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Failure mode analysis of ramie fiber reinforced composite material

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Abstract. This study aims to determine the failure mode of ramie fiber reinforced epoxy composite materials (RFRECM). The method used is testing the composite test sample that includes tensile test according to ASTM D 3039/D3039M, compression test according to ASTM D 695, simulation by using computer software, and morphology analysis by using Scanning Electron Microscope (SEM). The results show that RFRECM has SR ≥1 for failure criteria derived from stress theory, strain theory, and Tsai-Wu criteria, while having SR <1 only for the criteria of Tsai-Hill. Theoretically, the epoxy flax fiber composite has good strength in fiber or longitudinal direction (0^0) and decreases with the addition of the angle of the fiber. The failure mode of RFRECM is caused by voids, initial cracks, delimination and debonding occurring between 5-10% of the total area observed in the test sample. This condition can occur in all test samples as a result of imperfections of the fabrication process.

1. Introduction

One of the main problems in the development of natural fiber reinforced composite materials is knowing the failure mode, so it can be a reference in the process of loading given to components made of natural fiber reinforced composite materials. In general, the composite structure is said to fail when the structure cannot function properly. Thus, the definition of failure differs according to different needs. For the application of certain structures, small deformations are often considered to be a failure, while in other structures only total damage can be considered a failure [1], [2], [3], [4].The microscopic internal damage of the composite material cannot be easily observed directly in plain view. Damage can occur long before the damage is apparent. Microscopic internal damage includes fiber breaking, microcrack matrix, debonding anddelamination [5], [6], [7], [8]. The fiber may break because of the load it receives. If the matrix is capable of accepting a shear force and passing it to the surrounding fibers, the broken fibers will become more numerous resulting in cracks, which further leads to brittle failure. If the matrix is unable to accept the shear stress concentration that arises at the end of the broken fibers, the fibers can be detached from the matrix (in a process called debonding). The combination of the types of failure with broken fibers above occurs in any place accompanied by damage to the matrix causing brush-type damage [6], [7], [10], [11]. This type of microscopic internal damage cannot be visually observed at all, and is only visible when the frequency of damage is large enough in the same place. Therefore, in actual conditions, it is very difficult to determine when a composite material is declared damaged or failed. In most structural cases, the composite material fails when the material has been completely damaged, or the stress-strain curve shown is no longer linear. This condition applies both to lamina and laminate [6], [7], [8]. This study aims to determine the failure mode of RFRECM, by using the criteria of failure of maximum stress theory, maximum strain

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theory, Tsai Hill criterion and Tsai Wu criterion, so it can be used as a reference in designing components using RFRECM. An understanding of the failure mode can be used to anticipate failure of components made with RFRECM, making the process a lot safer to do.

2. Method and materials

2.1. Sample preparation

Samples of composite materials were prepared by using ramie fibers with epoxy matrix (RFRECM). Composite materials are manufactured by using hand lay up and laminate mat methods [12], [13], [14], [15].

2.2. *Mechanical properties testing*

RFRECM sample that has been made has its mechanical characteristics tested according to tests as follows Tabel 1.

Table 1. Mechanical properties testing [8], [9]

No.	Strength	Standard
1.	Tensile Strength	ASTM D3039/D3039M
2.	Shear Strength	ASTM D4255M-83
3.	Compressive Strength	ASTM D695

2.3. Calculation of failure criteriausing software

By using the result data of mechanical characteristics weand calculation of strength using composite micromechanical equation, strength ratio and failure criterion from RFRECM can be obtained by using Promal Composite Software [7].

2.4. Morphological analysis of RFRECM by scanning electron microscope

The result of this research is equipped with morphological analysis by using SEM to get interface information between the fiber and the matrix, so that the failure mode of RFRECMcan be known [6], [7], [8], [9].

