# Aerofracturelastic: A study on the Interaction of Crack and Aeroelastic Instability of Aircraft and Lifting Surfaces


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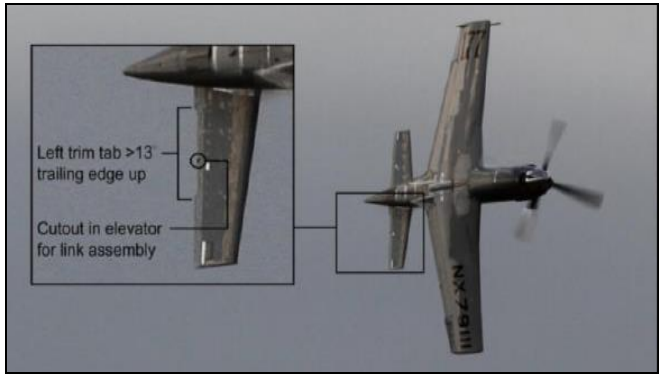
# Research Motivation

## Research significance




North American P-51D Mustang at National Championship Air Races in Reno/Stead Airport, Nevada, USA

- Pilot and other 10 people dead
- 64 people faced serious injury

*NTSB Forensic Report*

- *Existing fatigue crack in one screw.*
- *Caused elevator trim tab stiffness been reduced.*
- *Has triggered aerodynamics flutter to be happened at racing speeds.*

-National Transportation Safety Board (**NTSB**) (2012)

Sources of the photos:

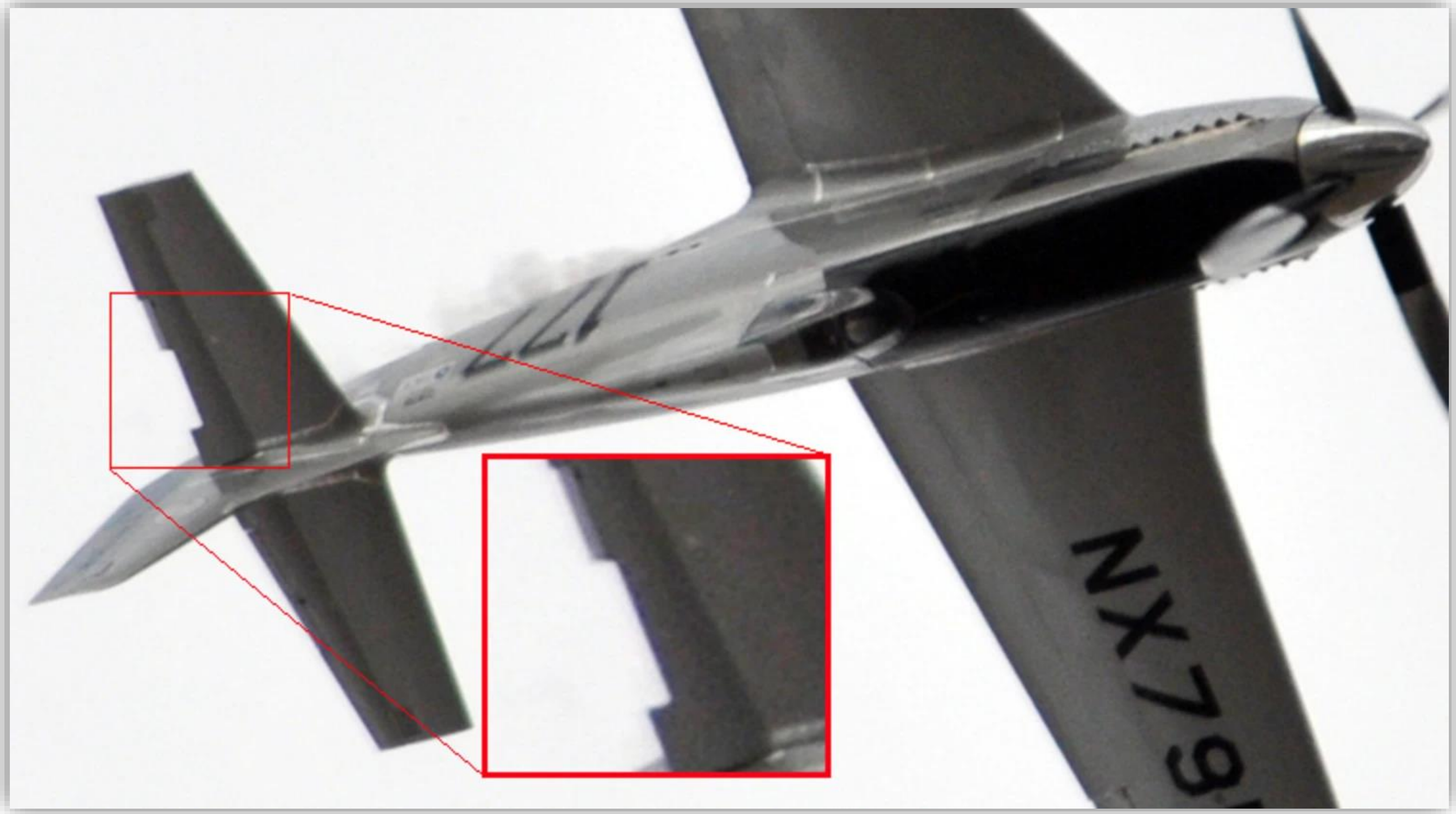
1. https://www.washingtontimes.com/news/2011/sep/17/3-dead-more-50-hurt-nev-air-race-crash/
2. https://www.timesunion.com/news/article/P-51-studied-in-horrific-crash-2176216.php

# Research Motivation

## Research significance

Balance tab mode Anti-Balance tab mode LH Balance tab & RH Anti-Balance tab

## Research significance



# Research Motivation

Fracture numerical approach? - XFEM

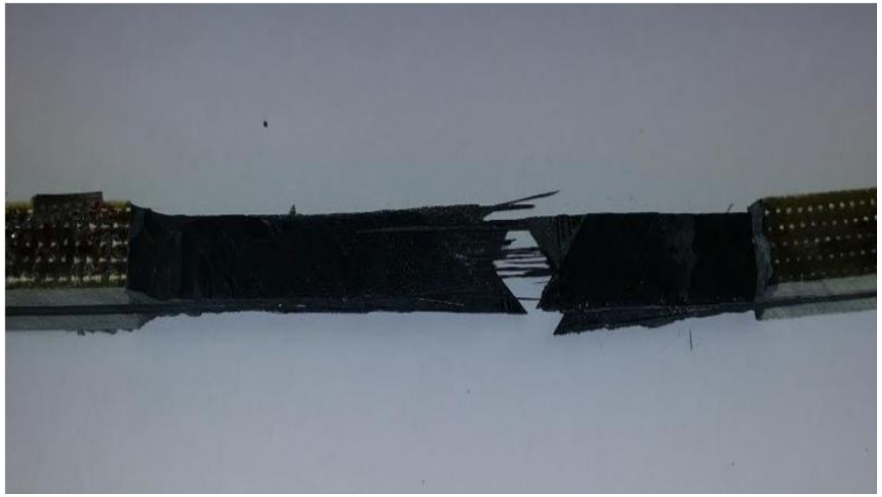
**<u>1st objective:</u>**

To model transversal crack and delamination of laminates using XFEM.

