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STRUCTURAL INTEGRITY ASSESSMENT OF CRACKED COMPOSITE PLATE UNDER AEROELASTIC LOADING BY MEANS OF XFEM

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ABSTRACT

In this paper, a novel procedure to analyse dynamic crack under aeroelastic loading by means of XFEM and Doublet Lattice Method (DLM) - FEM coupling is presented. The present work performed a new investigation on the crack propagation on the composite plate exerted by the unsteady aerodynamic loading during the cruise speed. The study on whether the failure due to instability, i.e., flutter, comes first or the crack propagates first until the structural failure is focused. The flutter speed is determined, and the maximum cruise speed is assessed based on the regulation guided by the FAR 23. The proposed method is used to solve the limitation in XFEM within Abaqus that only general static and implicit dynamic analysis can be performed. As the propagation of crack should be analyzed, the composite plate is assigned based on the energy release rate (ERR) of that type of material. The influence of a crack growth on a composite plate at cruise speed is shown in some details. Despite the fact that the crack is propagated at this speed, with initial crack ratio of 0.25, the crack has just grown slightly.

Keywords: flutter, composite, time-domain response, aerodynamic load, XFEM

INTRODUCTION

Flutter phenomenon always deals with the interaction between structural elasticity, inertia forces and aerodynamics load which analyzing the failure of the structure. In general, common know that flutter will lead to the destruction of the structure when it is excited at the vibrational frequency. The question raises when the structure that is consists of a small fracture (in this case crack) will show which type of failure comes first; flutter failure or the fracture failure. Based on Wang *et al.* (2004), they modelled unidirectional composite plates with the existence of crack to analyze the flutter speed.

The composite structures were analysed based on structural beam element, coupled with strip theory for aerodynamic modelling. The flutter method implemented by Wang *et al.* (2004) was based on Galerkin method. The flutter assessment on the unidirectional composite plates with cracks has been performed by Abdullah *et al.* (2018) using *pk*- method based on FE-DLM coupling. The results show a good agreement with Wang *et al.* (2004). Moreover, Abdullah *et al.* (2008), provided an interesting insight in which the critical flutter speed may increase due to the existence of small crack has been highlighted based on the flutter responses and aerodynamic parameters.

However, Wang *et al*., (2004) and Abdullah *et al*., (2008) only considered the static crack; where the crack was assumed not propagate as the speed increases. This assumption can be applied in that sense the material strength is very high. Theoretically, as the freestream speed increase, the aerodynamic loads acting on the surface also increase. This phenomenon can be seen in some of the researches such as long-span suspension bridges interaction with wind (Zhang *et al*., 2002), transient load and tornado effect on buildings investigation (Sengupta *et al*., 2008) and aerodynamic load control using blade on wind turbine (Theotokoglou *et al*., 2014). In that sense, the aerodynamic load increment might deform the structure, and hence trigger the crack to propagate.

FRACTURE MODELLING TECHNIQUE

Therefore, the implementation of the fracture modelling technique interacted with the unsteady aerodynamic load is initiated herein. The fracture modelling technique presented in this work is using a computational method called Extended Finite Element Method (XFEM). XFEM was founded by Ted Belytschko and collaborators in 1999 (Belytschko and Black, 1999). The fracture modelling evaluation by XFEM is using the level set method. One of the proposed techniques that can be used to model the crack propagation is by using XFEM within Abaqus (Abdullah *et al*., 2017; Curiel-Sosa *et al*., 2018). Nevertheless, there is a limitation in XFEM within Abaqus where only general static and implicit dynamic analysis can be performed (Gigliotti, 2012). For this reason, an algorithm that could transform the frequency response to time-domain should be introduced to solve this limitation.

One of the best solutions is by implementing a small gust load to the structure when the structure is considered in flight. Nevertheless the gust deals always with an extreme flow and cause perturbation (Tang and Dowell, 2002), the gust load implemented here should be as lower as possible. The commercial computational software of MSC Nastran is used to model the gust load, with time-varying. In that sense, the displacement under the aerodynamic load can be obtained and can be expressed in a vibration equation of Fourier Series Function (FSF).

In this paper, a novel step in assessing the crack propagation on 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 has been achieved. Hence, the fracture modelling can now be performed by means of XFEM. To the authors' knowledge, this work is the first time the fracture mechanism has successfully modelled using XFEM under aerodynamic load.

PROPOSE FLOWCHART

In Figure 1, the flowchart is constructed to allow the analysis using XFEM under aerodynamic load been performed. Initially, the structure was modelled with a small crack ratio (0.25). The normal vibration computational was performed, and the same model has been submitted for flutter speed evaluation. Once the flutter data has been obtained, the flutter speed was set as the maximum operating speed, which is the flight should not be exceeded.

