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Effect of low velocity impact damage on the natural frequency of composite plates

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Abstract. Biodegradable natural fibers have been suggested to replace the hazardous synthetic fibers in many aerospace applications. However, this notion has been limited due to their low mechanical properties, which leads to the idea of hybridizing the two materials. Many aircraft components such as radome, aft body and wing are highly susceptible to low velocity impact damage while in-service. The damages degrade the structural integrity of the components and change their dynamic characteristics. In worst case scenario, the changes can lead to resonance, which is an excessive vibration. This research is conducted to study the dynamic characteristic changes of low velocity impact damaged hybrid composites that is designed for aircraft radome applications. Three materials, which are glass fiber, kenaf fiber and kenaf/glass fiber hybrid composites, have been impacted with 3J, 6J and 9J of energy. Cantilevered and also vertically clamped boundary conditions are used and the natural frequencies are extracted for each of the specimens. The obtained results show that natural frequency decreases with increasing impact level. Cantilevered condition is found to induce lower modes due to the gravitational pull. To eliminate mass and geometrical effects, normalized modes are computed. Among the three materials considered, glass fiber composites have displayed the highest normalized frequency that reflects on its higher stiffness compared to the other two materials. As the damage level is increased, glass fiber composites have shown the highest frequency reduction to a maximum of 35% while kenaf composites have the least frequency reduction in the range of 1–18%. Thus, kenaf fiber is taken to be helpful in stalling the damage progression and reducing the effect of damage. This has been proven when the percentage frequency decrement shown by kenaf/glass fiber composite lies between glass fiber and kenaf fiber composites.

1. Introduction
Owing to their comparably high mechanical properties, natural fibers especially kenaf fibers have been suggested to replace many highly hazardous synthetic fibers such as glass fibers that are commonly used for structural loads. However, as established in several studies, kenaf fibers have been unable to fully replaced glass fibers because the differences in mechanical properties between the two fibers are very high. This is why a lot of research works nowadays are focusing more on the hybridization of the natural and synthetic fibers [1–4]. Hybridization process can maintain the individual advantages of the two fibers and also alleviate some of their disadvantages. Hence the idea of hybridizing kenaf fiber with glass fiber is believed to be helpful in reducing the hazards from glass fiber and also enhancing the mechanical properties of kenaf fibers through the aid of glass fiber. Since then, a lot of researches have been carried out to investigate the mechanical properties of this hybrid material.
According to these studies, while non-hybrid composites exhibit the highest or lowest mechanical properties, the hybrid composites lie in between depending on the reinforcement fibers ratio [5]. This is generally referred to as the rule of mixture. Although hybrid composite is less likely to exhibit the highest material properties, it is often considered in order to tailor the material to the exact need of the structure under design. The needs typically revolve around the cost and weight factors, and also the biodegradability of the material. However, an impact damage can act as a limitation to the composites’ widespread application in the field. During operation, an aircraft is exposed to a number of events that can cause impact damage, mostly involving low velocity impact damages. For instance, dropped tools during maintenance routine and in-service impacts by foreign objects or debris can introduce an out of plane impact on the aircraft structures, which can be of low and high velocity impact. High velocity impact damage usually involves instant damage and failure on the impacted subject as it is dominated by wave propagation [6]. However, since fiber reinforced composites are highly sensitive to the low velocity impacts [7], the effect of this type of impact is studied in this research work. The effect of low velocity impact damage on the dynamic characteristic of a structure can be studied through a vibration testing and there are a number of studies that have been carried out on this matter. For instance, carbon fiber has been utilized as the reinforcement of a composite material and from the obtained results, it is concluded that natural frequency tends to decrease with increasing impact level [7–9]. Similar results have also been observed and reported in other experimental studies [10–12]. Therefore, it is crucial to assess the changes in dynamic characteristic at the early stage through accurate, time and cost effective tool such that service life of the structure can be extended and coincidence with resonant frequencies can be avoided.

The dynamic characteristics with impact damage have been widely researched for synthetic fibers and the induced impact has been shown to vary with low velocity, medium velocity and/or in ballistic form. However, there is an absence in post impact dynamic characteristics studies that involve natural fibers. There is also no studies found on the effects of hybridizing natural fiber with synthetic fibers to the modal properties after being damaged in a low velocity impact. Hence, this study is dedicated to study the effect of a low velocity impact damage on the modal properties of a natural fiber, synthetic fiber and hybrid natural/synthetic fiber composites, and investigate the resultant difference in dynamic response between the materials. Moreover, comparison of modal parameters between these materials without damage is also of interest in this study. The relationship between impact damage level and natural frequency has been highlighted in several previous studies. The effect of impact damage on the natural frequency of the materials is discussed but significant reviews on the vibration characteristics of natural fibers and its hybrid with synthetic fibers after impact damage can hardly be found, resulting in the lack of understanding when comparing the modal parameters change between the two materials.

