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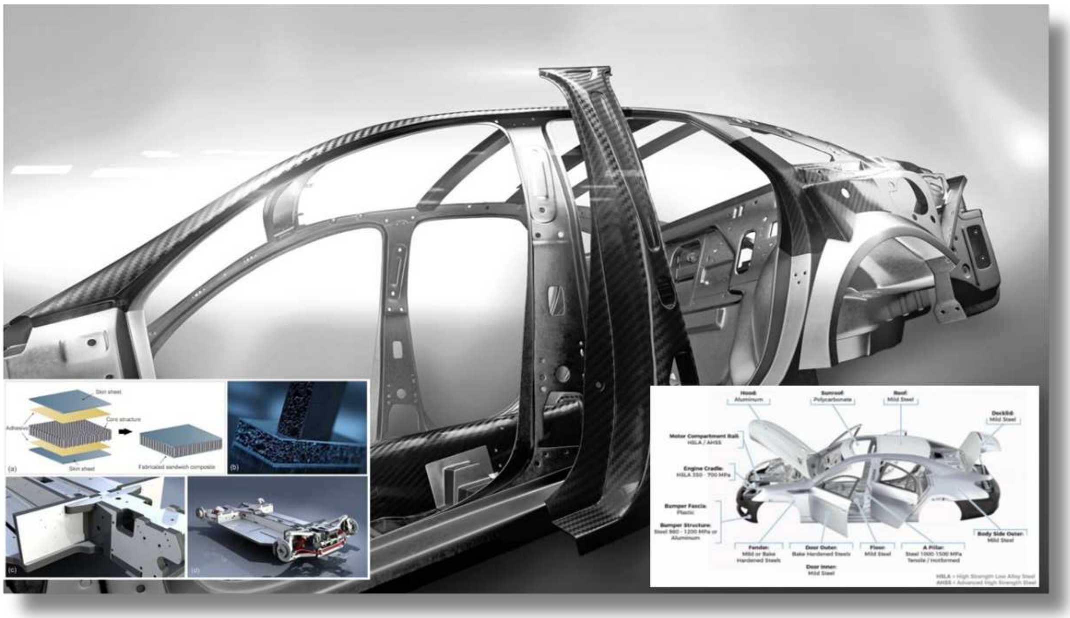
COMPOSITE MATERIAL FOR AUTOMOTIVE APPLICATION



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Composite Material for Automotive Application

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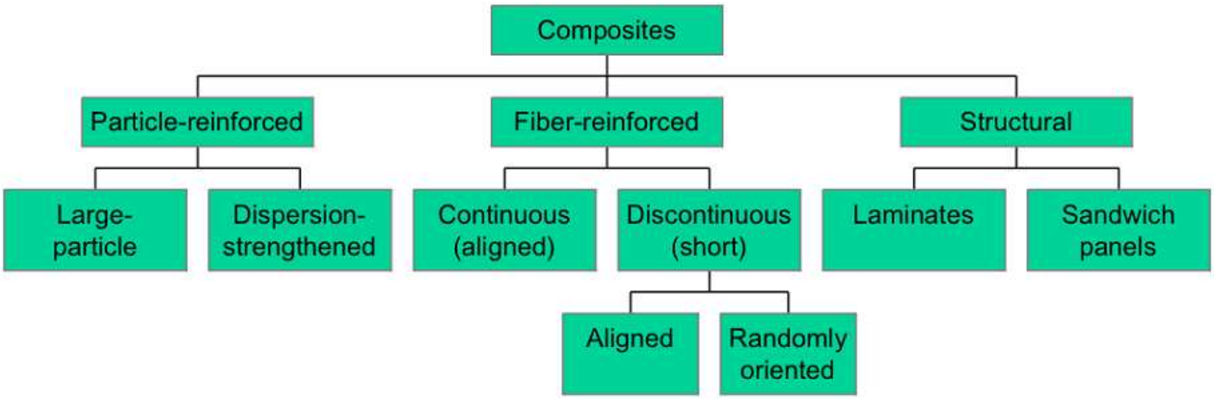
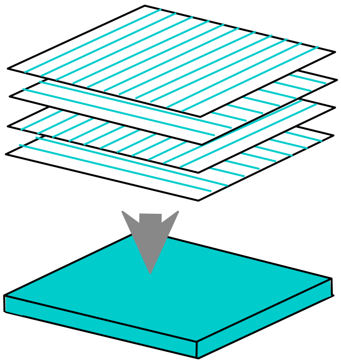
Introduction