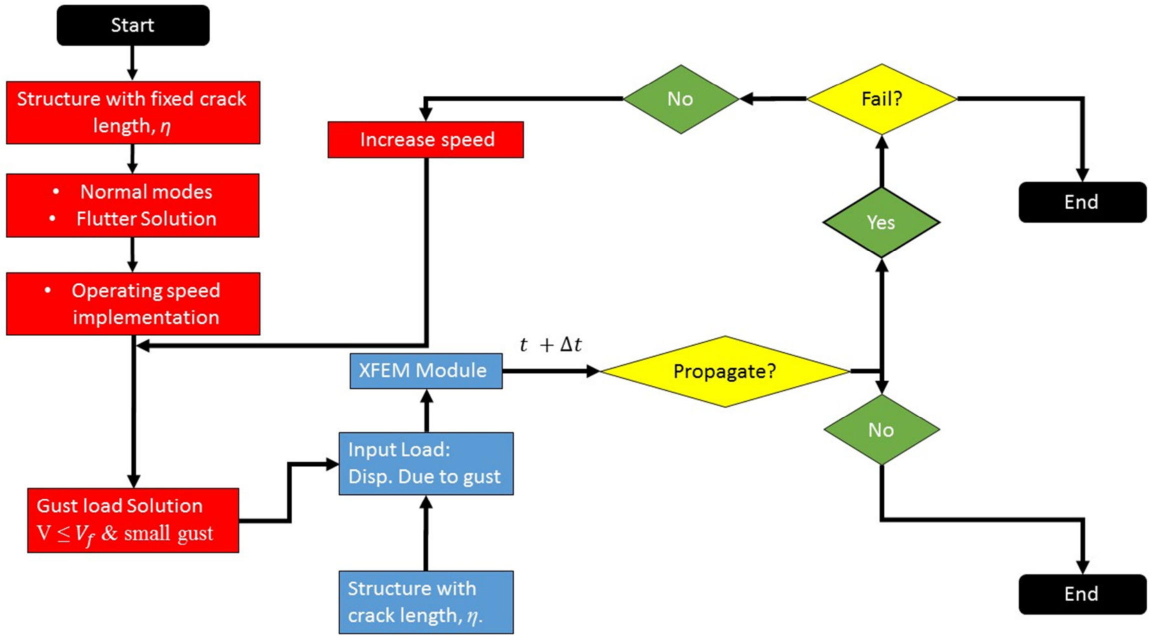


Fig. 1 - Propose flowchart for numerical computational of structural integrity assessment on cracked composite plate under aeroelastic loading by means of XFEM

BENCHMARKING, SETTING UP THE CRUISE AND GUST SPEED

The composite plate in Abdullah *et al*. (2018) is used in the present work. The steady aerodynamics result is used to set-up the gust speed required to provide a reasonable displacement during the cruise speed. The cruise speed is determined based on FAR 23, in which the flutter speed is 1.5 times the cruise speed. The flutter results by Abdullah *et al.* (2018) shows the critical flutter speed around 90-108 m/s, hence 72 m/s of cruise speed is used in the current simulation.

The lift forces are computed by 10 segments, and the forces are applied in term of pressure by area for static analysis. To get the plate displacement varying with time, the small gust response is plotted as presented in Figure 2.

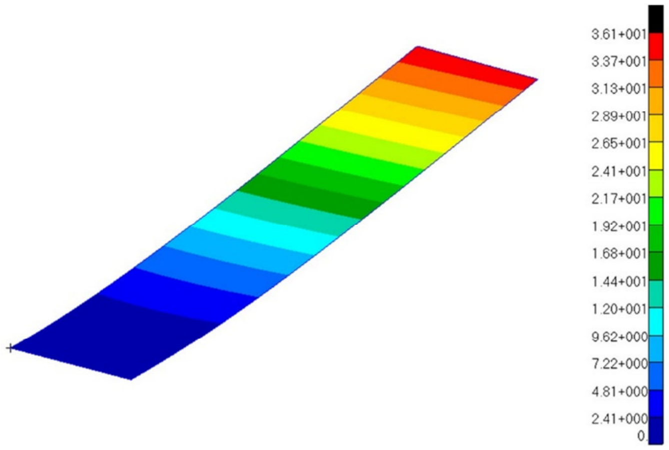


Fig. 2 - 5 seconds gust with 0.5% of cruise speed for 0º of graphite/polyimide composite [unit: mm]

