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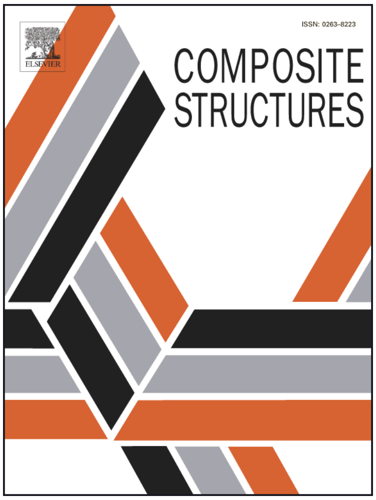

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Structural Integrity Assessment on Cracked Composites Interaction with Aeroelastic Constraint by Means of XFEM

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Abstract

In this paper, a novel approach in assessing the structural integrity of cracked composite plates under the aeroelastic condition by using XFEM is presented. To the authors' knowledge, this is the first time that aeroelastic condition is coupled in XFEM to model the crack propagations. Previous researches from the literature had only considered a static crack condition. This research focuses on determining the first failure experienced by the cracked composite plate, either the crack will propagate causing a fracture, or the composite plate will fail due to aeroelastic instability imposed at the critical flutter speed. The proposed scheme is used to solve the limitation in XFEM within Abaqus that only general static and implicit dynamic analysis can be performed. The structure is assumed to interact with minimal gust, and the deflections by time are expressed in the equation of periodic motion based on Fourier Series Function (FSF). The results show that at a particular fibre orientation, once the damaged composite plate is deformed due to the dynamics load at dive speed, it fails due to the crack propagation first instead of the flutter. In contrast, another fibre configuration shows good resistance to crack propagation and fails due to flutter instability.

Keywords: Aeroelastic; Crack; Composite Structure; Extended Finite Element Method (XFEM); Fourier Series Function (SFS); Gust.

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1. Introduction

In recent years, the composite has been widely used in UAV and small aircraft applications. However, to the authors' knowledge, the references on the composite structure analysis on this kind of aircraft are minimal. Most of the analyses focus on flight dynamics and control systems [1, 2]. In the circumstance, flight conditions and the propulsion engines cause some vibrations on the aircraft structure during its cruising condition [3]. The same consequence could be experienced to an exposed wing during the flight condition. This article presents an investigation of cracked composite plates under aeroelastic constraint state. The analysis purposed to assess the structural integrity of the plate which represents a small UAV wing spar under flight condition.

Prior to this objective, the same composite plate, exhibit as a 2D wing developed by [4] is used in this study. Over the past few decades, researchers began to investigate the effect of aerodynamic loading acting on a flying surface if the loads could trigger the crack propagation. For instance, an experimental has been carried out by [5] on sheet aluminium specimen with central notch and two fatigue cracks, to assess the crack propagation under lower and higher gust loads. Based on the fractographic inspection, there was a fracture surface transition from the bending(tensile) mode to the torsional(shear) mode during the crack growth. In the state of this condition, the flight simulations for the assessment has been done to validate the results [6].

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In addition, there are some concerns about in the event of aerodynamic load can cause a vibrational motion. A crack identification on rotor was done by [7], which managed to predict the possibility of having another cracks development once the pre-existing open crack underwent a vibrational mode. There is an interesting approach that was established by [8] to model the transversal crack and delamination of laminated carbon fibre reinforced polymer (CFRP) under vibration fatigue by applying the Virtual Crack Closure Technique (VCCT). In another hand, the VCCT was used to calculate the Strain Energy Release Rate (SERR) at the crack tip of opening delamination under vibration conditions. Another high fidelity approach such that continuum damage mechanics [9] in damage modelling has been utilised.

One of the destructive aeroelastic phenomenons is known as flutter. Flutter phenomenon occurs when there is an interaction between the structural elasticity, aerodynamic loads, and the inertia forces. When a structure been excited near to the flutter speed, the structure begins to vibrate. In the case of horizontal planform structure such as wing or bridge that deals with the proportional direction of freestream flow, the structure will vibrate and begin to oscillate. In severe condition, when the structure deforms, the aerodynamic distribution on the structure will increase, and subsequently, increase the oscillating rate. If the structural damping could not sustain the load, the structure will fail.

However, due to several reasons, it has cast doubt on the failure potential when there is existing damage such as a crack on the structure when it interacts with the aerodynamic load. In this case, there is a curiosity on either the flutter will come first or the cracked structure will fail due to the fracture circumstance. The flutter computational results on cracked unidirectional composite plates by [4], where the structures were modelled as beam elements. The flutter results were computed using the Galerkin method, where the structures were coupled with strip theory for the aerodynamic modelling. The same investigation has been continued by [10] where the flutter on the cracked composite structures have been assessed using an advanced computational technique of *pk-* method by coupling the 2D structures using finite element (structural) and doublet lattice method (unsteady aerodynamic). The flutter assessment results published by [10] shows a good agreement with results presented by [4]. In addition to that compliance, [10] found an exciting discovery where the critical flutter speed may increase due to the small crack appearance, supported by the flutter responses and the aerodynamics insight.