Increasing demands for weight reduction, improved crash performance and stiffness requirements are shifting vehicle development towards advanced composite material. The recent trend shows that composite applications are not limited to sports cars but have also been introduced in serial production in various structural components. In this article foundation of composite materials, crash characteristics of crash materials, mathematical material models, failure modes of composite material, failure of bonds, delaminating, a testing method for materials, and some practical examples are demonstrated. The article is written keeping in mind the students and Engineers working in the area of research, CAE projects, and Manufacturing projects which involve composite applications.

A composite material is a combination of two or more materials to obtain a desirable combination of properties based on the principle of combined action. An example is low density and high strength. The composites are classified based on reinforcement and manufacturing methods. The following figure 1.1 shows the classification of Composites,

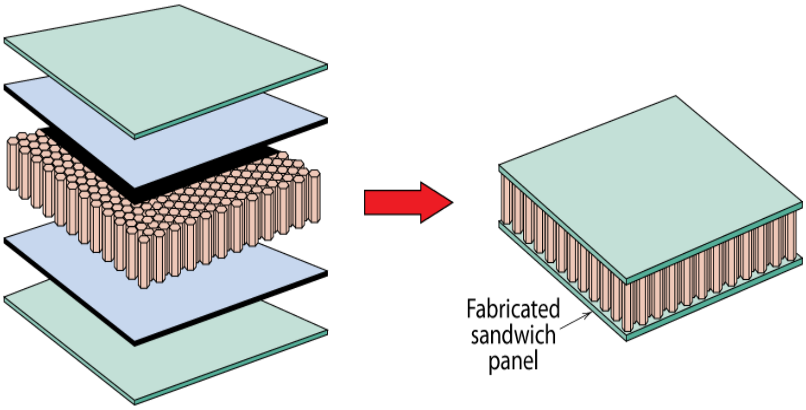


In this paper, the structural part of composites is covered. The typical structure of these composites is elaborated in Fig 1.2 Laminates and in Fig 1.3 sandwich panels.



The Laminates consist of staked and bonded fiber - reinforced sheets. These sheets have staking sequences e.g. 0deg,45 deg, 90 deg etc. The main benefits of this construction is in plane stiffness

Figure 1.3 below shows the sandwich panels. It consists of a honeycomb core between two sheets. The main advantage of sandwich structure is low density and high bending resistance.



Mechanics of Laminates

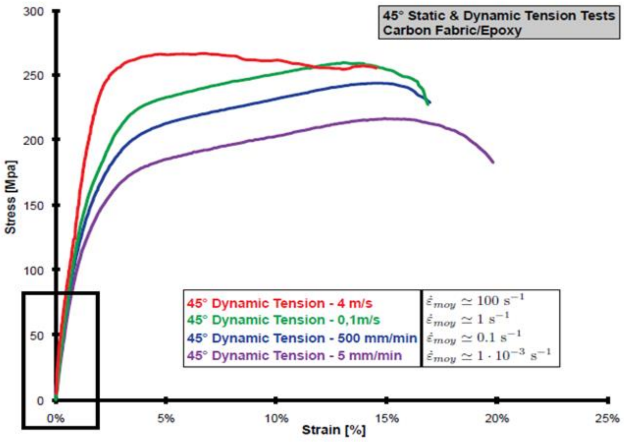
The objective of this session is to understand the code of stacking sequence and understand the relationship of stiffness. The stiffness of the laminate structure is mainly a function of elastic modulus, stacking position, thickness of ply, and angle of orientation. In crash-related behavior which is the dynamic event, the nonlinear material behavior, strain rate dependency, visco elastic behavior, effect of rotation of laminates, and failure of individual ply or many plies plays a very important role. Many theories specify the behavior of stiffness modeling.