2.5. Maximum stress theory

In this criterion, lamina failure occurs when one of the stresses σ_1, σ_2, and τ_{12}reaches the allowable amount of stress.

$$\begin{aligned} &-\left(\sigma_1^C\right)_{ult} < \sigma_1 < \left(\sigma_1^T\right)_{ult} \text{ or} \\ &-\left(\sigma_2^C\right)_{ult} < \sigma_2 < \left(\sigma_2^T\right)_{ult} \text{ or} \\ &-\left(\tau_{12}\right)_{ult} < \tau_{12} < \left(\tau_{12}\right)_{ult} \end{aligned} \quad (1)$$

2.6. Maximum strain theory

In this criterion, lamina failure occurs when one of the strain components ε_1, ε_2, and ε_{12} reaches the allowable amount of strain.

$$\begin{aligned} &-\left(\varepsilon_1^C\right)_{ult} < \varepsilon_1 < \left(\varepsilon_1^T\right)_{ult} \text{ or} \\ &-\left(\varepsilon_2^C\right)_{ult} < \varepsilon_2 < \left(\varepsilon_2^T\right)_{ult} \text{ or} \\ &-\left(\gamma_{12}\right)_{ult} < \gamma_{12} < \left(\gamma_{12}\right)_{ult} \end{aligned} \quad (2)$$

2.7. Tsai Hillcriterion
This criterion was developed based on distorsion energy failure theory by Von Mises for anisotropic materials. For orthotropic lamina, this criterion becomes:

$$\left[\frac{\sigma_1}{(\sigma_1^T)_{ult}}\right]^2 - \left[\frac{\sigma_1\sigma_2}{(\sigma_1^T)_{ult}^2}\right] + \left[\frac{\sigma_2}{(\sigma_2^T)_{ult}}\right]^2 + \left[\frac{\tau_{12}}{(\tau_{12})_{ult}}\right]^2 < 1 \quad (3)$$

2.8. Tsai Wucriterion
This criterion was developed based on total strain energy failure theory by Bestrami. This theory is applied to determine stresses on the lamina.

$$H_1\sigma_1 + H_2\sigma_2 + H_6\tau_{12} + H_{11}\sigma_1^2 + H_{22}\sigma_2^2 + H_{66}\tau_{12}^2 + 2H_{12}\sigma_1\sigma_2 < 1 \quad (4)$$

with: $H_1 = \frac{1}{(\sigma_1^T)_{ult}} - \frac{1}{(\sigma_1^C)_{ult}}$, $H_{11} = \frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}}$

$$H_2 = \frac{1}{(\sigma_2^T)_{ult}} - \frac{1}{(\sigma_2^C)_{ult}}, H_{22} = \frac{1}{(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}}, H_{12} = -\frac{1}{2(\sigma_1^T)_{ult}^2}$$

$$H_6 = 0, H_{66} = \frac{1}{(\tau_{12})_{ult}^2}$$

3. Results and discussion
3.1. Strength Ratio

Tabel 2. Summary of lamina micromechanical calculations

No.	Vf	σ_1 (MPa)	σ_2 (MPa)	τ_{12} (MPa)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	ε_1	ε_2	γ_{12}
1	0.1	131	46	12	5.1	3.2	1.2	0.290	0.02587	0.01439	0.0099
2	0.2	179	41	13	7.2	3.5	1.4	0.280	0.02473	0.01165	0.0099
3	0.3	226	38	15	9.4	3.9	1.5	0.270	0.02412	0.00955	0.0099
4	0.4	274	35	17	11.5	4.5	1.7	0.260	0.02374	0.00778	0.0099
5	0.5	322	32	20	13.7	5.2	2.0	0.250	0.02348	0.00622	0.0099

Note:
Ramie fiber: σ_f = 560 MPa, τ_f = 36 MPa, E_f 24.5 GPa, ε_f = 0.0287
Epoxy Matrix: σ_m = 40 MPa, τ_m = 34 MPa, E_m 2.9 GPa, ε_m = 0.021

Strength Ratio (SR) is the ratio between the load that can be accepted by the composite structure and the given load [7].

$$SR = \frac{Maximum\,load\ which\,can\,be\,applied}{load\ apllied} \quad (5)$$

The analysis by using SR is as follows:
a) If SR> 1, the lamina is safe and can accept the load
b) If SR <1, the lamina is not safe and cannot accept the load
c) If SR = 1, the lamina is not safe in accepting the load and is damaged.