The numerical results by [4] and [10] have brought new observations in the aeroelastic field, however, the analyses were based on the static crack condition. Hence, crack propagations were not considered. In general, with the increment of speed, the aerodynamic load will also increase. This event is supported with several occurrences in some researches such as long-span suspension bridges interaction with freestream flow [11], transient load and tornado effect on buildings investigation [12] and aerodynamic load control using blade on wind turbine [13]. In the state of this condition, the aerodynamic load will deform the structure, or increase the displacement. Thus, in the case of an already cracked structure, the crack propagation is expected.

In the event of this matter, an extended investigation is significantly applied for any cracked structure to observe the propagations possibility. In this present work, the cracked unidirectional composite plates failure subjected to the aerodynamic load is investigated. The newly proposed mechanism seeks to bridge the computational aeroelasticity module, i.e., flutter and gust load, with the computational fracture analysis module. A novel approach by introducing the Extended Finite Element Method (XFEM) is proposed herein. XFEM is applied to establish the fracture mechanism, i.e., crack propagation.

2. Mathematical and Computational Model of the Aerofracturelastic Investigation

2.1. Aeroelasticity model

In the present work, as stated earlier, the focus will be on performing crack propagation for a lifting structure under aeroelastic condition. Hence, there are two main concerns whether the structure will fail due to instability caused by aeroelastic load, i.e., flutter, or it will fail before instability occurs, i.e., crack growth caused a major fracture. To do so, crack is initiated in the structure, and it is exposed to the aerodynamic load.

The present work will focus on the flutter instability as the critical limit for the speed. Computational flutter analysis in aircraft industries mostly performed by means of panel method unsteady aerodynamic, i.e., the Doublet Lattice Method, and series of flutter solution models, i.e., k method, p-k method. Detailed computational model and algorithm of these methods can be found in [14]. However, it is important to note that these methods are based on the frequency domain and eigenvalue solutions on the instability. Hence, the flutter responses obtained is in the form of the eigenvector, not a real displacement. Therefore, to gain real displacement as input for fracture analysis, another approach is required.

During a flight, an aircraft regularly encounters atmospheric turbulence of ranging degrees of severity. Technically, turbulence is considered as a movement of the air through which the aircraft passes [15]. Therefore, any component of the velocity of the air (so-called 'gust velocity') that is normal to the flight path shown in Figure 1. Also, the vertical gust situation will change the effective incidence of the aerodynamic surfaces, so causing abrupt changes in the lift forces and hence a dynamic response of the aircraft involving flexible deformation and gust inputs are also considered along the flight path.

In the present work, a concept of the small gust is introduced to obtain the displacement on each speed variation. Although the gust always deals with an extreme flow and cause perturbation [16], the gust load implemented here should be lower as possible. The discrete 1-cosine gust is applied as the source of excitation as illustrated in Figure 1. Equation 1 expressed the gust speed, w_g, in terms of 1-cosine function of the distance, x_g. The gust length and maximum gust speed are denoted by L_g and w_{g0}, respectively.

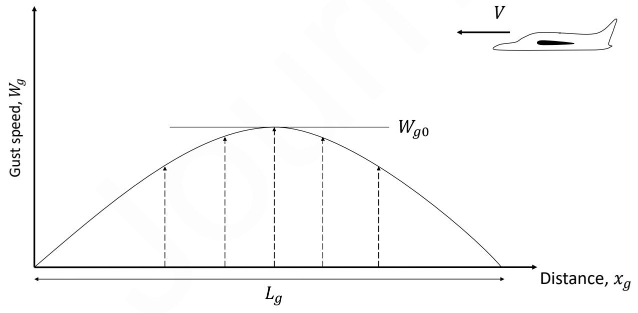

Figure 1: '1-Cosine' Gust Illustration

$$w_g(x_g) = \frac{w_{g0}}{2}(1 - cos\frac{2\pi x_g}{L_g}), 0 \leq x_g \leq L_g \quad (1)$$

In the present analysis, the total lift acting on the plate is summed as in Equation 2, where $L(V_\infty)$ is the lift due to the aerodynamic distributions and $\Delta L(V_g, t)$ is the lift generated by the gust load. However, in this work, the lift due to the airstream, $L(V_\infty)$, is assumed to be dominating the lift distribution while the lift due to the gust load is minimal. In the next sections, an approach to quantify a reasonable value of the small gust is discussed. The airstream velocity, V_∞, is increased from cruise until the critical flutter speed while the crack propagation is observed.

$$L_{Total} = L(V_\infty) + \Delta L(V_g, t) \quad (2)$$

2.2. Introduction to Extended Finite Element Method (XFEM)

For completion, in this section, a brief introduction to XFEM is presented. Ted Belytschko and collaborators initiated XFEM in 1999 [17]. One of the most significant features of XFEM is the enrichment function. This enrichment function allows minimum or even no remeshing to simulate the crack propagating on the structure. It solves the discontinuity within the element by introducing an additional shape function to a standard FEM formulation. Equation 3 shows the approximate displacement in the standard FEM formulation, where $N(x)$ is the shape function, and d is the change of displacement in every node.