Strain rate effects in composite

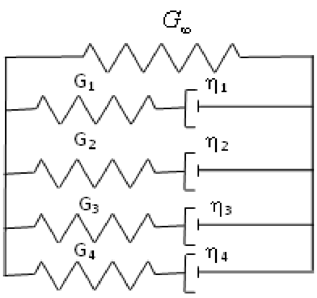
The following graph 1.4 shows the viscos elastic behavior of carbon fiber epoxy. There are two important aspects of viscosity as follows,

1. Visco-elastic Region: In this region the stiffness of a material is strain rate dependent. The increase in loading rate results in higher material stiffness. This region is marked in Graph 1.4 with a rectangular window. After unloading the material comes to the initial stage.

1. Visco-Plastic Region: In this region the stiffness of a material is strain rate dependent. This. After unloading the material has rest strain



The strain rate effect can be better explained by the Maxwell Model. This model is elaborated in Fig 1.5. In this model. In this model, the dashboards are added with the stiffness spring. The response of the dashboard is strain rate dependent. These dashboards result in additional deviatoric stress tensors. The additional stiffness is based on the Pony series sequence as a function of time.



Maxwell model

- The strain rate effect has the influence of yield of material in the form of material hardening. This effect can be mathematically plotted using the following formula. This formula can be used in compression, Tension, and Yield directions.

$$\sigma_y^i(W_P,\varepsilon)=\sigma_{0y}^i\left(1+bW_P^n\right)\left(1+c\ln\frac{\varepsilon}{\varepsilon_0}\right)$$

Where Wp is plastic work, b is hardening component

« i » stands for orthotropic directions 1, 2 and shear direction 12

The most commonly followed theory is Tai-Wu theory. The Tai-Wu composite material stiffness modeling is elaborated in detail below,

Tai-Wu Composite Material Theory

The theory addresses the following main crash composite material characteristics

- Linear elastic behavior until the yield stress value followed by a plastic behavior
- Lamina yield surface is the TSAI-WU yield criteria function
- Plastic hardening, the function of plastic work
- Strain rate dependency
- Failure model in tensile and maximum plastic work

The Tai-Wu failure criteria is expressed with below formula,

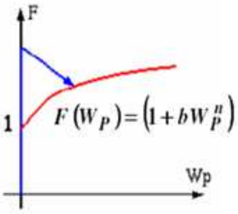
- Tsai-Wu criteria

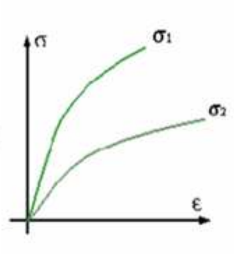
$$F=F_1\sigma_1+F_2\sigma_2+F_{11}\sigma_1^2+F_{22}\sigma_2^2+F_{44}\sigma_{12}^2+2F_{12}\sigma_1\sigma_2\leq F\left(\frac{W_p}{W_{ref}^p}\right)$$

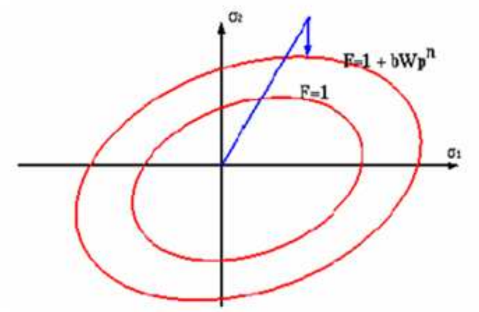
The Wp is plastic work and Wpref is reference maximum plastic work. The Wp value can be evaluated from the material stress strain curve which is derived by tensile test. The ply are failed when the ratio of plastic work to Wpref reaches to limiting value.