2. Research Methodology
The flow of experimental work for this study is shown in Figure 1. The main materials used are kenaf fiber and glass fiber, together with the resins to produce the kenaf, glass and kenaf/glass fiber hybrid laminates. To obtain uniform thickness, the composites are designed according to their own physical properties as described below:

- Glass fiber composite – six layers of chopped strand mat fiber (random oriented)
- Kenaf fiber composite – two layers of woven kenaf fiber mats
- Hybrid kenaf/glass fiber composite – two layers of glass fiber mats with a layer of kenaf fiber mat sandwiched in between.

Typical setup for modal testing is depicted in Figure 2. Specimens for both damaged and undamaged cases are impacted with the roving hammer.
The experiment is conducted by varying two different clamping conditions: vertically clamped and cantilevered as shown in Figure 3. It is very common for EMA test to be conducted with cantilevered
condition as it represents the actual situation of most applications in the various fields such as the wing of an aircraft. However, in order to eliminate the gravitational force of a specimen under cantilevered condition, this study has also utilized the vertical clamping technique to investigate the behaviour of a structure without the interference of gravitational pull.

Modal analysis is conducted on the three types of materials: kenaf fiber reinforced composite, glass fiber reinforced composite and kenaf/glass fiber hybrid reinforced composite. This is the continuation work from previous study in [13]. All specimens are modelled to the dimension of 9.5 cm × 14 cm with the average weight is about 57 g for prior impact test [13]. For this study, the dimension is taken to be 9.5 cm × 14 cm, with 2 cm of the length is used for clamping. Each category of specimen for impact damaged (3J, 6J and 9J) and undamaged conditions is tested three times to obtain the average reading.

3. Results and Discussion

From frequency response function (FRF) graph comparing all three undamaged materials in vertical clamping condition in Figure 5, it can be seen that the pristine kenaf/glass fiber composite exhibits the highest natural frequency in all four modes. It is followed by the glass and kenaf fiber composites. The difference in frequency is not obvious in the first mode (i.e. first peak) among all three. Nonetheless, the variance gets higher while progressing to higher modes. On the other hand, for the cantilevered boundary condition shown in Figure 6, a similar trend to that of vertical clamping condition can be seen. However, the material with the lowest frequency in this case is the kenaf fiber composite and the highest is the hybrid kenaf/glass fiber composite. The main difference between the two FRF graphs for both cantilevered and vertically clamped is the variance of peaks in higher frequency. In this boundary condition, the shifting in higher modes or frequency is less significant compared to the previous graph.

The finding for all three types of materials is the same when comparing between cantilevered and vertical clamping conditions. Cantilevered is found to exhibit a lower frequency than vertical clamping condition. Although cantilevered is the boundary condition normally found in actual applications such as the aircraft wing, vertical clamping is preferred in order to maximize the isolation of gravitational
pull for the purpose of designing. At the same time, vertical clamping is also used in some parts of the aircraft structures like the stiffeners. The conclusion that can be drawn from the overlaid FRF graphs is that any shift in frequency as an effect of material or clamping conditions will take place in higher frequencies (higher modes).

The extent of damage effects on natural frequencies of the three configurations is discussed based on the graph representations for both clamping conditions shown in Figure 7. It can be observed that regardless of materials and clamping direction, the natural frequency will decrease with the increasing impact damage level and the natural frequency obtained under cantilevered condition is lower than the other clamping condition. This is because cantilevered structures suffered gravitational pull that tends to deform the structure. In other words, cantilevered boundary condition tends to reduce the stiffness of structure. The reduction trend has been expected because the introduction of damage will reduce the strength of a material.

An important thing to highlight in this study is the change in the dynamic response of each material with increasing level of damage. This can be discussed by analyzing the modes shift and percentage difference (shown in Figures 8 – 13). The frequency shift from undamaged to damaged states (3 J, 6 J and 9 J) for all three types of materials is observed to be high in the higher frequency range or higher modes. Based on this observation, it can be concluded that the effect of impact damage on a structure is much more apparent in higher frequency. The frequency shift in kenaf fiber composites is less when compared with that of sole glass fiber composite and hybrid kenaf/glass fiber composite. This shows that the impact resistance of the kenaf fiber composite is better than the other two materials as it can absorb the impact energy.