Based on the test results of RFRECM and analysis using the Promal Software [7] and use equation (5), graph of the relationship between SR and fiber orientation can be made referring to some failure theory.

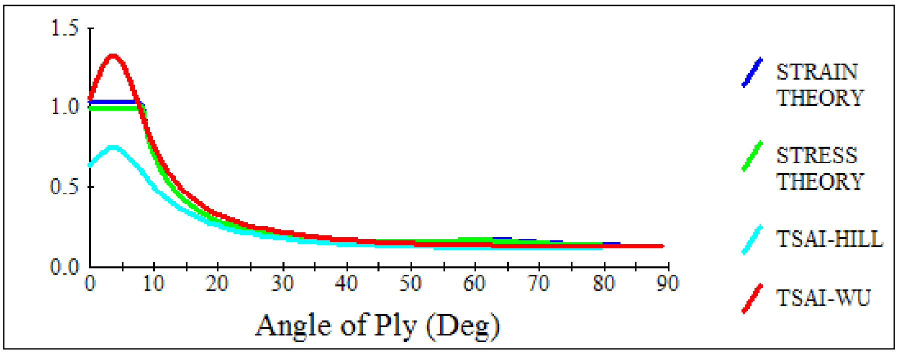
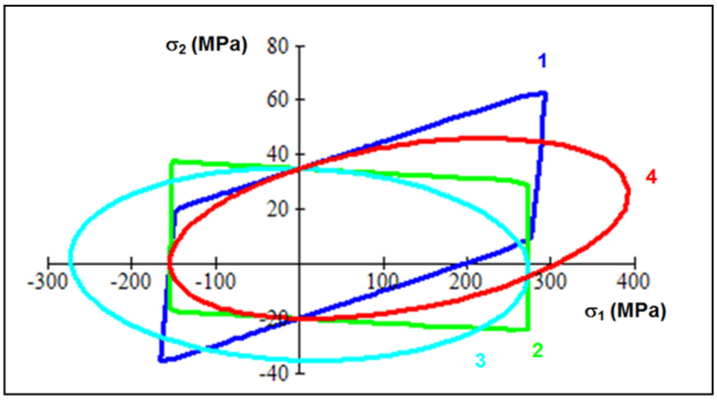


Figure 1. Strength Ratio (SR) of RFRECM

Based on Figure 1, the RFRECM has SR ≥1 for three failure criterias and SR <1 only for the Tsai-Hill failure criteria. Thus,RFRECM is theoretically capable of coping stress or strain and will not fail as long as the applied load does not exceed the maximum limit. In this case, it is necessary to set the maximum limit of load acceptable to the RFRECM.In accordance with theoretical studies,in the direction of longitudinal fiber (0^0), the fiber's ability to receive the load is excellent; however it will decrease along with changes in fiber orientation [17], [18], [19].

3.2. RFRECM failure mode

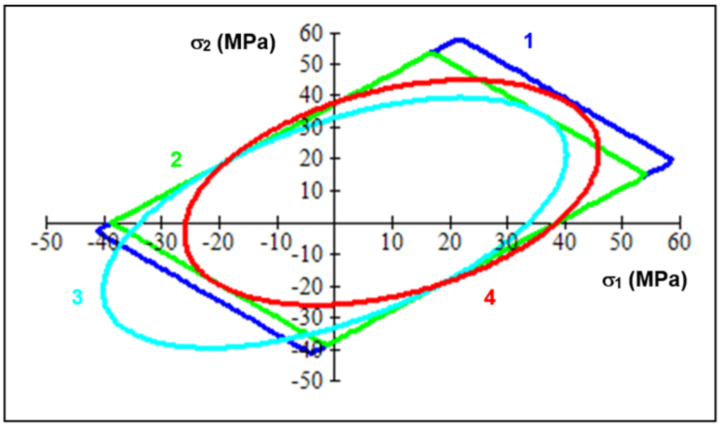
By using Promal Software [7] and use equation (1), (2), (3), (4), the failure envelope of RFRECM based on the four failure criterias can be described as one graph based on the following fiber orientation.