$$u(x) = \sum_{j=1}^{n} N_j(x) d_j \quad (3)$$

By means of XFEM formulation, discontinuity within an element is incorporated in the enriched nodes. The added enrichment function is shown in Equation 4. The shape function in the second term is added as the enrichment for solving the extra degree of freedom node, which is expressed as a_j with m as the nodes enriched by the Heaviside function. However, for solving the crack at the crack tip, a third notation is required. As the last point of the crack tip is in a singular point form, the $F(x)$ function is used in terms of the singular point radius, where mt is the number of nodes enriched by crack tip asymptotic field enrichments and mf is the number of crack tip enrichment functions.

$$u^h(x) = \sum_{j=1}^{n} N_j(x) d_j + \sum_{j=1}^{m} N_h(x) H(x) a_j + \sum_{k=1}^{mt} N_k(x) \left[\sum_{l=1}^{mf} F(x) b_k \right] \tag{4}$$

XFEM has widely used since and has been implemented as an optional module in Abaqus commercial software to model fracture mechanics. XFEM via Abaqus has proven able to simulate fracture behaviour on composites such as investigated by [18], [19] and [20]. However, it has certain limitations where only general static and implicit dynamic analysis in modelling the fracture can be performed [21].

Research to date has not yet managed to develop fracture modelling due to aerodynamic loads. In this paper, a novel step in assessing the crack propagation on the composite plate using XFEM coupled with aerodynamic load is presented. By implementing a small gust load to the composite structure, the transformation from frequency response to time-domain response is achieved. In that sense, the displacement under the aerodynamic load can be obtained and can be expressed in an intercorrelated vibration equation of Fourier Series Function (FSF). Hence, fracture modelling can now be performed using XFEM. To the authors' knowledge, this is the first time the fracture mechanism is modelled by using XFEM under aeroelastic condition.

2.3. Periodic motion via Fourier Series Function (FSF)

As previously stated, it will be a difficulty to apply the frequency domain as load given to XFEM in Abaqus as mentioned by [21]. Therefore, the gust response in the time domain is approximated by FSF such as shown in Equation 5.

$$a = A_0 + \sum_{n=1}^{N} [A_n cos n\omega(t - t_0) + B_n sin n\omega(t - t_0)] \quad t \geq t_0 \tag{5}$$

In this work, FSF is applied to interrelated the structural displacement under gust loads for the crack analysis by using XFEM in Abaqus commercial software. Initially, the structural displacement due to gust function with respect to time was predicted by using SOL 146 in MSC Nastran. Hence, by using FSF, XFEM is allowed to model the crack propagations at the required gust experienced in time domain function which is technically restricted only for the static analysis.

Considering the gust load is minimal and dominated by aerodynamic load, it is significant for modelling the aerodynamic load through this process, where A_0 is the initial amplitude, while ω and n are the frequencies and the number of frequencies to be included in the approximation via the Fourier Series Function, respectively. Meanwhile, A_n and B_n are the related approximation constants for each frequency involved. In addition, t_0 is the initial time, and t is the time during the analysis.

2.4. Proposed research flow

The proposed aerofracturelastic computational simulation technique is displayed in Figure 2. Initially, the composite plate is modelled with a small crack length. The structure is assessed from the view of vibration modes via modal analysis and critical speed flutter using pk - method. If the operating speed is unknown for the case studied, then the operating speed is defined from the critical flutter speed concerning the regulation in [22].

Once the operating and critical flutter speeds are determined, the amount of the small gust needs to be defined. In the current case, the reasonable level of the small gust is estimated by the comparison with a static deflection exerted by steady aerodynamic at the cruise speed. The gust speed is tuned so that the deflection considering aeroelastic condition as explained in Equation 2 is similar to the static deflection condition. However, to be noted, this step is essential only if the operating state and natural disturbance are unknowns.

The gust analysis is performed concerning the '1-cosine' discrete gust load. The wing displacements varying with time due to the gust load are intercorrelated by using Fourier Series Function to represent a periodic motion of vibration. Through this approach, the periodic motion is assigned to the cracked composite plate, and the fracture modelling method of XFEM is activated to demonstrated the crack propagation. Since the evolution used in this approach is based on the energy release rate, it is aware that there crack might not propagate if the loads applied to the structure are not enough to make it fails; hence the structure will be safe.