The Tsai-Wu function is updated according to plastic work and strain rate dependency. The equation for the same is given below,

$$F\left(\frac{W_p}{W_p^{ref}}\right) = \left(1 + b\left(\frac{W_p}{W_p^{ref}}\right)^n\right)\left(1 + c\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)$$





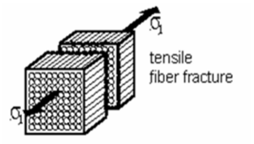


Composite Failure Models

The composite failure can be understood using three main failure models, namely Chan-Chan, Puck and Hashin failure Model.

Chan-Chan Failure model

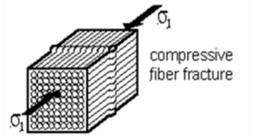
This model is suitable mainly for unidirectional composite. The failure occurs because of either each mode or a combination of these modes. These modes are namely tensile fiber fracture mode, compressive fiber fracture mode, tensile inter fiber fracture, and compressive inter fiber fracture mode. These modes and the formulas associated with them are elaborated below



$$e_f = \left(\frac{\sigma_{11}}{\sigma_1^t}\right)^2 + \beta\left(\frac{\sigma_{12}}{\bar{\sigma}_{12}}\right)^2 - 1.0$$

≥ 0 failed

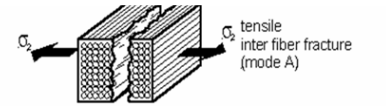
< 0 elastic − plastic



$$e_c = \left(\frac{\sigma_{11}}{\sigma_1^c}\right)^2 - 1.0$$

≥ 0 failed

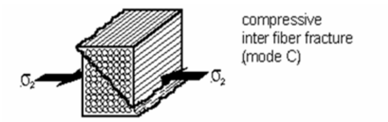
< 0 elastic − plastic



$$e_m = \left(\frac{\sigma_{22}}{\sigma_2^t}\right)^2 + \beta\left(\frac{\sigma_{12}}{\bar{\sigma}_{12}}\right)^2 - 1.0$$

≥ 0 failed

< 0 elastic − plastic



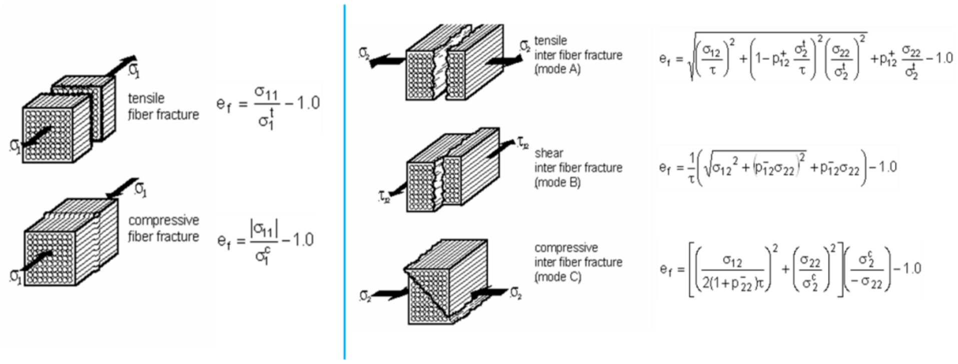
$$e_d = \left(\frac{\sigma_{22}}{2\bar{\sigma}_{12}}\right)^2 + \left[\left(\frac{\sigma_2^c}{2\bar{\sigma}_{12}}\right)^2 - 1\right]\frac{\sigma_{22}}{\sigma_2^c} + \left(\frac{\sigma_{12}}{\bar{\sigma}_{12}}\right)^2 - 1.0$$