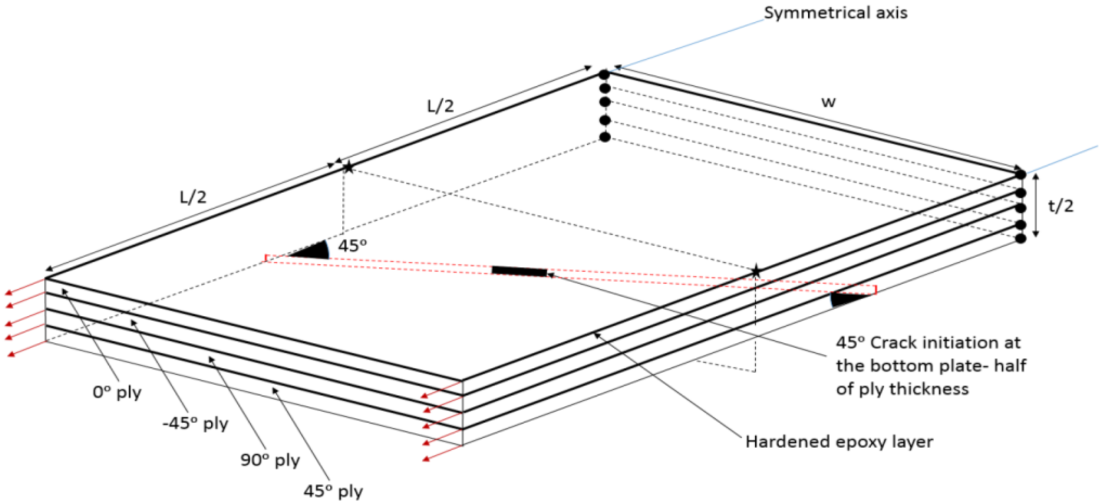
# Transversal crack and delamination of laminates using XFEM

## Fracture study

*study the sample of carbon fiber laminates by Hallet et al. (2008)



Experimental results of crack and delamination




Symmetrical model of present composite structure

# Transversal crack and delamination of laminates using XFEM

## XFEM Enrichment function

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

approximate displacement applied

shape function and *d* is the changes of displacement in every node

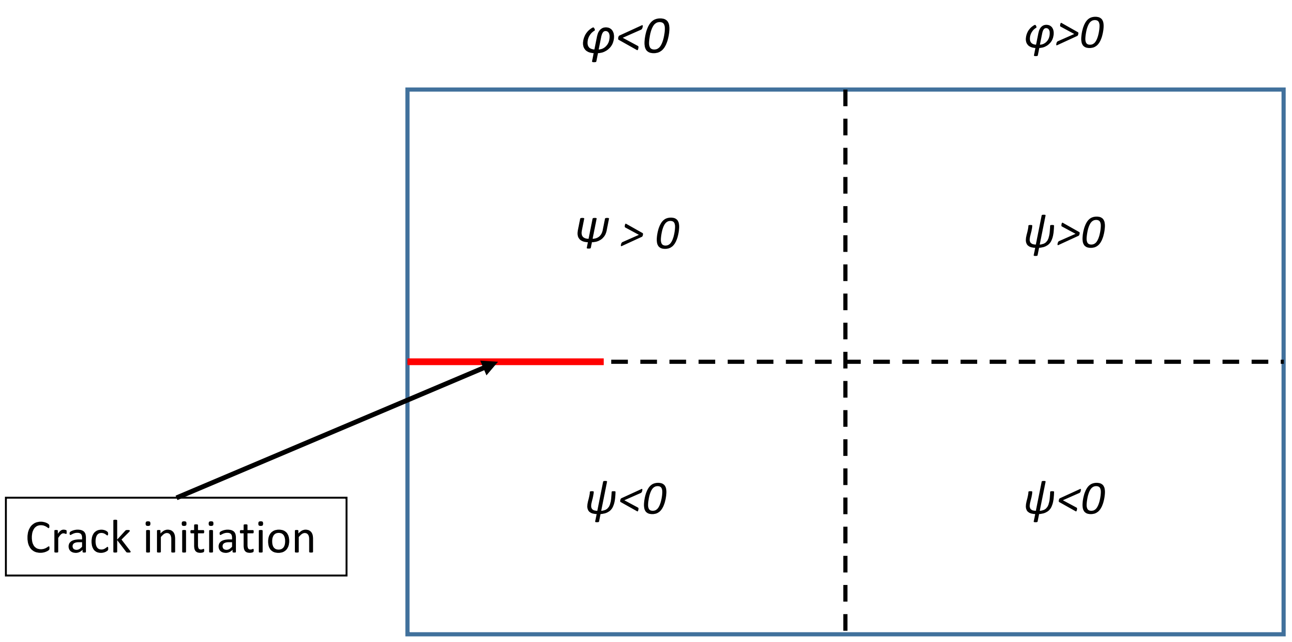
extra degree of freedom node denoted by *aj* with m as the nodes enriched by Heaviside function

*mt* is the of nodes enriched by crack tip asymptotic field enrichments

**Enrichment applied to solve the discontinuity within the element by providing additional shape function.**

# Transversal crack and delamination of laminates using XFEM

## XFEM Enrichment function

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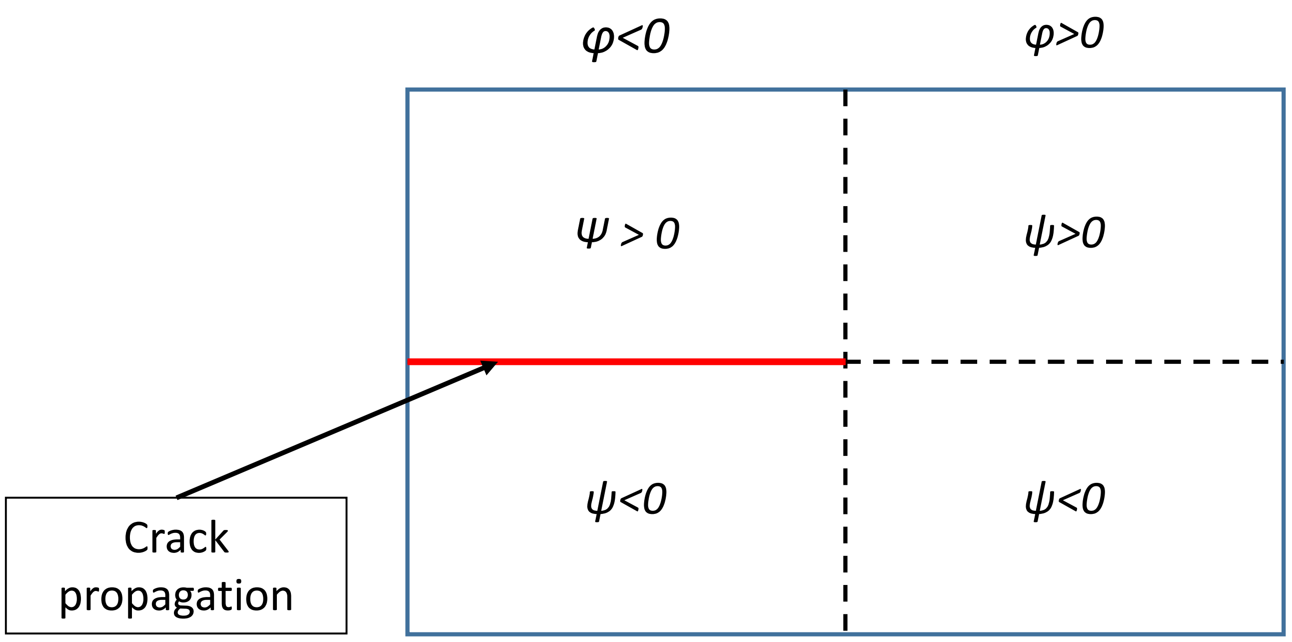
# Transversal crack and delamination of laminates using XFEM