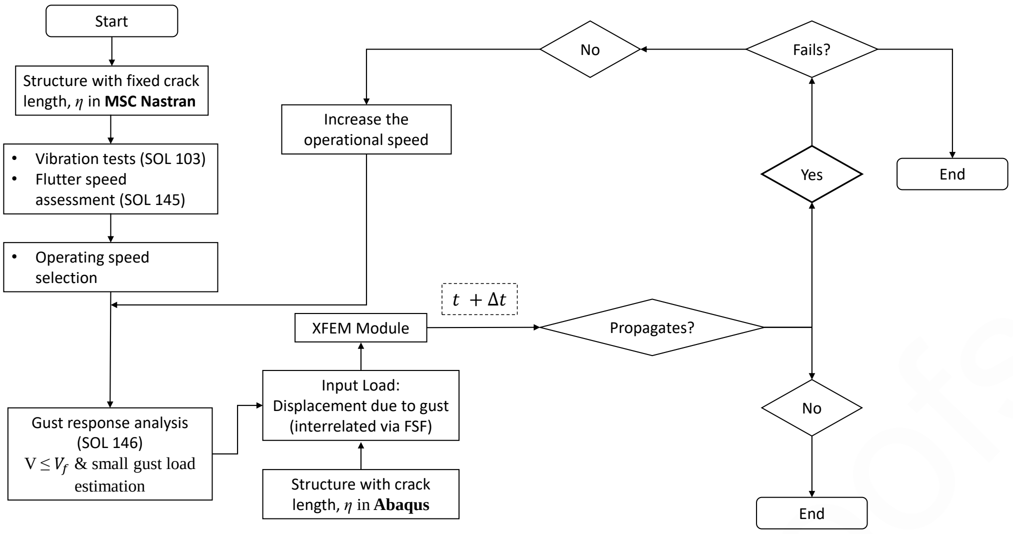

Figure 2: Research diagram for the present work

Furthermore, the operational speed is varied from the cruise speed to the critical flutter speed. If the structure is not yet failed due to the crack propagation, the speed is increased. If at a particular speed below the critical flutter the crack growths can induce significant failure, then the structure is concluded fail due to fracture. In contrast, if the critical flutter speed the crack growths is still low then it can be said that the structure fails due to instability.

3. Static Analysis Consideration for Gust Speed Determination

In the present work, the unidirectional composite plates that were analysed by [4] and [10] are investigated. There are two types of the composite fibre angles evaluated here, 0° and 135°. The specimen model is illustrated in Figure 3, where the fibre angle is measured from y-axis in a counter-clockwise direction. Both [4] and [10] concluded that the static crack condition influenced the critical flutter speed, which in the most case reduced this speed limit. Therefore, the objective of this case study is to determine in the interactive aeroelastic and crack condition, whether it is sufficient to assume a static crack condition as defined by [4] and [10], or it is necessary to perform a crack propagation evaluation in the case that the structure fails due to crack.

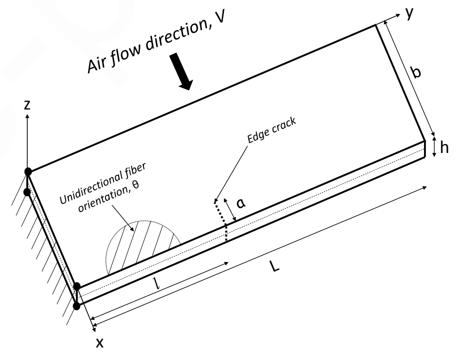

Figure 3: Unidirectional composite plate model illustration

In the section, undamaged specimen (without crack) is modelled and tested under static loading at the cruise speed. As the current case considered a lifting plate, not an actual flying structure, the operating condition is unknown. Therefore, the critical flutter, cruise and gust speeds need to be determined. The critical flutter speeds obtained by [10] are used, 107.84 m/s (for 0° fibre direction) and 92.27 m/s (for 135° fibre direction), respectively. Based on the regulation guided by FAR 23, the cruise speeds are obtained as 71.89 m/s (for 0° fibre direction) and 61.51 m/s (for 135° fibre direction). The uniform lift distributions on the composite plate at the cruise speed is estimated using a lifting line theory.

Figure 4 depicts the general pattern of lift distribution where the highest load is acting at the wing root while the lowest load at the wing tip. The lift distribution data is extracted for each segment, and assigned to the composite plate for the static deformation analysis. Figure 5 depicts the results obtained

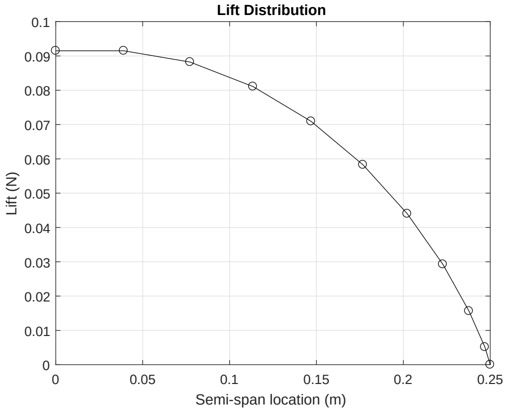

Figure 4: Unidirectional composite plate for 0° fibre direction: Steady lift distributions at cruise = 71.89 m/s

via this approach. From here, the result is used as the benchmark deformation in estimating the small gust load acting on the plate, which is expected to give a similar deflection on the analysed plate.

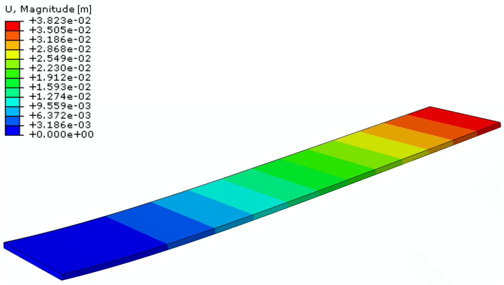

Figure 5: Unidirectional composite plate for 0° fibre direction: Displacement plots on cracked composite under aerostatic load cruise = 71.89 m/s

In Figure 5, the maximum displacement plotted at the specific speed is found to be 38.23 mm. Hence, it is a necessity to acquire an approximate small percentage of gust implementation to compute the same level of displacement of 38.23 mm. The same procedure is repeated for 135° unidirectional composite plate.