≥ 0 failed

< 0 elastic − plastic

Puck Failure Model

This model is suitable mainly for unidirectional composite. The failure occurs because of either each mode or combination of these modes. These modes are namely tensile fiber fracture mode, compressive fiber fracture mode, tensile inter fiber fracture, compressive inter fiber fracture mode and shear inter fiber fracture. These modes and the formulas associate with them is elaborated below



$$e_f = \frac{\sigma_{11}}{\sigma_1^t} - 1.0$$

$$e_f = \frac{|\sigma_{11}|}{\sigma_1^c} - 1.0$$

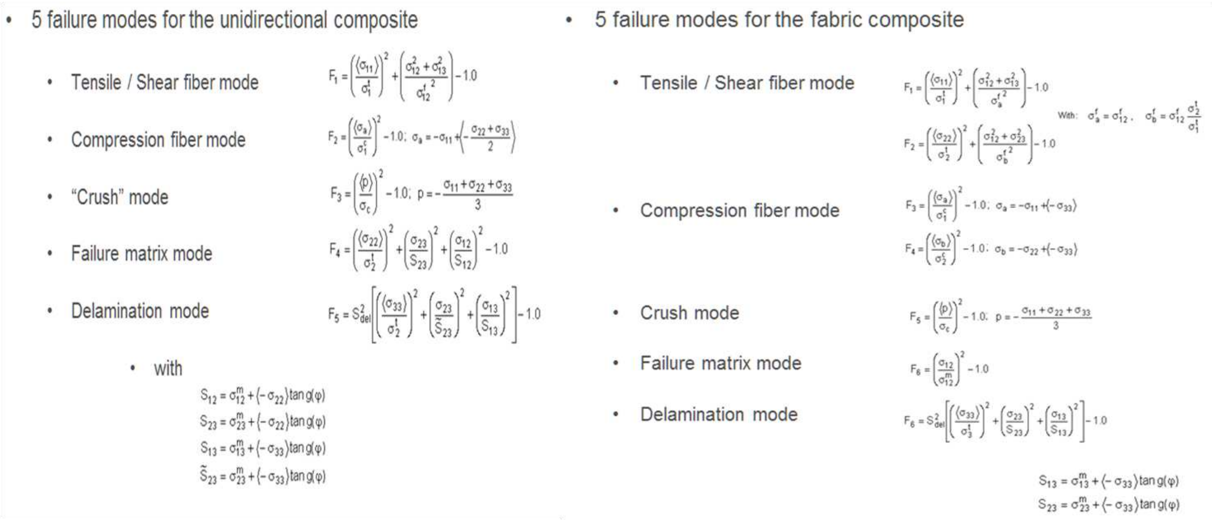
$$e_f = \sqrt{\left(\frac{\sigma_{12}}{\tau}\right)^2 + \left(1 - p_{12}^{+}\frac{\sigma_2^t}{\tau}\right)^2\left(\frac{\sigma_{22}}{\sigma_2^t}\right)^2} + p_{12}^{+}\frac{\sigma_{22}}{\sigma_2^t} - 1.0$$

$$e_f = \frac{1}{\tau}\left(\sqrt{\sigma_{12}^{\,2} + \left(p_{12}^{-}\sigma_{22}\right)^2} + p_{12}^{-}\sigma_{22}\right) - 1.0$$

$$e_f = \left[\left(\frac{\sigma_{12}}{2(1+p_{22}^{-})\tau}\right)^2 + \left(\frac{\sigma_{22}}{\sigma_2^c}\right)^2\right]\left(\frac{\sigma_2^c}{-\sigma_{22}}\right) - 1.0$$

Hashin Failure Model

This failure criterion is very widely used to model the failure of composites. This has five failure modes these modes are as follows, Tensile/shear fiber mode, Compression fiber mode, Crush mode, Failure matrix mode, and Delamination mode. The mathematical description is given below,