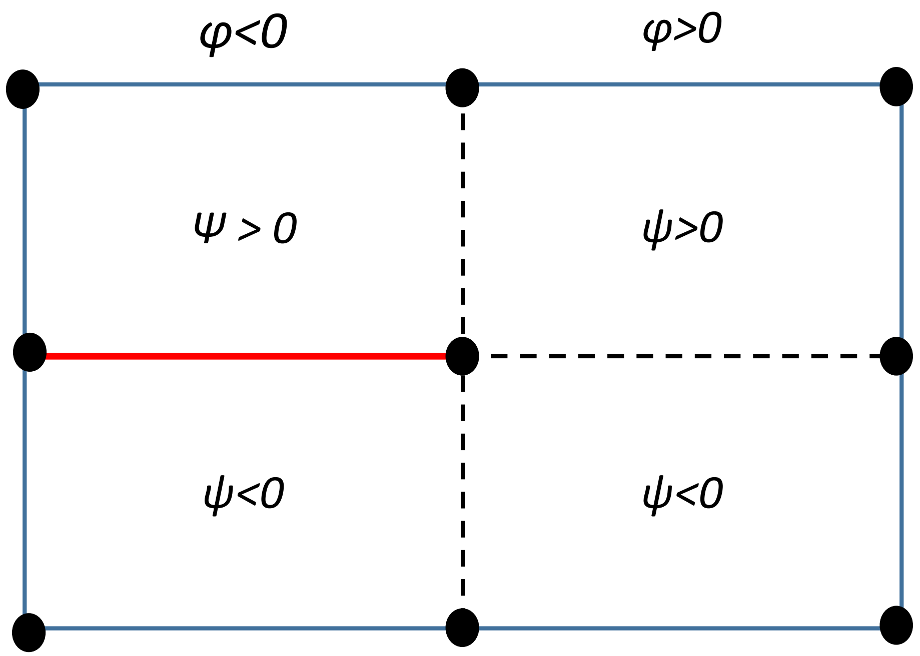
## XFEM Enrichment function




**Enrichment applied to solve the discontinuity within the element by providing additional shape function.**

## XFEM Enrichment function

Nodal enrichment

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# Transversal crack and delamination of laminates using XFEM

## XFEM Enrichment function

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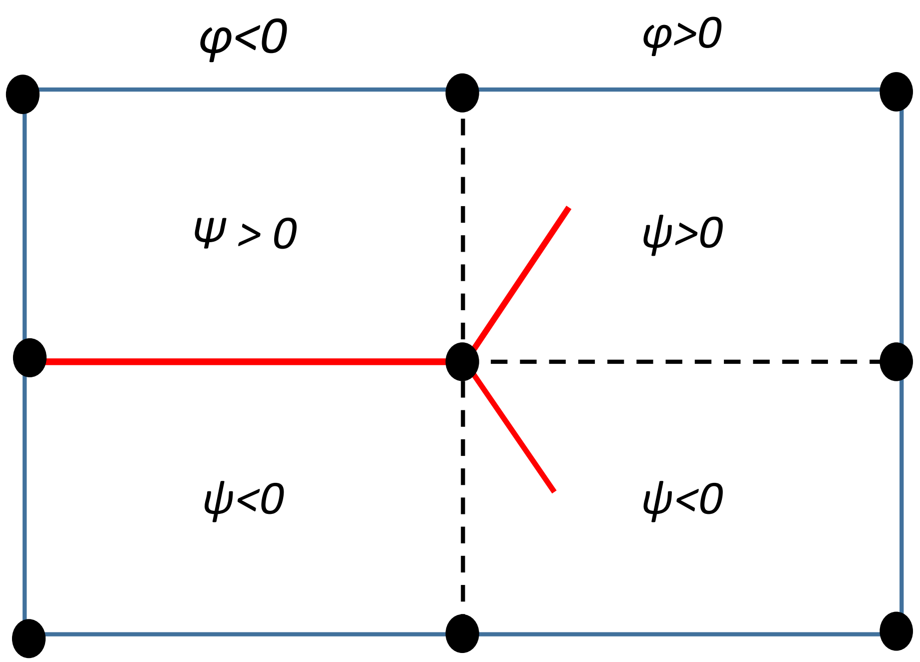


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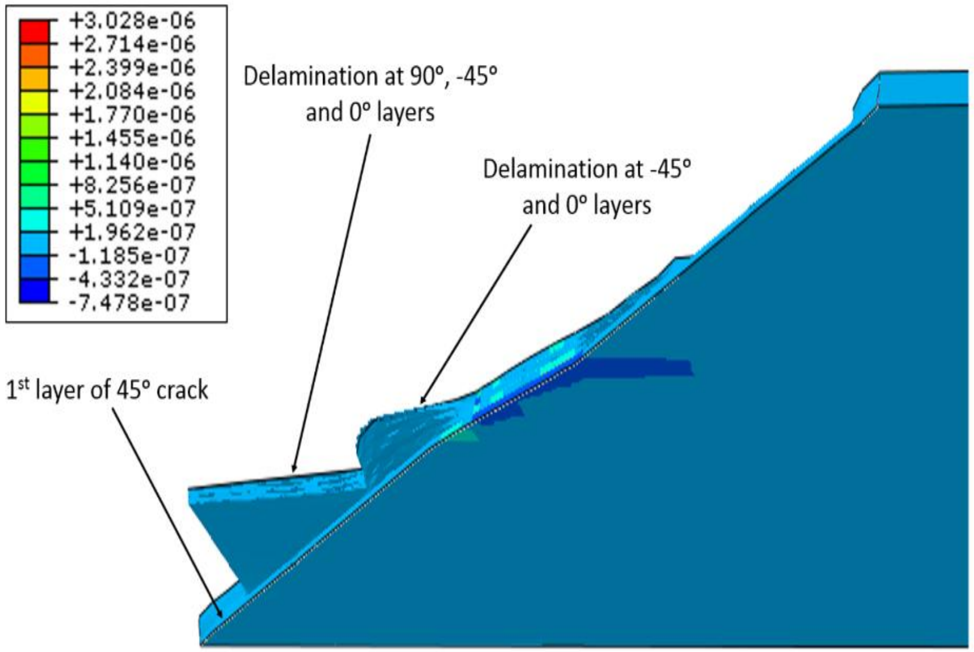
# Transversal crack and delamination of laminates using XFEM

## Fracture study

*Abdullah, N.A et al.* , Vol. 173, pp. 78–85
*Composite Structures (2017)*




Strain contour of transversal crack and delamination – bottom view

The expected strength (analytical), experimental by Wisnom et al. (2008) & failure stress - present work (XFEM)

| Case | Lay-up | Expected strength (MPa) | Experimental (MPa) | Failure stress - present work (Mpa) |
|---|---|---|---|---|
| 1 | $(45\,/\,90/\,-45/\,0)_s$ | 1074 | 842 | 1076.36 |
| 2 | $(45_2/\,90_2\,/-45_2\,/0_2)$ | 642 | 660 | 692.47 |
| 3 | $(45_4/\,90_4\,/-45_4\,/0_4)$ | 454 | 541 | 546.59 |