Figure 6 presents the aerostatic of this composite plate, which is computed through the obtained lift distributions from the lifting line theory. Here, the maximum displacement plotted for this specimen is 25.72 mm, which is used to estimate the applicable small gust in the next section.

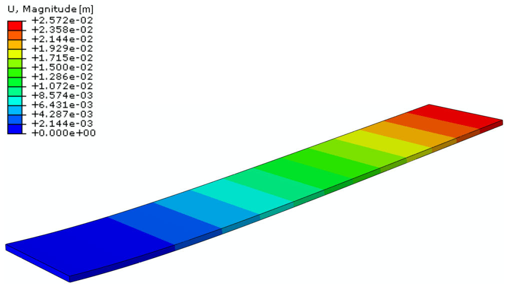

Figure 6: Unidirectional composite plate for 135° fibre direction: Displacement plots on cracked composite under aerostatic load cruise = 61.51 m/s

For the unidirectional composite at 0° fibre direction, the whole specimen is investigated under several gust loads distribution. Figure 7 presents the structural displacement of the unidirectional composite plate 0° where the gust loads are estimated through the percentage of the cruise speed. Here, the small gust loads have been imposed to transform the frequency domain to the time domain.

According to the result, gust speed around 0.5% of the cruise speed is found to provide the same level of maximum displacement with static cruise load considered at the steady aerodynamic condition in Figure 5. Meanwhile, it is found that 0.7% gust for unidirectional composite plate 135° is comparable with the deflection result illustrated in the static analysis.

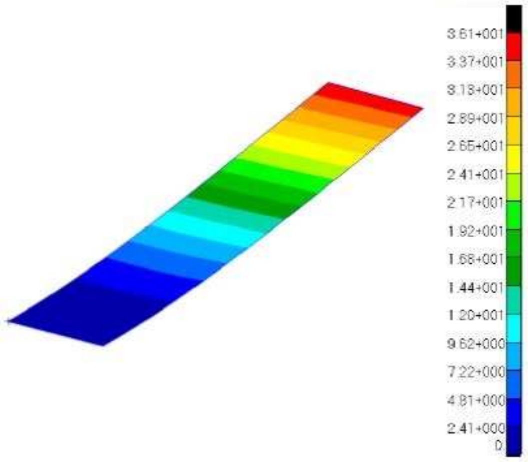

Figure 7: Displacement plots under 0.5% gust on unidirectional cracked composite plate 0° at 71.89 m/s [unit:mm]

4. Numerical Results: Unidirectional cracked composite plate 0°

4.1. Response due to small gust: static crack condition

As previously discussed in Section 2.4, to build an initial input for aerofracturelastic analysis, the

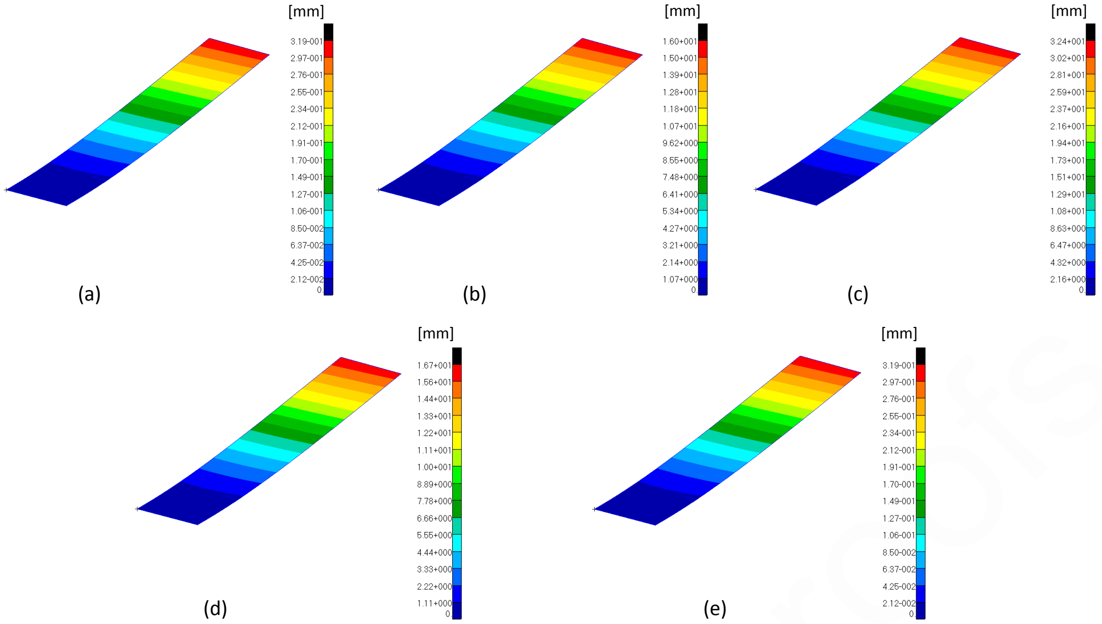

Figure 8: Displacement plots on cracked composite at 71.89 m/s where (a) t = 0 s, (b) t = 1.25 s, (c) t = 2.5 s, (d) t = 3.75 s, and (e) t = 5.0 s

gust response considering static crack needs to obtain. Figure 8 shows the displacement plots of the cracked composite plate at the designed cruise speed of 71.89 m/s. The displacements obtained through this plot are intercorrelated into a periodic motion equation via Fourier Series Transform (FSF).