According to the result, 5 seconds gust with 0.5% of cruise speed provided the same level of maximum displacement with static cruise load considered at the steady aerodynamic condition. At this condition, the load acting on the plate is the summation of the aerodynamic load and the gust load, as follows:

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

Where $L(V_{\infty,}t)$ is the unsteady aerodynamic lift as a function of freestream airspeed V_∞ and time, $\Delta L(V_g, t)$ is the additional lift due to gust load at a certain speed, V_g. An interested reader on unsteady aerodynamic load for aeroelastic analysis is referred to the articles by Albano and Rodden (1969), Ueda and Dowell (1982), the detailed computational procedure of the aeroelastic analysis, i.e., flutter and gust load analysis, is explained in the aeroelastic guideline by MSC Software Corporation (2009).

PRELIMINARY RESULTS ON STRUCTURAL DEFORMATION AT CRUISE LOAD UNDER SMALL GUST

A transformation from frequency response to time-domain response has been presented in this work by introducing a small gust load (less than 0.5% of the cruise speed) and the airspeed at the cruise condition.

The time response of the plate with a small crack (crack ratio 0.25) under the unsteady aerodynamic load is shown in Figure 3.

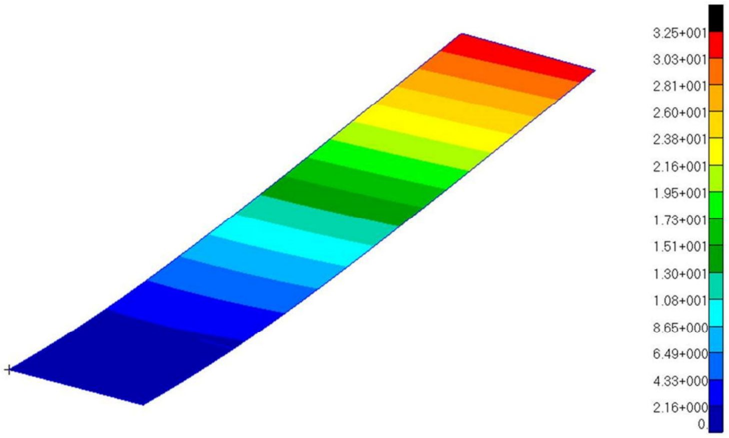


Fig. 3 - Displacement plots for 0º of graphite/polyimide composite with crack ratio 0.25 at operational speed 72 m/s [unit: mm]

The stress tensor plots for the presented cracked composite plate are shown in Figure 4. Based on the results, the stress at the crack tip has exceeded the maximum material stress. In this case, the cracked composite plate should fail. However, the discussion is still ongoing since the presented tensor plots are only displayed for a 2D plate.

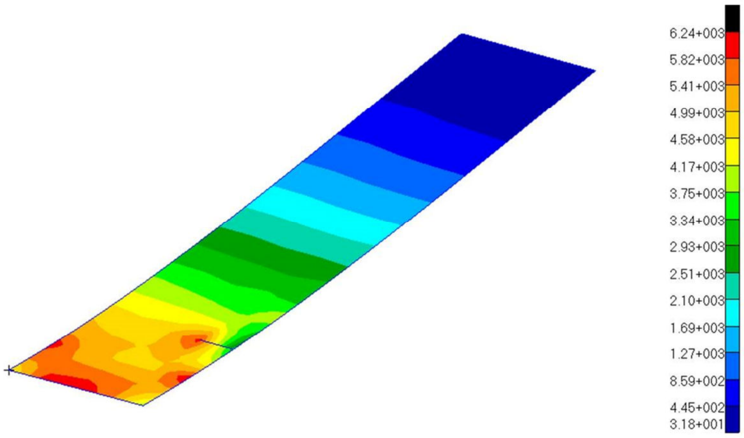


Fig. 4 - Stress tensor plots for 0º of graphite/polyimide composite with crack ratio 0.25 at operational speed 72 m/s

APPLICATION OF XFEM TO MODEL CRACK WITH AERODYNAMIC LOAD

As the displacement varying with time plots have been obtained in the previous section, the displacement results are integrated via a Fourier series function and expressed in a periodic motion.