# Transversal crack and delamination of laminates using XFEM

## Fracture study

Size effect

*Abdullah, N.A et al.* , Vol. 173, pp. 78–85
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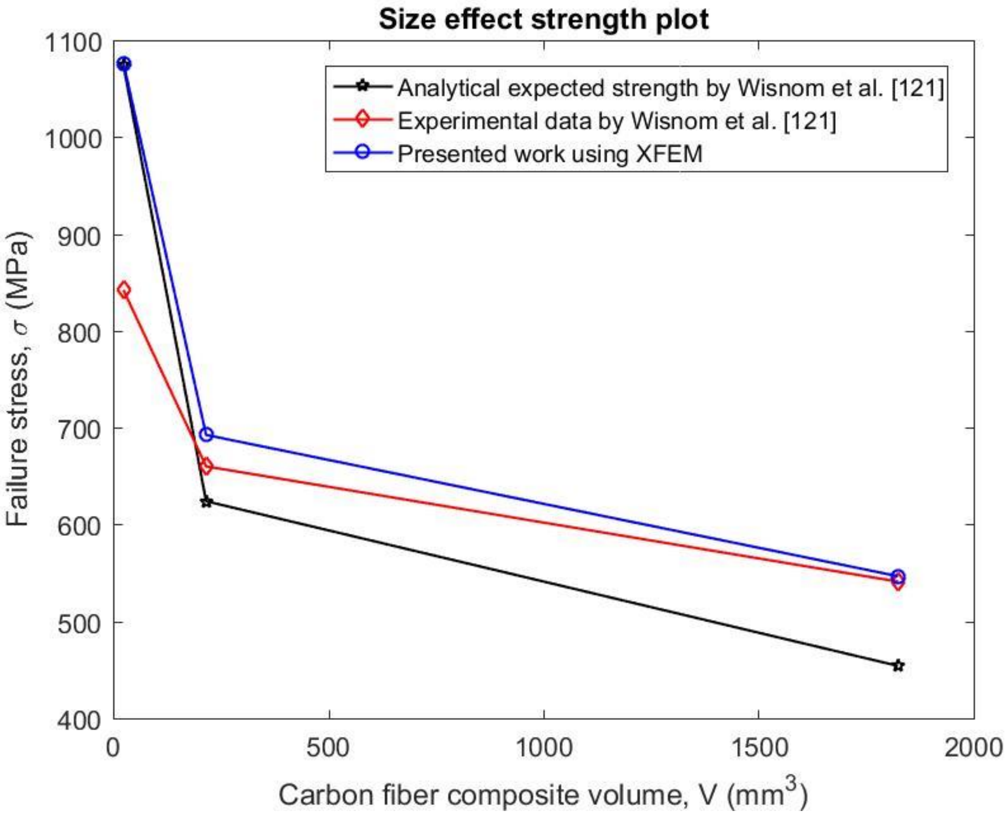
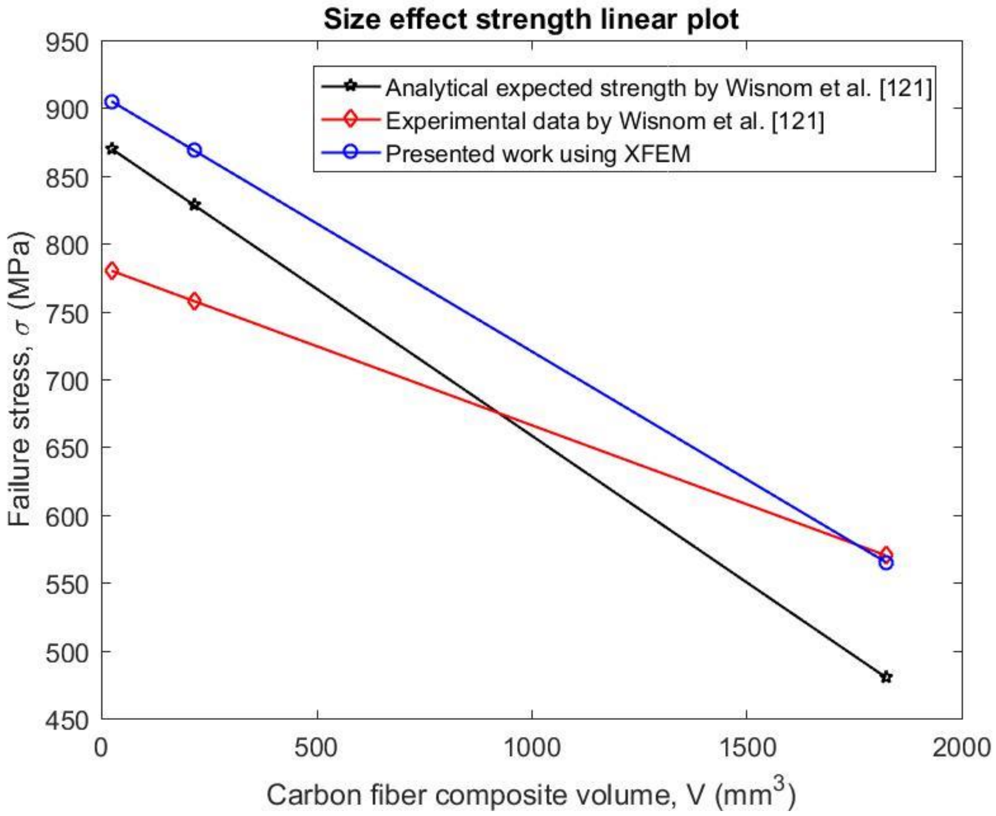



Size effect in scaled specimen of carbon fiber composite




All cases- linear approximation of size effect strength plot

# Transversal crack and delamination of laminates using XFEM

## Research highlights

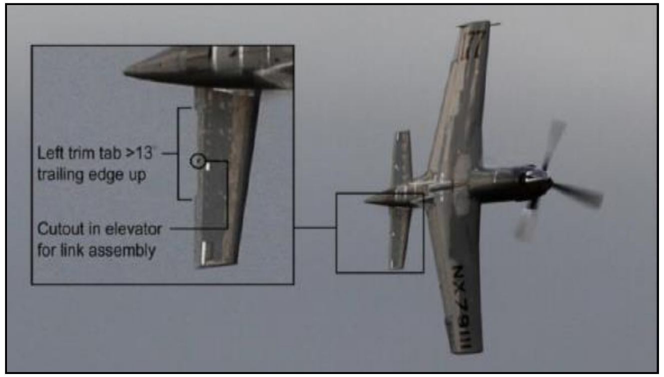
- This is the first time that transversal crack and delamination of laminates successfully modelled by using XFEM.
- The first time that the size effect on the addition of same ply orientation blocked together using XFEM successfully assessed.

**Publication:**

Abdullah NA, Curiel-Sosa JL, Taylor ZA, Tafazzolimoghaddam B, Vicente JLM, Zhang C. *Transversal crack and delamination of laminates using XFEM*. Vol. 173, pp. 78-85. Composite Structures (2018)

# Revision of the problem

## Research significance

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Based on the research motivation → How Could Fracture Affect Flutter?