The stress contour based on maximum principal stress for this case is presented in Figure 9. In these figures, the stress distributions are found to be concentrated at the crack tip. This observation may support the hypothesis that if the stress concentration is exceeding the maximum material principal stress, the crack might propagate. The similar patterns are found when assessing the stress contour for the cracked composite plate at higher speeds, 89.97 m/s and 107.84 m/s.

4.2. Periodic motion via Fourier Series Function (FSF)

As explained earlier in Section 2.3, FSF is used to approximate the displacement response from the aeroelastic (gust) analysis. The periodic motion acting on the structure is approximated for each operational speeds. For example, at a cruise speed of 71.89 m/s, the displacements such as shown in Figure 8 are extracted. The displacements are used as boundary condition input in Abaqus for the fracture mechanics simulations via XFEM.

Table 1: Periodic motion via FSF in Abaqus for 0° direction

		Periodic motion parameters			
Speed (m/s)	Node	Initial Amp.	A_1	B_1	Freq. ω (rad/s)
71.89	lower-rear	16.0	-15.8	-0.43	1.26
	lower-front	16.3	-16.2	-0.45	1.26
89.87	lower-rear	16.2	-16.1	-0.36	1.26
	lower-front	16.6	-16.4	-0.37	1.26
107.84	lower-rear	16.5	-16.4	-0.32	1.26
	lower-front	16.9	-16.8	-0.32	1.26

Nodes displacements are approximated for the observed time period. A computational code is built in MATLAB to obtain the FSF parameters. Following the notations in Equation 5, the parameters for tip nodes are summarised in Table 1.

4.3. Fracture under aerodynamic load by means of XFEM

The damage criterion for fracture analysis based on energy released rate of the composite structures used in this research is presented in Table 2, taken from [23]. The crack propagation at of the composite at the cruise speed, at the sea level, 71.89 m/s are shown in Figure 11.

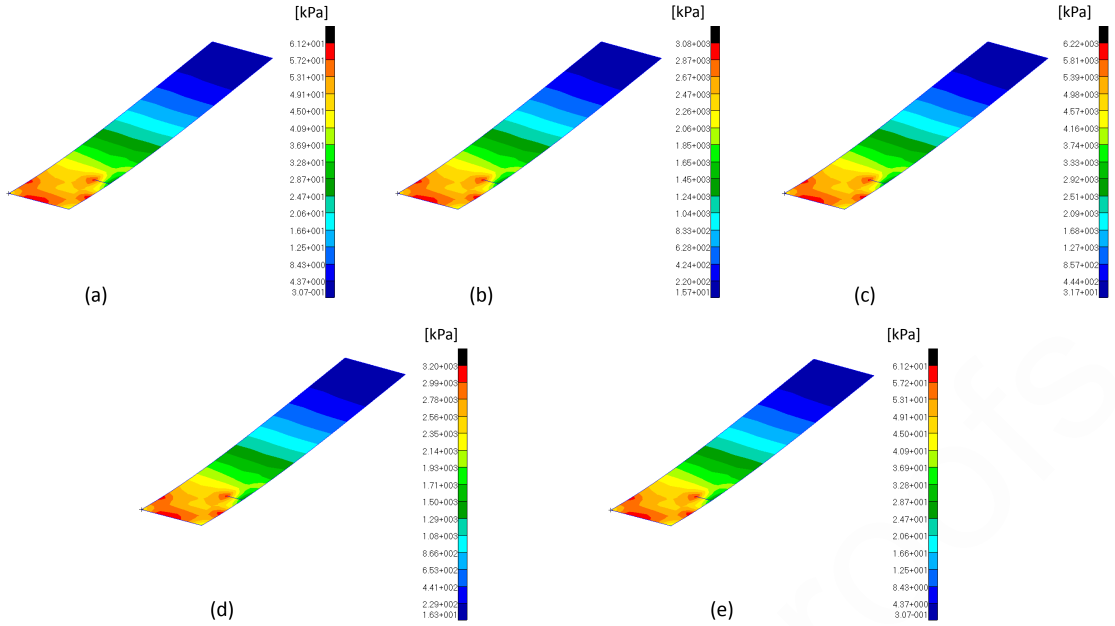

Figure 9: Stress contour based on maximum principal stress plots on cracked composite at 71.89 m/s where (a) t = 0 s, (b) t = 1.25 s, (c) t = 2.5 s, (d) t = 3.75 s, and (e) t = 5.0 s

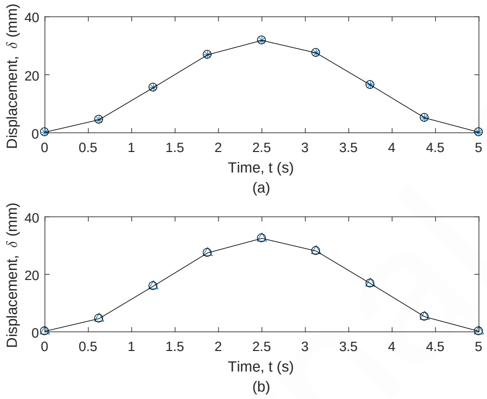

Figure 10: Time-domain periodic motion for 5 seconds intercorrelated via Fourier Series Function at operating speed 71.89 m/s where (a) for lower-rear node, and (b) for lower-front node

In this part, crack modelling has been performed using XFEM, where the damage is expected to evolve through the assignment of the material damage evolution. Based on the results in Figure 11, the crack has slightly propagated due to the aerodynamic forces developed at 71.89 m/s. However, the structure has undergone a bending mode, where the lower surface has stretched due to the tension forces, while the upper surface in compression. From the results, the crack propagation has stopped at 5.0 seconds.