- 5 failure modes for the unidirectional composite
  - Tensile / Shear fiber mode $F_1 = \left(\frac{\langle\sigma_{11}\rangle}{\sigma_1^t}\right)^2 + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{\sigma_{12}^{t\,2}}\right) - 1.0$
  - Compression fiber mode $F_2 = \left(\frac{\langle\sigma_a\rangle}{\sigma_1^c}\right)^2 - 1.0;\ \sigma_a = -\sigma_{11} + \left\langle -\frac{\sigma_{22}+\sigma_{33}}{2}\right\rangle$
  - “Crush” mode $F_3 = \left(\frac{\langle p\rangle}{\sigma_c}\right)^2 - 1.0;\ p = -\frac{\sigma_{11}+\sigma_{22}+\sigma_{33}}{3}$
  - Failure matrix mode $F_4 = \left(\frac{\langle\sigma_{22}\rangle}{\sigma_2^t}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 - 1.0$
  - Delamination mode $F_5 = S_{del}^2\left[\left(\frac{\langle\sigma_{33}\rangle}{\sigma_2^t}\right)^2 + \left(\frac{\sigma_{23}}{\tilde{S}_{23}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2\right] - 1.0$
    - with

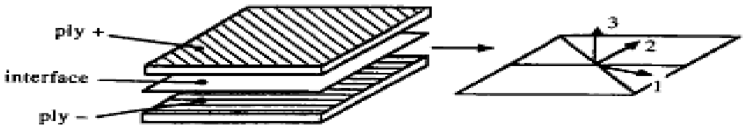
$$S_{12} = \sigma_{12}^m + \langle -\sigma_{22}\rangle \tan g(\varphi)$$
$$S_{23} = \sigma_{23}^m + \langle -\sigma_{22}\rangle \tan g(\varphi)$$
$$S_{13} = \sigma_{13}^m + \langle -\sigma_{33}\rangle \tan g(\varphi)$$
$$\tilde{S}_{23} = \sigma_{23}^m + \langle -\sigma_{33}\rangle \tan g(\varphi)$$

- 5 failure modes for the fabric composite
  - Tensile / Shear fiber mode $F_1 = \left(\frac{\langle\sigma_{11}\rangle}{\sigma_1^t}\right)^2 + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{\sigma_a^{f\,2}}\right) - 1.0$ With: $\sigma_a^f = \sigma_{12}^f,\ \sigma_b^f = \sigma_{12}^f\frac{\sigma_2^t}{\sigma_1^t}$
    $F_2 = \left(\frac{\langle\sigma_{22}\rangle}{\sigma_2^t}\right)^2 + \left(\frac{\sigma_{12}^2 + \sigma_{23}^2}{\sigma_b^{f\,2}}\right) - 1.0$
  - Compression fiber mode $F_3 = \left(\frac{\langle\sigma_a\rangle}{\sigma_1^c}\right)^2 - 1.0;\ \sigma_a = -\sigma_{11} + \langle -\sigma_{33}\rangle$
    $F_4 = \left(\frac{\langle\sigma_b\rangle}{\sigma_2^c}\right)^2 - 1.0;\ \sigma_b = -\sigma_{22} + \langle -\sigma_{33}\rangle$
  - Crush mode $F_5 = \left(\frac{\langle p\rangle}{\sigma_c}\right)^2 - 1.0;\ p = -\frac{\sigma_{11}+\sigma_{22}+\sigma_{33}}{3}$
  - Failure matrix mode $F_6 = \left(\frac{\sigma_{12}}{\sigma_{12}^m}\right)^2 - 1.0$
  - Delamination mode $F_6 = S_{del}^2\left[\left(\frac{\langle\sigma_{33}\rangle}{\sigma_3^t}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2\right] - 1.0$

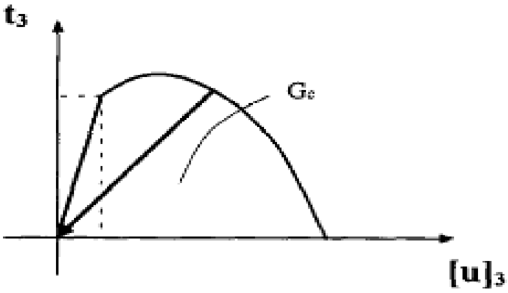
$$S_{13} = \sigma_{13}^m + \langle -\sigma_{33}\rangle \tan g(\varphi)$$
$$S_{23} = \sigma_{23}^m + \langle -\sigma_{33}\rangle \tan g(\varphi)$$

Delamination of Composite

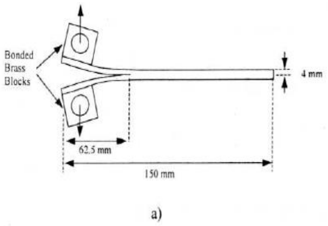
This is a complex phenomenon. The most used approach to describe it is so-called „meso-modeling “of fiber laminate and interface between them. In the simplest case these are two homogeneous layers and connecting interface between them. The following figure shows plies and their interface.