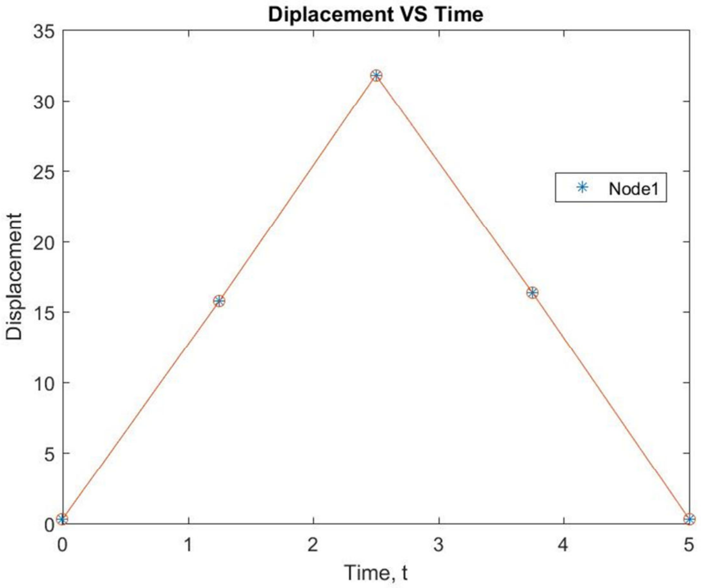
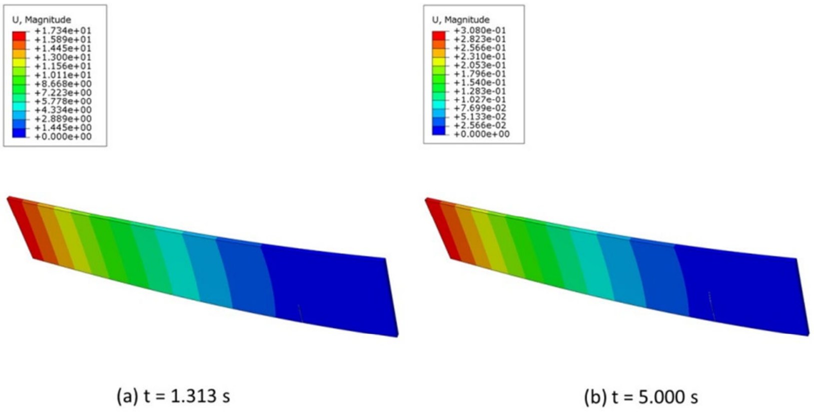


Fig. 5 - Displacement VS Time plots for boundary condition at operational speed 72 m/s [unit: mm]

As XFEM has limitations to model the crack under dynamic loading varying with time, this study approximate the periodic function using Fourier series. Table 1 presents the approximate parameters of the periodic function using Fourier series.

The fracture analysis results by means of XFEM are shown in Figure 5 (displacement) and Figure 6 (strain). Based on Figure 6(a), there is no crack until it reaches time 1.313s. The crack is detected to propagate at t = 1.313s, shown in Figure 7 and stop until t = 5s.



(a) t = 1.313 s

(b) t = 5.000 s

Fig. 6 - Displacement load plots of fracture by means of XFEM varying with time at 72 m/s [unit: mm]

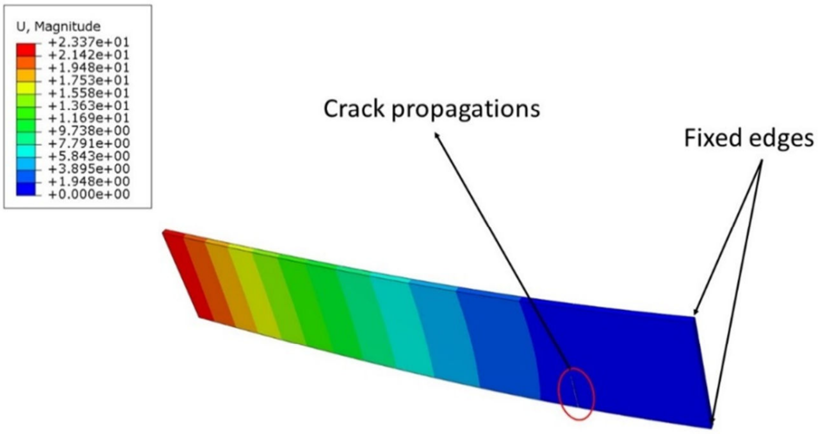
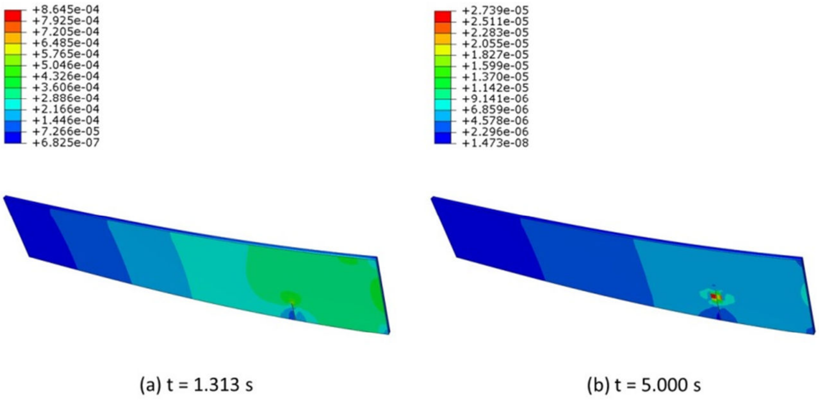