**2nd objective:**

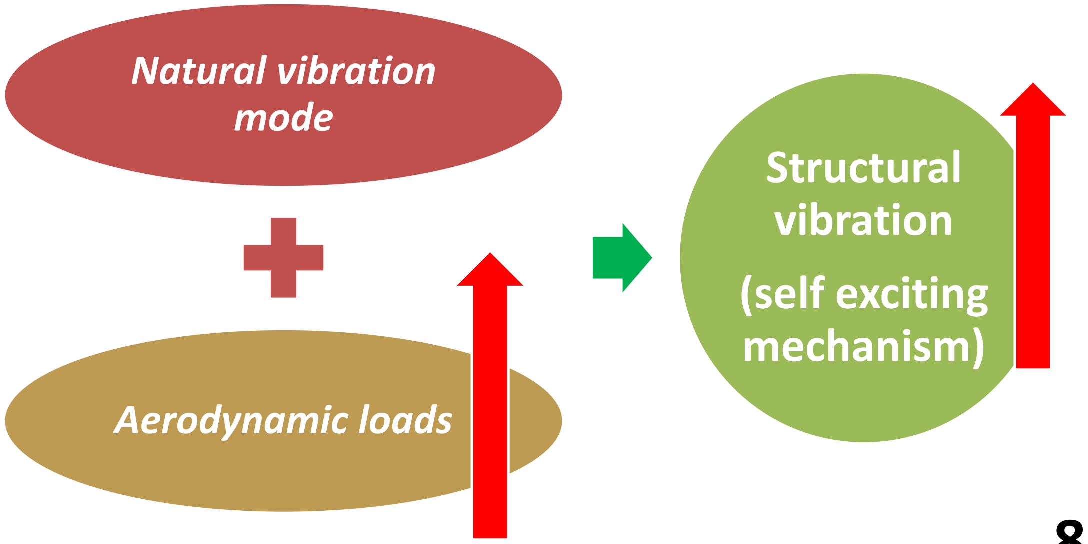
To develop and validate the flutter solution, and at the same time investigate the flutter effect on cracked composite plates with different fiber orientation.

## Definition of flutter

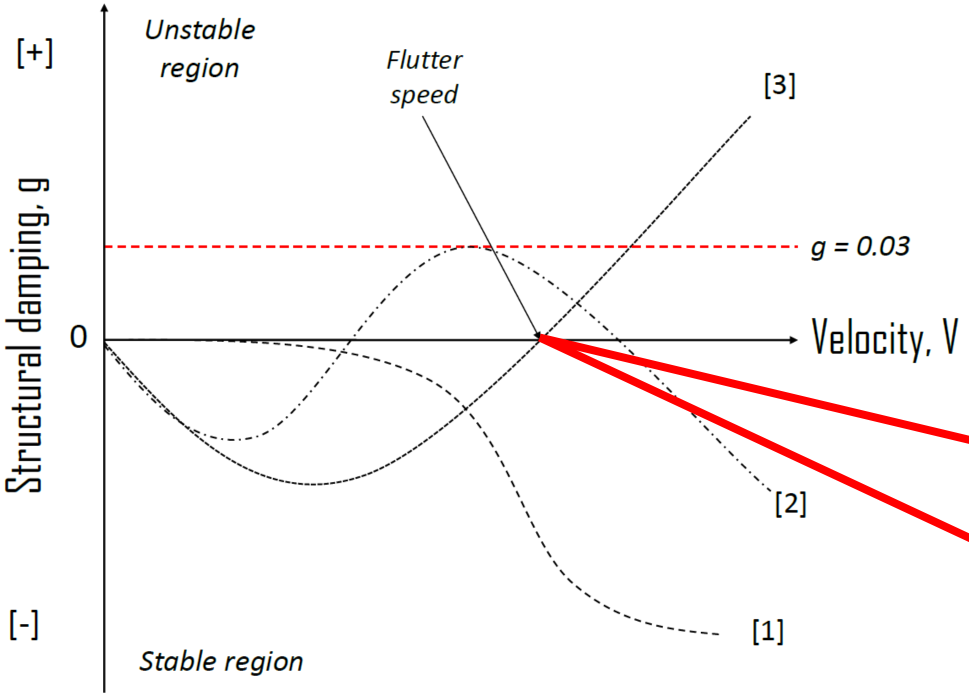
# What is flutter?

- Flutter can deform an aircraft due to dynamics instability (Potkafiski, 1986).

- Flutter as the state or a phenomenon of flight instability which can cause structural failure due to the loss interaction of aerodynamics, elastic and inertia forces (Kehoe, 1995).



## Flutter assessment




Graphical representation of required structural damping by FAA (2004)

*pk*-method of flutter solution

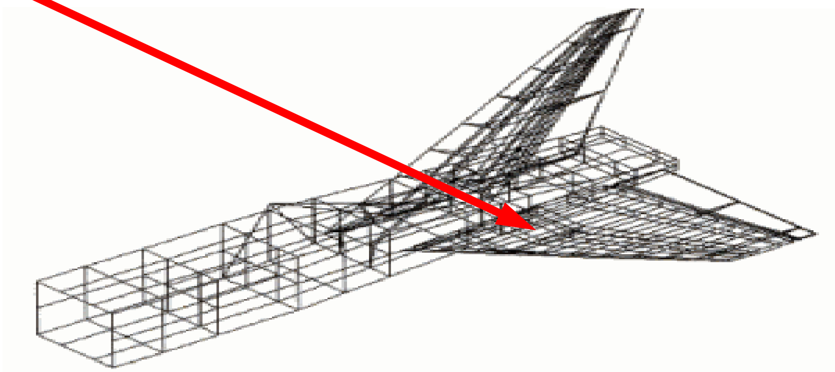
$$\left[M_{hh}p^2 + (B_{hh} - \frac{\frac{1}{4}\rho\bar{c}VQ^l_{hh}}{k})p + (K_{hh} - \frac{1}{2}\rho V^2 Q^R_{hh})\right][U_h] = 0$$

$M_{hh}$ : modal mass matrices
$B_{hh}$: modal damping matrices
$k_{hh}$: modal stiffness matrices
$Q^I_{hh}$: generalized aerodynamics damping matrices
$Q^R_{hh}$: generalized aerodynamics stiffness matrices
$\rho$: air density
$\bar{c}$: mean aerodynamics chord length
V: velocity