Table 2: Damage criterion of graphite polyimide composite

Maximum principal stress, 0°	$\sigma = 4$ MPa
Maximum principal stress, 135°	$\sigma = 28$ MPa
Fracture toughness	$G_{lc} = 162\ kJ/m^2$

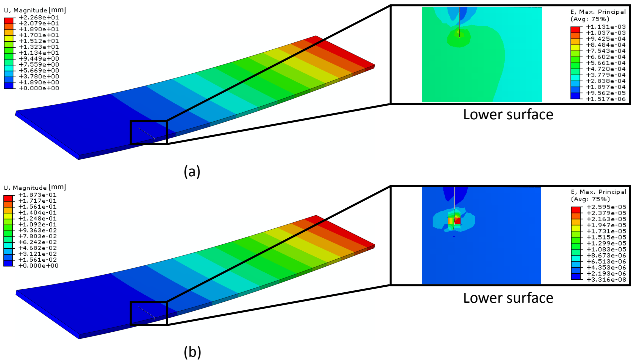

Figure 11: Crack modelling by means of XFEM at 71.89 m/s where (a) t = 1.59 s and (b) t = 5.0 s

At the end of the analysis, the crack at the lower surface found did not propagate until it reached the other plate, which could make the plate to be cut off into two pieces. This finding was unexpected and suggested that the compression on the upper surface did not trigger any crack on the surface. Hence, it could conceivably be hypothesised the possible reason that breaks at the lower surface will stop before it reaches half of the structure in the chordwise direction.

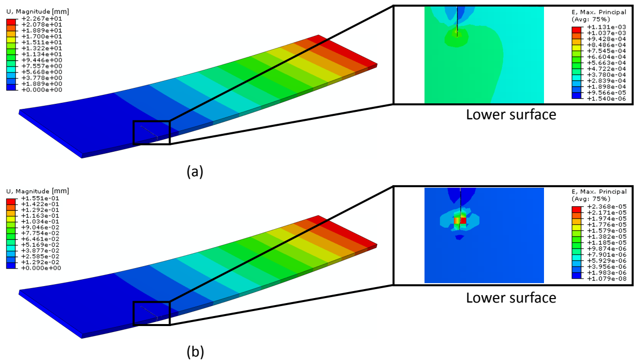

Figure 12: Crack modelling by means of XFEM at 89.97 m/s where (a) t = 1.57 s and (b) t = 5.0 s

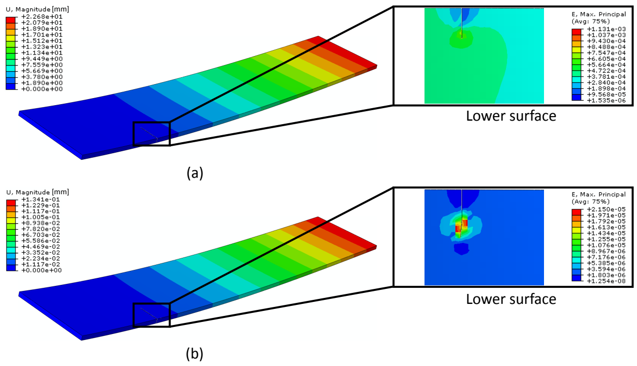

Figure 13: Crack modelling by means of XFEM at 107.84 m/s where (a) t = 1.55 s and (b) t = 5.0 s

The same modelled plate has also been tested for the higher speeds analysis, in this case, dive speed at 89.97 m/s and flutter speed at 107.84 m/s, respectively. With the increment of speed, the aerodynamic forces also increase. In this case, the load increment has increased the structural deformation. As can be seen in Figures 11(a), 12(a), and 13(a), the crack at the lower surface has propagated slightly faster when operating at higher speed.

One of the issues that emerge from these findings is which failure comes first when the damaged structure interacts with the aerodynamic loads. These findings raise intriguing curiosity regarding the nature and extent of flutter damage or fracture damage on cracked composite plate. Although the plate seems not propagated until it splits into two parts, it will be a serious matter in the case of load incrementation.

5. Numerical Results: Unidirectional cracked composite plate 135°

The same approach is repeated to provide aerofracturelastic analysis for the plate with 135° fibre orientation. Figure 14 depicts stress contour based on the maximum principal stress plot of the unidirectional cracked composite plate at 135°. The results of these plots indicate that the stress distributions are concentrated more at the root, instead of at the crack tip. Contrary to expectations from the previous case of 0°, this fibre direction has eliminated the potential of crack propagations since the stress at crack tip is lower than the maximum material principal stress. The similar stress concentration plots trend are also identified for airstream speed at 76.89 m/s and at 92.27 m/s.