Fig. 7 - Focus view: Displacement load plots of fracture by means of XFEM varying with time at 72 m/s, t= 1.623 [unit: mm]

The strain plots of the analysed composite plate are shown in Figure 8. In this figure, the strain indicator shows the crack propagations until it stopped at t = 5s.



(a) t = 1.313 s

(b) t = 5.000 s

Fig. 8 - Strain plots of fracture by means of XFEM varying with time at 72 m/s

CONCLUSION

This paper presents the new computational approach using XFEM in modelling crack propagations under aerodynamics load. The new procedure has been successfully implemented for a time domain analysis of unidirectional composite plate at the cruise speed under small gust load. At the current configuration of the composite plate, it is shown that the crack just slightly propagated at the cruise load. The current result supports, the assumption used by Abdullah *et al.* (2018) in which a static crack is used to determine the flutter boundary of the cracked composite. However, further investigation is required to obtain the crack behavior for different configuration plates, i.e., different orientations, crack ratios and crack locations.

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REFERENCES

[1] Abdullah, N A., Curiel-Sosa JL., Akbar, M. Aeroelastic assessment of cracked composite plate by means of fully coupled Finite Element and Doublet Lattice Method. Composite Structures 2018.

[2] Abdullah, N A., Curiel-Sosa, JL., Taylor, ZA., Tafazzolimoghaddam, B., Vicente, JLM., Zhang C. Transversal crack and delamination of laminates using XFEM, Composite Structures, 2017, 173, pp. 78-85.

[3] Albano, E., and Rodden, W. P. A doublet-lattice method for calculating lift distributions on oscillating surfaces in subsonic flows. AIAA Journal, 1969, 7(2), pp. 279-285.

[4] Belytschko, T, Black, T. Elastic crack growth in finite elements with minimal remeshing, International Journal for Numerical Methods in Engineering, 1999, 45(5), pp. 601-620.

[5] Curiel-Sosa, J.L., Tafazzolimoghaddam B., Zhang C., Modelling fracture and delamination in composite laminates: Energy release rate and interface stress, Composite Structures, 2018, 189, pp. 641-647.

[6] Djojodihardjo H., Akbar M., Gunawan L., Kusni M. (2010). Unified aerodynamic-acoustic formulation for aero-acoustic structure coupling, Paper ICAS, 2010-9.10.1.

[7] Gigliotti, L. (2012). Assessment of the applicability of XFEM in Abaqus for modelling crack growth in rubber, *Master Thesis*, KTH School of Engineering Sciences, Sweden.

[8] Mohammadi.S., Extended Finite Element Method for Fracture Analysis of Structures, Blackwell Publishing Ltd (2008), ISBN 978-1-4051-7060-4.

[9] MSC Software Corporation, MSC. Nastran Aeroelastic Analysis User's Guide, MSC Software Corporation (2009).

[10] Sengupta, A., Haan F.L., Sarkar, P.P., & Balaramudu, V., Transient loads on buildings in microburst and tornado winds, Journal of Wind Engineering and Industrial Aerodynamics, 96 (10-11), 2008, pp. 2173-2187.

[11] Tang D., & Dowell, E. H., Experimental and theoretical study of gust response for high-aspect-ratio wing, AIAA Journal, 2002, 40(3), pp. 419-429.

[12] Theotokoglou E.E., & Balokas, G.A., Computational analysis and material selection in cross-section of a composite wind turbine blade. Journal of Reinforced Plastics and Composites, 2014, 34 (2), pp. 101 - 115.

[13] Ueda T. & Dowell, E. H., A new solution method for lifting surfaces in subsonic flow, AIAA Journal, 1982, 20(3), pp. 348-355.

[14] Wang, K,. Inman, DJ., Farrar, CR. Crack-induced changes in divergence and flutter of cantilevered composite panels. Structural Health Monitoring, 2005, 4 (4), pp. 377-392.

[15] Zhang, X., Xiang, H., & Sun, B., Nonlinear aerostatic and aerodynamic analysis of long-span suspension bridges considering wind-structure interactions. Journal of Wind Engineering and Industrial Aerodynamics, 2002, 90 (9), pp. 1065-1080.