$k = \frac{\omega c}{2V}$: reduced frequency

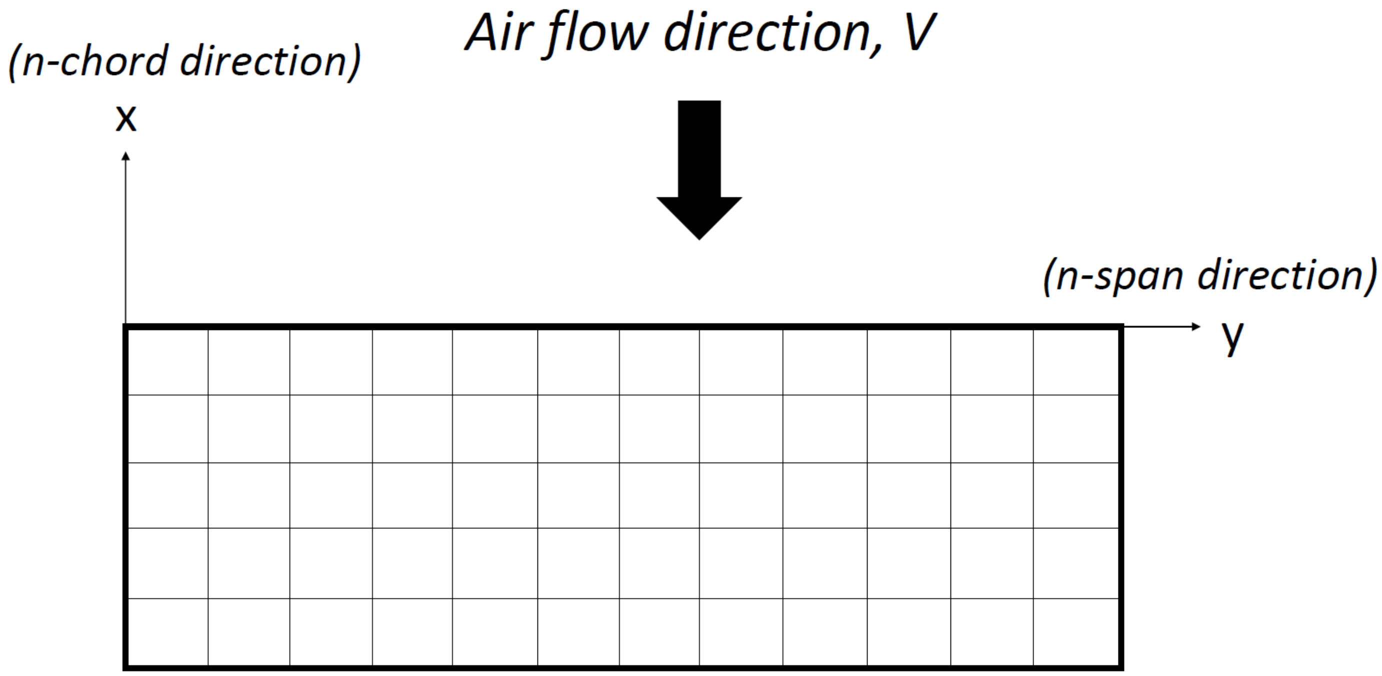
$\omega$: circular frequeny
p : $\omega$ (2g + i)
$u_h$: modal displacements

**Flutter Mode**
V flutter where *g* = 0



# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

## Structural Modelling




Aerodynamics modelling of for coupling FE-DLM

# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

*Abdullah, N.A et al., Composite Structures (2018)*

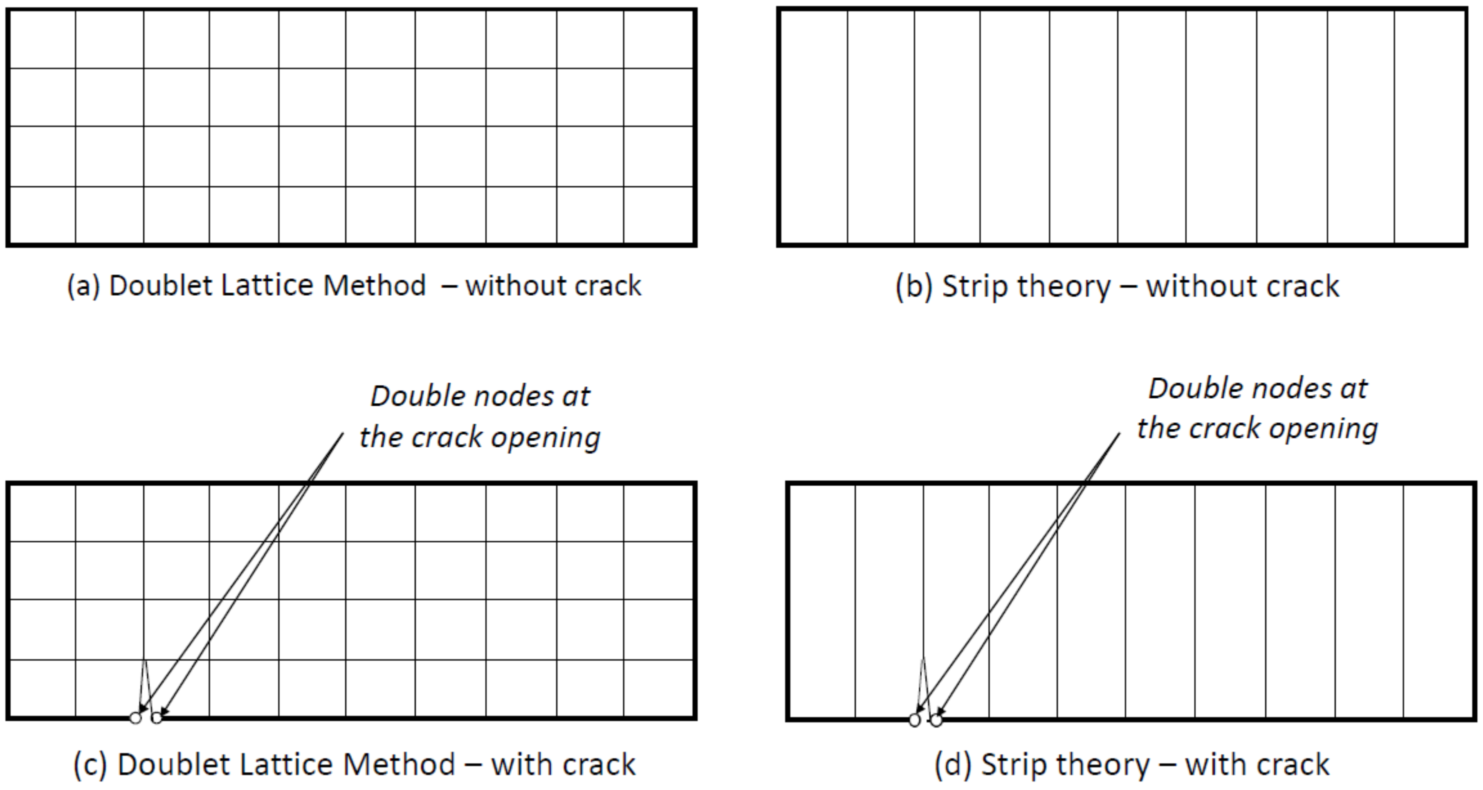
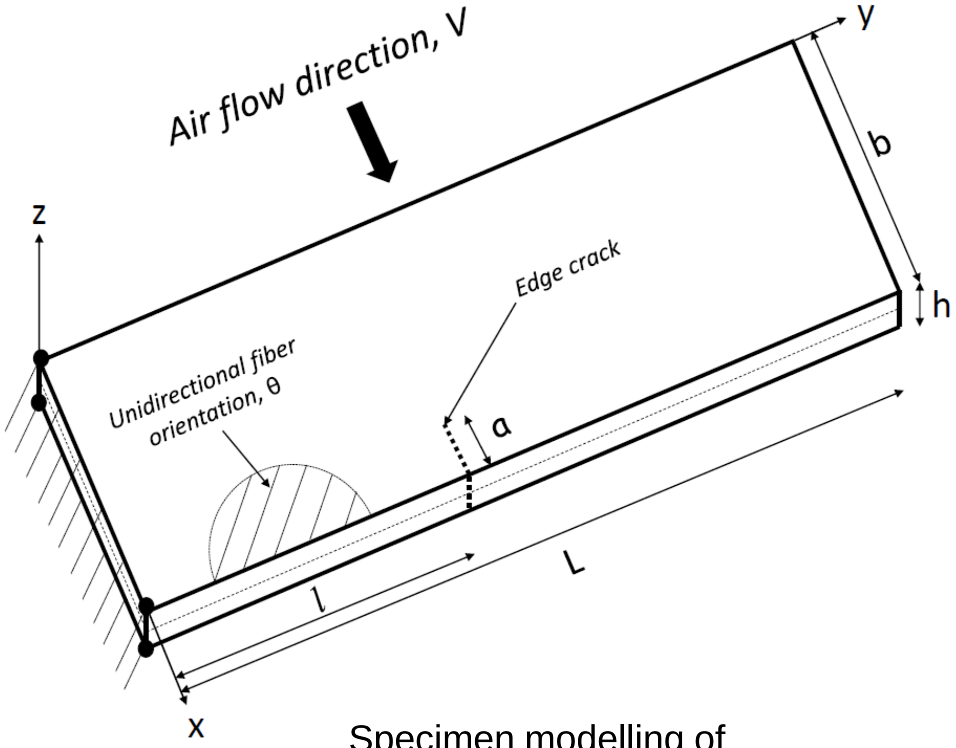
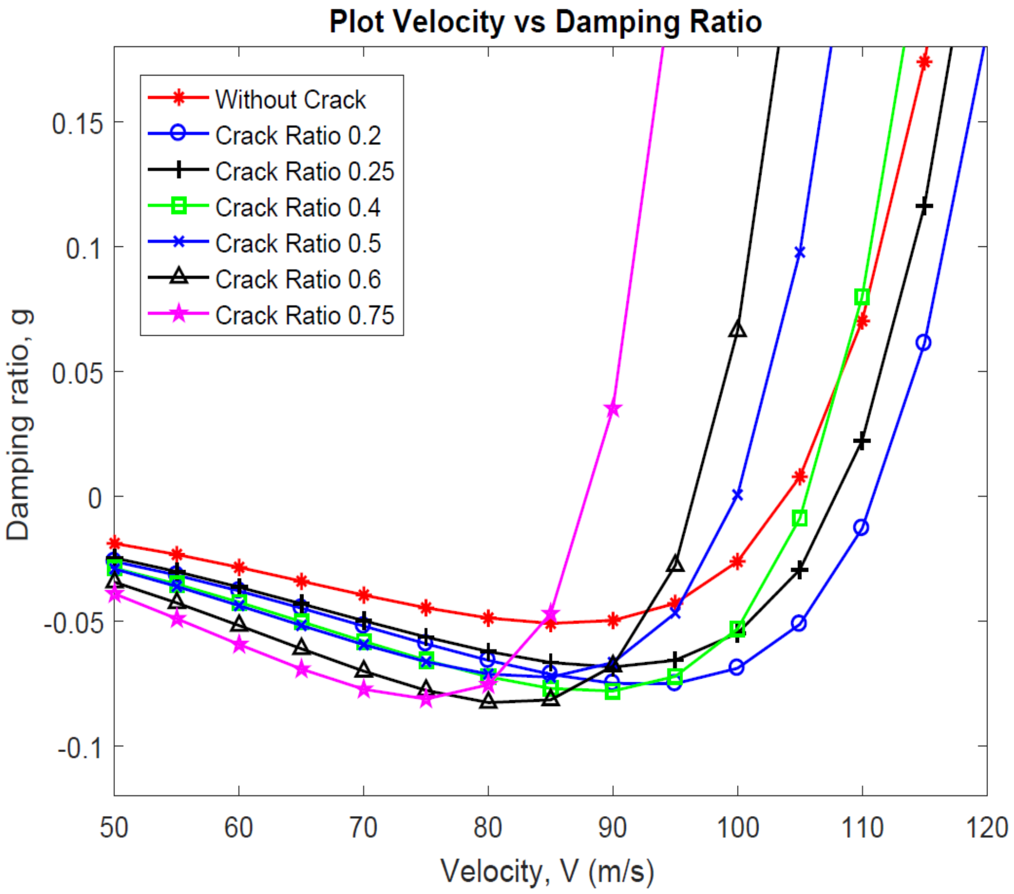



