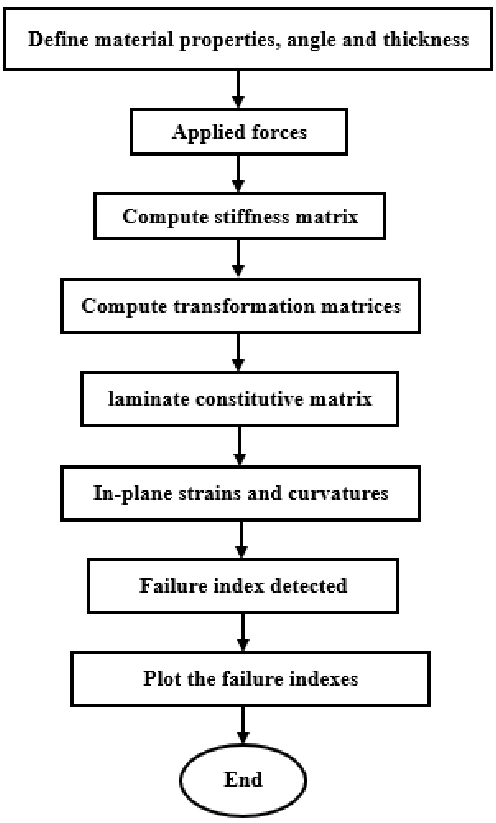


Fig. 17. Flow chart of Tsai-Wu failure index

Figures 18-22 show the effect of thickness parameters on Tsai-Wu failure index for different thickness values (3, 4, 5, 6, 8) mm.

It was noted from the results that the increase in thickness plays an important role in determining the criterion of Tsai-Wu failure. When the thickness is 3 mm, the Tsai-Wu failure criterion is greater than 1 in the transverse direction 22, this means that failure occurs, while when the thickness increases from 4-8 mm, the value of the criterion is smaller than 1, so the thickness values are safe from failure and withstand the impact load under different velocities.

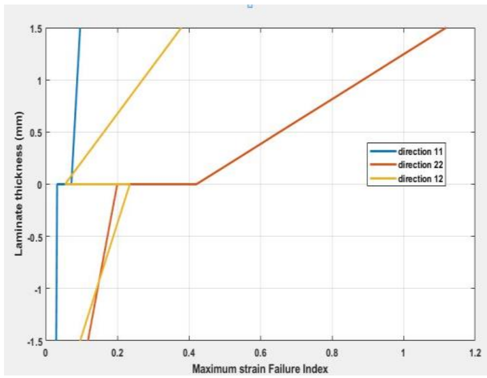


Fig. 18. Tsai-Wu failure vs thickness (3 mm)

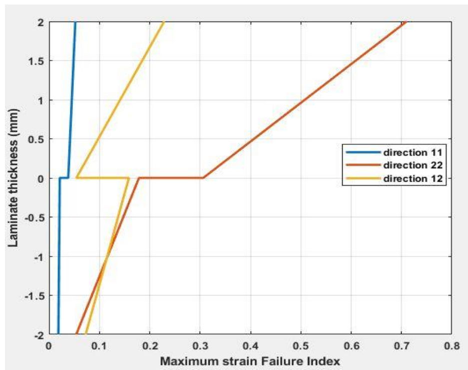


Fig. 19. Tsai-Wu failure vs thickness (4 mm)

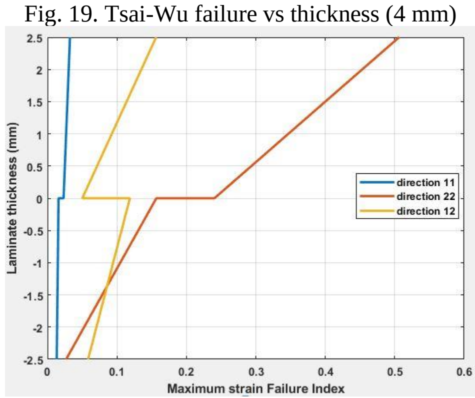


Fig. 20. Tsai-Wu failure vs. thickness (5 mm)

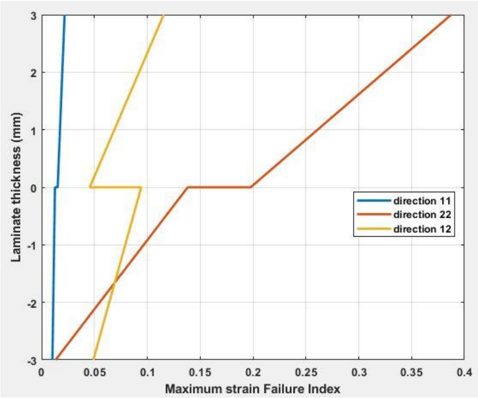


Fig. 21. Tsai-Wu failure vs. thickness (6 mm)

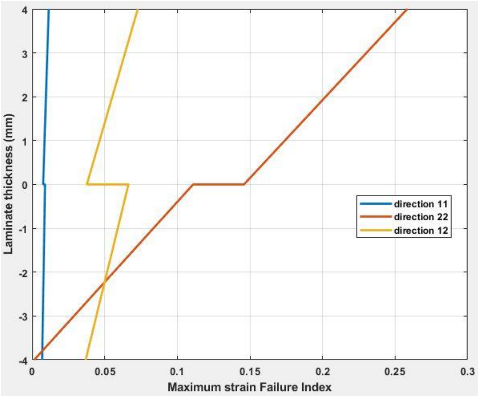


Fig. 22. Tsai-Wu failure vs. thickness (8 mm)

## 4. CONCLUSIONS

Failure criterion and damage development methodologies are incorporated into finite element models for a composite laminated shell's with low and high velocity impact behavior. The variance of the general mechanical response, as indicated by strain, stress, displacement, energy dissipation, and local damage, is thoroughly investigated. The significance of failure parameters and accumulation of damage techniques for estimating laminate impact damage at low and high velocity is examined. The following are the main findings:

1. The specified failure criteria work well for predicting the overall structural response. When compared to experimental data from tests, failure criteria that exhibit less error in predicting the amount of dissipated energy typically tend to yield larger derivations in the prediction of maximum force, peak displacement, as well as impact time during contact.
2. The losses of energy of impact collision increase as an increase in impact velocity. The dissipation of energy which depend on the stress and strain distribution during elastic deformations is influenced by the rate of deformation and increases with growing impact velocity.
3. In high impact velocity, the material's plasticity greatly lowers rebound height due to high strain and stress. Due to significant plastic deformations, the height of rebound decreases with material ductility.
4. When compared to experimental data from tests, failure criteria that exhibit less error in predicting the amount of dissipated energy typically tend to yield larger derivations in the prediction of maximum force and peak displacement.
5. The effect of thickness of the lamina plays an important role in health monitoring the structure with the change of this parameter, in addition to the areas that are under the influence of a large load and can be treated to avoid the failure.

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