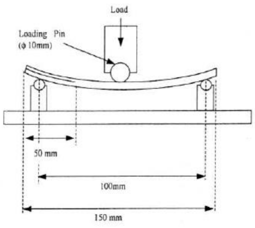
The figure shows below the vertical distance u3 vs interference force t3. The failure occurs when the energy absorbed by the bonding interface becomes greater than the allowed limit. In crash, the energy is absorbed by delaminating process



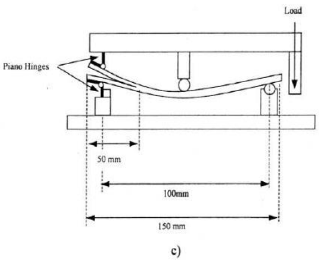
There are three standard test to describe the delamination phenomenon. These tests are Double Cantilever beam test, end notched flexure, Mixed mode bending. These all test are quasi static tests. These tests are performed with different ply orientations 0, 90, 45 Degrees.



Double Cantilever Beam



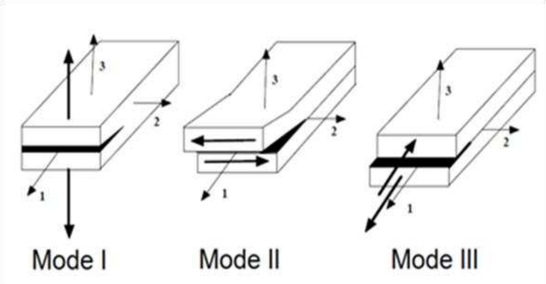
End Notched Flexure



Mixed Mode Bending

Ladeveze delamination failure Model

The delamination is explained well with Ladeveze delamination critia. The damage propagation in matrix by absorbing damage strain energy at damage interface. There are three modes of delamination as shown in below figure. The model consist of damage parameter d1,d2,d3 and Yi the value represent the energy absorbed by virtue of interface for corresponding failure mode, Y is the coupled energy coming from all failure modes, K values are linear stiffness of interface.



$$Y_{d_3} = \left.\frac{\partial E_D}{\partial d_3}\right|_{\sigma=cst} = \frac{1}{2}\frac{\langle\sigma_{33}\rangle^2}{K_3(1-d_3)^2}$$ Mode I

$$Y_{d_2} = \left.\frac{\partial E_D}{\partial d_2}\right|_{\sigma=cst} = \frac{1}{2}\frac{\langle\sigma_{32}\rangle^2}{K_2(1-d_2)^2}$$ Mode II

$$Y_{d_1} = \left.\frac{\partial E_D}{\partial d_2}\right|_{\sigma=cst} = \frac{1}{2}\frac{\langle\sigma_{31}\rangle^2}{K_1(1-d_1)^2}$$ Mode III

$$\begin{cases} K1 = \dfrac{2 \cdot G_{13}}{t} \\ K2 = \dfrac{2 \cdot G_{23}}{t} \\ K3 = \dfrac{2 \cdot E_{33}}{t} \end{cases}$$

$$Y = Y_{d_3} + \gamma_1 Y_{d_1} + \gamma_2 Y_{d_2} \quad \text{with } Y_{d_i}\Big|_t = \sup Y_{d_i}\Big|_{\tau \le t}$$

Conclusion

The composite materials can be effectively used for automotive crash application. The virtual material characteristics for composite material for perspective Visco elasticity, delamination is effectively possible through the mathematical formulation. The key is to formulate the composite ply construction for composite plies and bonding and evaluate through the mathematical tool the energy absorption of plies and bond through delamination.