**Figure 4.16:** Comparison of aerodynamic modelling technique between Doublet Lattice Method and Strip theory for without crack and with crack specimen

# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM




Specimen modelling of unidirectional composite based on Wang et al. (2005)




V-*g* plot: Flutter speed determination for $\theta = 0^{o}$

# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

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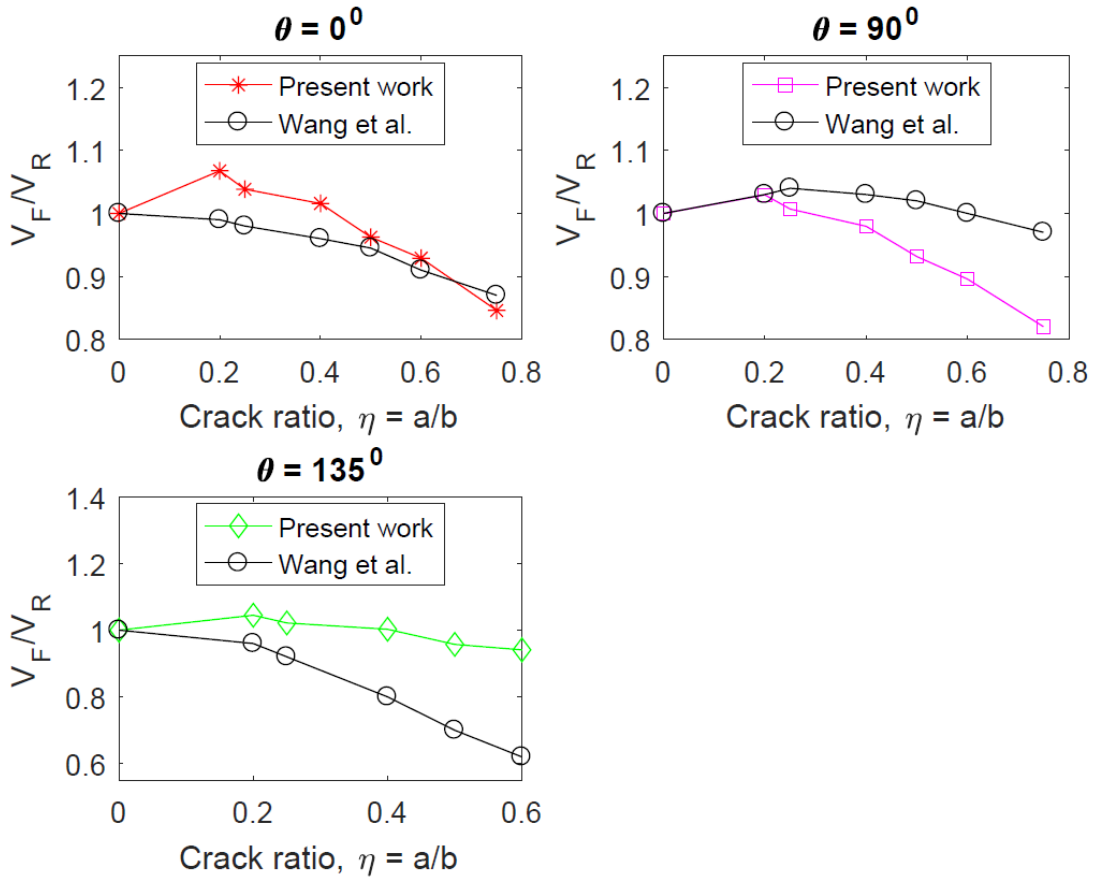
## Flutter speed plot – crack ratio analysis

*Abdullah, N.A et al., Composite Structures (2018)*




Normalized flutter speeds with respect to the crack ratio (DLM) for case $\theta$ = 0 º, $\theta$ = 90 º and $\theta$ = 135 º

$$\left[ M_{hh}p^2 + \left(B_{hh} - \frac{\frac{1}{4}\rho\bar{c}VQ^l_{hh}}{k}\right)p + \left(K_{hh} - \frac{1}{2}\rho V^2 Q^R_{hh}\right) \right] [U_h] = 0$$

$$\boldsymbol{Q}_{hh}(real\&imaginary) = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix}$$