The trends obtained for cantilevered condition is similar to the previous boundary condition. The frequency shift can be noticed in all categories of materials for both clamping conditions and the shift is the lowest in kenaf fiber composite. As mentioned before, the frequency shift is more pronounced in higher frequency. Kenaf composite has the lowest natural frequency when it is undamaged. Once the
damage is introduced, its natural frequency starts to decrease but the decrement (i.e. minimum 1.1% and maximum of 18.03%) is not as significant as the other two materials. Natural frequency decrement of kenaf/glass fiber composite is in the range of 4.3-25.7% whereas glass fiber composites exhibit the highest decrement up to 35.4%. From the obtained results, two significant statements can be drawn: natural frequency of kenaf fiber composite decreases the least when impact damage in induced and the frequency decrement when the glass fiber composite is damaged is significant since the magnitude of decrement is high.

**Figure 8**: FRF overlay of kenaf composite for vertically clamped condition with different impact damage level

**Figure 9**: FRF overlay of glass composite for vertically clamped condition with different impact damage level

**Figure 10**: FRF overlay of kenaf/glass fiber composite for vertically clamped condition with different impact damage level

**Figure 11**: FRF overlay of kenaf composite for cantilevered condition with different impact damage level

**Figure 12**: FRF overlay of glass fiber composite for cantilevered condition with different impact damage level

**Figure 13**: FRF overlay of kenaf/glass fiber composite for cantilevered condition with different impact damage level
Figure 14 and Figure 15 show the percentage decrement from undamaged to damaged states. From the figures, the effect of impact damage on glass fiber composite on both clamping conditions is very high even when the impact induced is of low velocity. This may be caused by the brittle nature of the composite. It is also determined in [13] that glass fiber composite has higher stiffness as compared to the other two. This means that the composite has less ability to absorb the impact energy when it is impacted, which explains the big reduction of its natural frequency after being damaged. From all the observations, two statements can be drawn as conclusions. The first being the hybridization of kenaf with synthetic fiber is shown to improve the natural frequencies. In general, the act of hybridizing glass fiber with kenaf fiber has helped in reducing the natural frequency of the glass fiber composite by up 19.4%. The high natural frequency exhibited by the hybrid kenaf/glass fiber composite is due to several factors namely the structural mass, stiffness and damping. The second conclusion is that the least frequency reduction exhibited by the kenaf fiber composite can be related to the better resistance of woven fiber composites against the initiation of delamination, hence the high residual strength. This is also supported in previous studies done [14–15].

Glass fiber composite consistently shows the lowest natural frequency in all damaged cases among the three materials. Meanwhile, kenaf/glass fiber hybrid composites generally have the highest natural frequency in almost all cases. As this research work is the continuation of previous study in [13], glass fiber composite has been predicted to produce higher frequencies due to its high stiffness. However, the lower frequencies obtained by this composite material in this study can be contributed to several factors such as mass and geometrical variations. In order to eliminate these contributions, Figure 16 shows normalized frequencies in which glass fiber composite has portrayed the highest frequencies. It can also be concluded that the hybridization of kenaf with synthetic fiber has positive effects in term of natural frequencies decrement with post impact damage. This statement is made by referring to the slopes in Figure 16 where the glass fiber composite has higher steepness than the other two materials. Hence, the effect of kenaf in kenaf/glass fiber hybrid composite is believed to be capable in reducing the effect of damage on the composite as the slope difference between the glass fiber composites and kenaf/glass fiber composites is in the range of 20% to up to 64%.

4. Conclusion
In general, natural frequency decreases as the level of impact damage is increased. Furthermore, the frequency obtained under a cantilevered condition is lower than that in a vertically clamped condition. This is due to the gravitational pull in the cantilevered condition. Besides, the natural frequencies of
undamaged kenaf/glass fiber composites prior to normalization are higher than glass fiber composites, with kenaf fiber composites exhibiting the lowest natural frequency for both cantilevered and also vertically clamped boundary conditions. From the results obtained, it is shown that in kenaf/glass fiber hybrid composite, glass fiber is responsible in the strength attribute in which higher natural modes can be acquired while kenaf functions as the restrainer of the damage propagation. This is apparent from the following results:

- After normalized frequency is computed, glass fiber composite has the highest natural frequency, followed by kenaf/glass fiber and then kenaf fiber composites.
- Natural frequency of glass fiber decreases the most as it marks a maximum of 35.4% decrement in natural frequency decrement when damage is induced.
- Kenaf composite suffered the least natural frequency decrement at the range of 1 – 18% while the reduction of kenaf/glass fiber composites lie between kenaf and glass fiber composites.
- Kenaf fiber is then inferred as a useful material to slow down and reduce the effect of damage on a structure.
- The effect of damage on a glass fiber composite can be reduced (lower percentage decrement of natural frequency) through the hybridization with kenaf fiber.

| Mode 4 | Mode 3 | Mode 2 | Mode 1 |
|--------|--------|--------|--------|
| Cantilevered | Vertically Clamped | Cantilevered | Vertically Clamped |
| ![Figure 16: Normalized frequencies for all materials under cantilevered and vertically clamped boundary condition](image)

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