This result may be explained by the fact that the maximum material stress for this specimen is higher than the stress developed due to the aerodynamic load. As all samples have been evaluated through several aerodynamic speed using XFEM, no indication is showing any crack propagation for 135° composite plate.

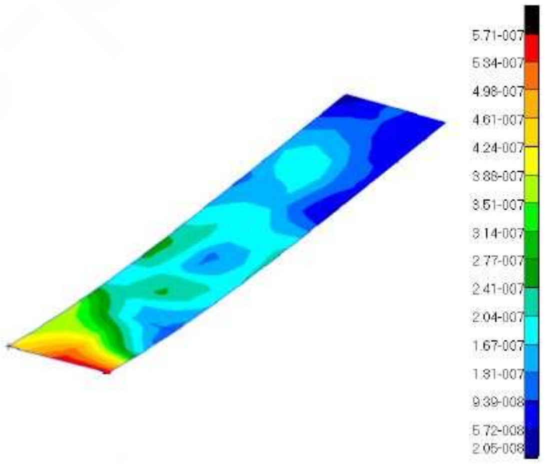

Figure 14: Stress contour based on maximum principal stress plot on cracked composite at 61.51 m/s [unit:kPa]

Hence, this observation may support the hypothesis that the cracked specimen of 135° composite plate can sustain the aerodynamics load until it reached the flutter speed. It is concluded that this finding supports the results published by [4] and [10] for the cracked specimen of 135° composite plate.

6. Conclusions

This paper presents a novel technique in developing a fracture mechanism on cracked composite plates under aerodynamic loads by means of XFEM. To the

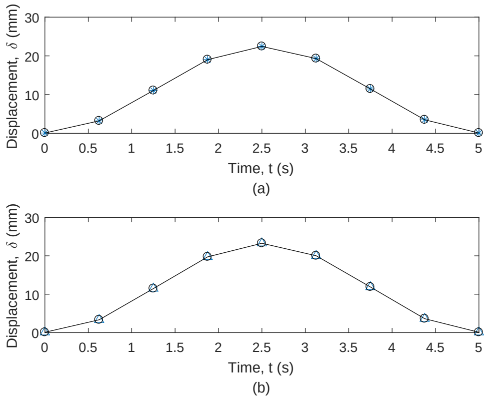

Figure 15: Time-domain periodic motion for 5 seconds intercorrelated via Fourier Series Function at operating speed 61.51 m/s where (a) for lower-rear node, and (b) for lower-front node

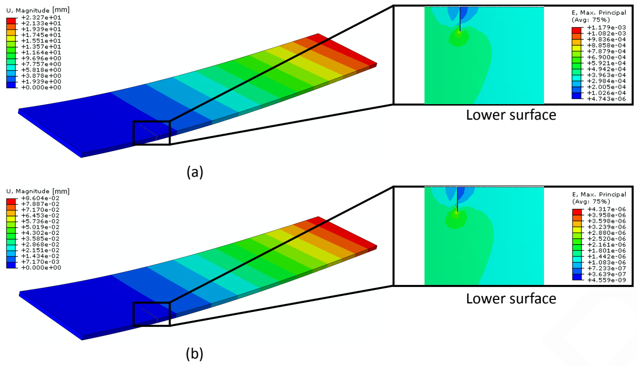

Figure 16: Crack modelling by means of XFEM at 61.51 m/s where (a) t = 2.5 s and (b) t = 5.0 s

authors' knowledge, this study provides new insights into the airworthiness evaluation of an aircraft wing when there is an existence of crack.

In this research, two type of cracked composite plates were studied, such that 0° and 135° fibre angle orientations. The flutter boundary of the specimens initially predicted through the coupling of FE-DLM presented in [10] using pk-method of flutter condition.

The most critical limitation lies in the fact that XFEM in Abaqus can only be used in general static and implicit dynamic analysis when modelling the fracture. Therefore, this study makes a significant contribution to research on unidirectional cracked composite by demonstrating the fracture mechanism of crack under the computed aerodynamic load, by the implementation of minimal gust loads. The results are in good agreement when compared with the steady flight condition.

Using this approach, the deflection/ displacement at a specific time has successfully computed. The loads were intercorrelated using the Fourier Series Function to represent the periodic motion of vibration function.

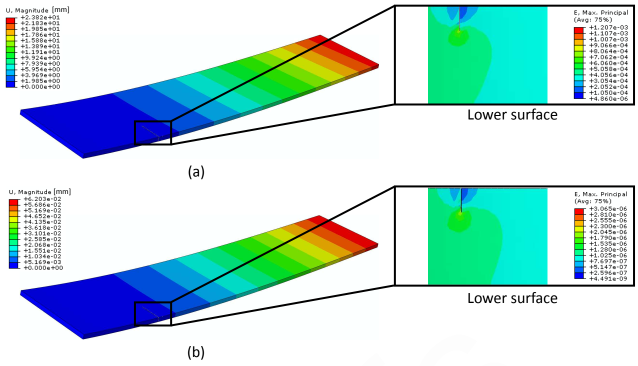

Figure 17: Crack modelling by means of XFEM at 92.27 m/s where (a) t = 2.5 s and (b) t = 5.0 s

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