(1) Maximum stress theory; (2) Maximum strain theory;
(3) Tsai – Hill criterion; (4) Tsai – Wu criterion

Figure 2. Failure envelope of RFRECM (0^0)

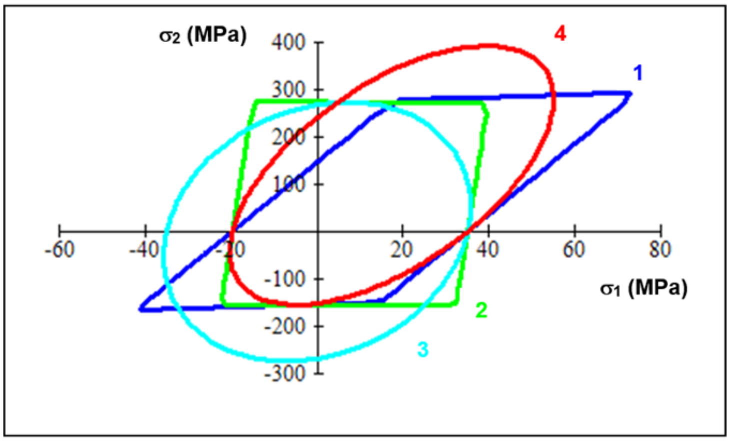
Based on the envelope image of lamina failure (Figure 2), it is seen that in the fiber orientation 0^0 (longitudinal), the fiber's handling of both the compressive load (positive X axis) and the compressive load (negative X axis) has greater value when compared to the same aspect in Y axis direction. This applies to all failure criteria. Lamina will fail in accordance with each criterion of failure if the received stress goes beyond the outer limit of each envelope. Lamina will be able to safely receive the load when the actual stress is still in the envelope [7], [20], [21], [22].



(1) Maximum stress theory; (2) Maximum strain theory;
(3) Tsai – Hill criterion; (4) Tsai – Wu criterion

Figure 3. Failure envelope of RFRECM (± 45^0)

In the fiber orientation ± 45^0, based on the failure envelope (Figure 3), it is seen that the lamina's ability to receive loads in the direction of ± 45^0 decreases when compared to the capability at the angle of 0^0. This applies to all failure criteria, either for tensile loads or directional tap X axis. Differences in the ability to with stand X-axis and Y-axis are not too large and tend to have the same value. This condition occurs because the load received by the lamina is distributed in a balance toward ± 45^0, although its ability is lower than the 0^0 angle.



(1) Maximum stress theory; (2) Maximum strain theory;
(3) Tsai – Hill criterion; (4) Tsai – Wu criterion

Figure 4. Failure envelope of RFRECM (± 90^0)

In fiber orientation 90^0 (Figure 4), lamina is able to accept larger quantity of load occurring on the Y axis, compared to the X axis. Thus, it can be concluded that the unidirectional loading of fiber will result in greater lamina strength to accept the load. As a result, the design of the loading direction of the lamina is cultivated in the direction of the fibers, which helps making the lamina not susceptible to damage due to the received load [6], [7], [9].

3.3. Morphological analysis of RFRECM by scanning electron microscope

The structure is declared to fail if it can no longer work properly. The definition of engineering material failure differs according to the application requirements of the product. For the application of certain structures, small deformations can already be considered a failure, while in the other structures, only total damage can be considered one. In composite materials, microscopic internal damage can occur long before the real damage is apparent. This microscopic internal damage occurs in several forms, such as fiber breaking, voids, matrix microcracks, debonding, and delamination [6], [7], [8], [9], [17], [20]. To obtain more real information on RFRECM damage mode, SEM (Scanning Electron Microscope) photos are used to observe delamination, debonding and void events of the test samples (Figure 5).

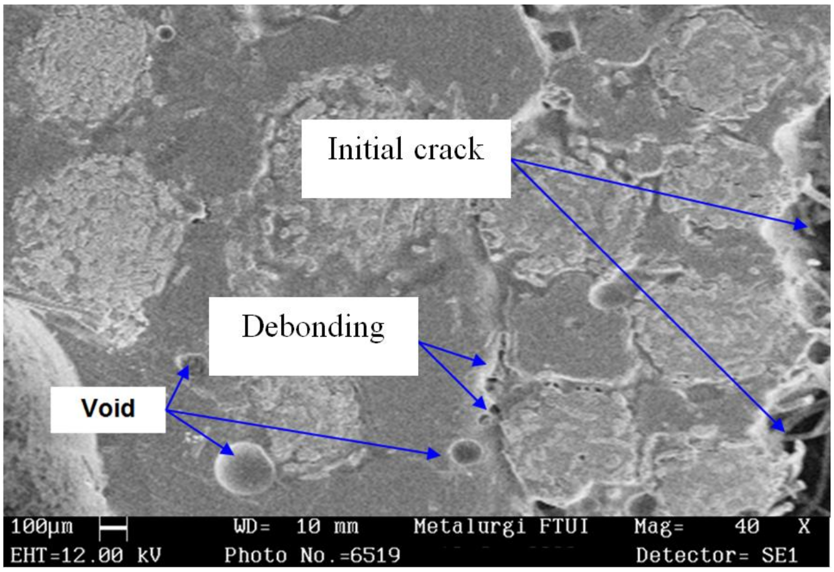


Figure5. Morphological analysis of RFRECM by SEM

Table 3. Result of morphological analysis of RFRECM by SEM

No.	Failure mode	% damage to total observation area
1	Initial crack	± 10%
2	Void	± 10%
3	Debonding	± 5%

In laminates with low fiber volume fraction (10-20%), there is a case of micro-cracking as a result of less strong bond between the composite layer and matrix. This occurs because in laminates with a small fraction of fiber volume (Vf <20%), the strength of the ramie fiber does not significantly affect the overall composite strength. The strength of the laminate composite is still influenced by the strength of the matrix. As a result of RFRECM with low fiber volume fraction,the failure occurs and the laminate becomes brittle. In laminate with medium fiber volume fraction between 30-40%, composite strength has been dominated by the strength of ramie fiber as a composite reinforcement. At Vf 30-40%, the bond between the fiber and the matrix is strong because the matrix is able to moisten the entire fiber perfectly, thereby greatly affect the final strength of the composite formed. The fracture form of the test sample is splitted in multiple areas, indicating the RFRECM with Vf 30-40% has good elastic strength and modulus. Damage does not occur in one place, but in many places in the form of fractures. At a high fraction of fiber volume (50%), the number of pre-delamination and voids occurring in RFRECM increases considerably. The matrix is unable to lubricate the entire fiber perfectly, so the bond between the fiber and the matrix is not strong. In these conditions, there is a lot of empty space that causes air to get trapped and therefore voids are produced. If the fiber is not dampened perfectly by the matrix, the bond between the fiber and the matrix becomes imperfect. In this case, the composite layer will easily experience debonding and delamination. Along with the occurrence of delamination and debonding, the composite strength also decreased [7], [15], [16], [17].

4. Conclusion

RFRECM has SR ≥1 for three failure criterias and SR <1 only for the Tsai-Hill failure criteria, which means that it has good strength,but will fail if the applied load exceeds the maximum limit of load. In accordance with theoretical studies, in the direction of longitudinal fiber (0^0), the fiber's ability to receive the load is excellent, however, it will decrease along with changes in fiber orientation [6], [7], [16], [17], [20]. RFRECM failure mode occurs due to voids, initial cracks, delamination, and debonding that take place between 5-10% of the total area observed in the test sample. This condition can happen due to imperfection of fabrication process by using hand lay up method at room temperature, in vacuum process with no pressure. With the imperfection of the fabrication process, ideal conditions such as the law of mixtures are difficult to obtain. In RFRECM fabrication process with hand lay up method, there are fabrication imperfections. Three major phenomena are successfully observed, either by direct observation of the test sample, fabrication process,and observation using SEM and macro photo aid. Therefore, it can be concluded that it is necessary to give correction factor to void, initial crack, and debonding to RFRECM.

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