Aerodynamic matrices data comparison between DLM and Strip theory for crack ratio 0.2

| Aerodynamic parameter | Doublet Lattice Method |
|---|---|
| $Q_{11}$ | $2.47\text{x}10^1 - 8.68\text{x}10^2 i$ |
| $Q_{12}$ | $-1.32\text{x}10^4 - 6.43\text{x}10^2 i$ |
| $Q_{21}$ | $8.58\text{x}10^1 + 8.13\text{x}10^2 i$ |
| $Q_{22}$ | $1.29\text{x}10^4 - 1.57\text{x}10^3 i$ |

## Research highlights

- This is the first time that the flutter of cracked composite plate was assessed via FE-DLM.
- Successfully explained the scientific reason of the flutter increment subjected to the existence of small crack ratio → increment of the stiffness system

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

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## Research question

Is the crack propagates before it reaches the flutter speed?

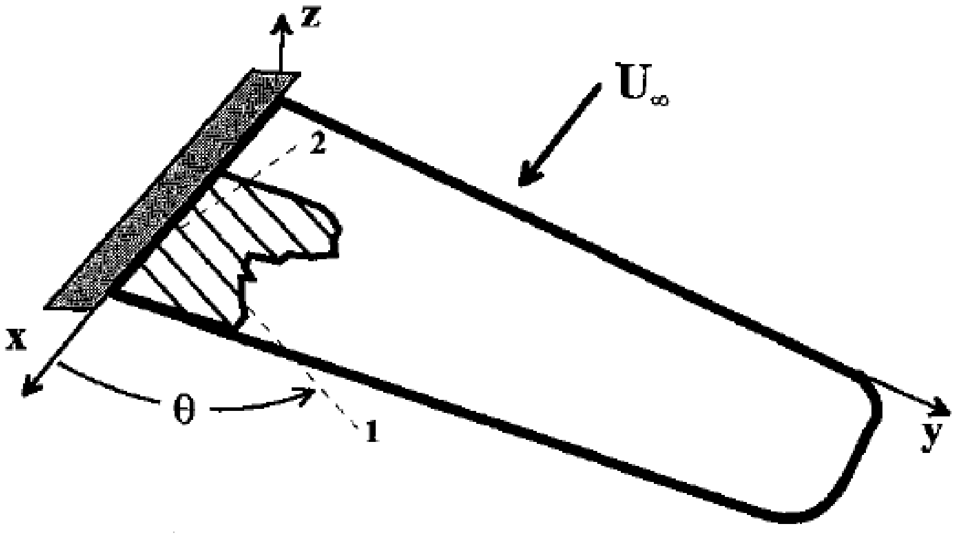
If No, means previous analysis is correct and needs no revision.

**Why?**

Because the crack is assumed to be static (based on Wang et al. 2008), while in reality its propagates with the increment of speed

If Yes, means that the previous analysis procedure is correct, but it needs some revisions.

## Supportive argument




Aeroelastic response for cantileved composite laminate plate

- The stress level is larger for the flow conditions associated with the higher dynamics pressure
- Damage will occur at a faster rate as the dynamic pressure is increased

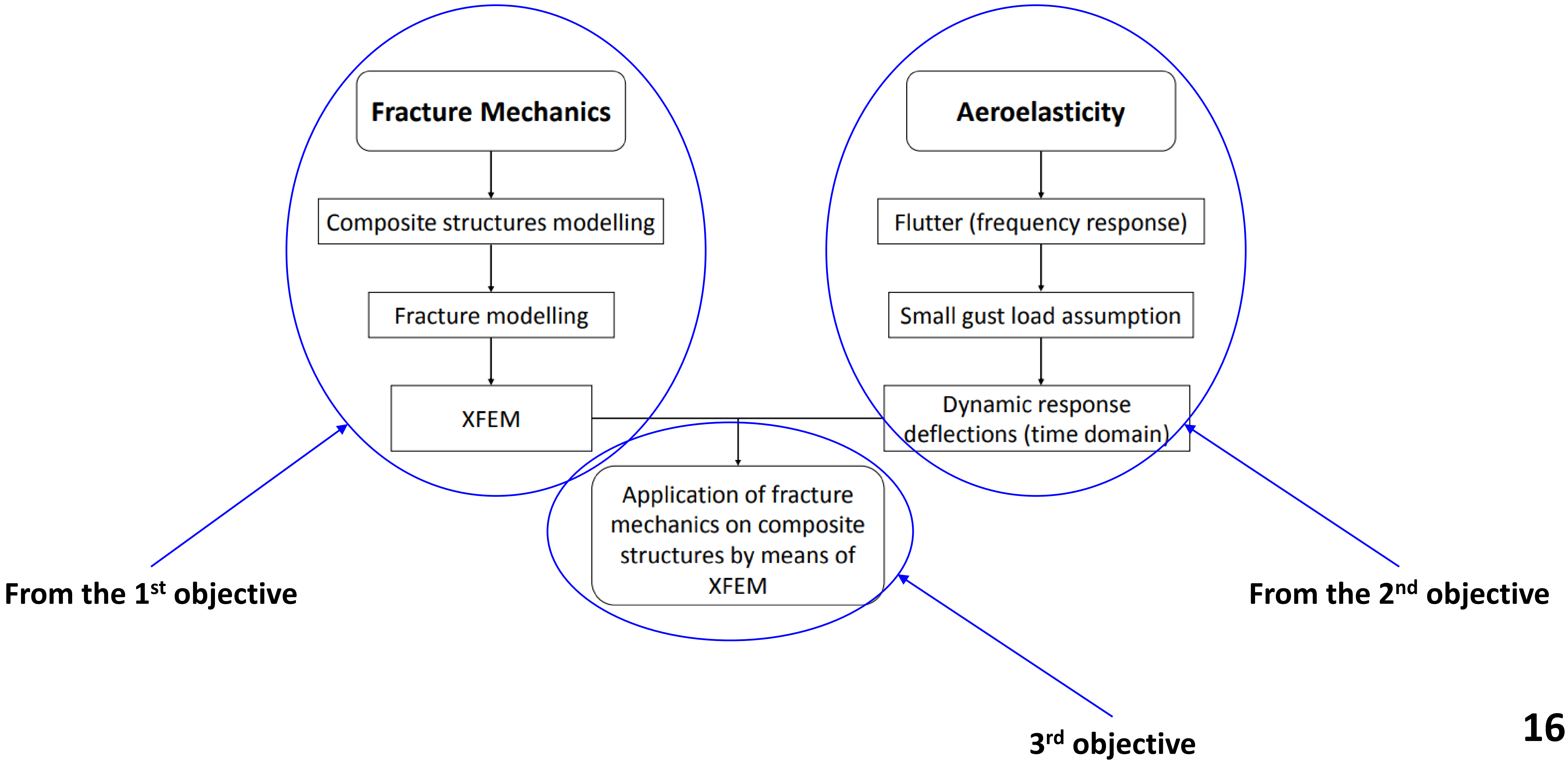

- Strganac, T. W., Kim, Y.I., "Aeroelastic Behavior of Composite Plates Subject to Damage Growth," AIAA Journal, Vol. 33, No. 1, 1996, pp. 68-73

Based on that doubt:

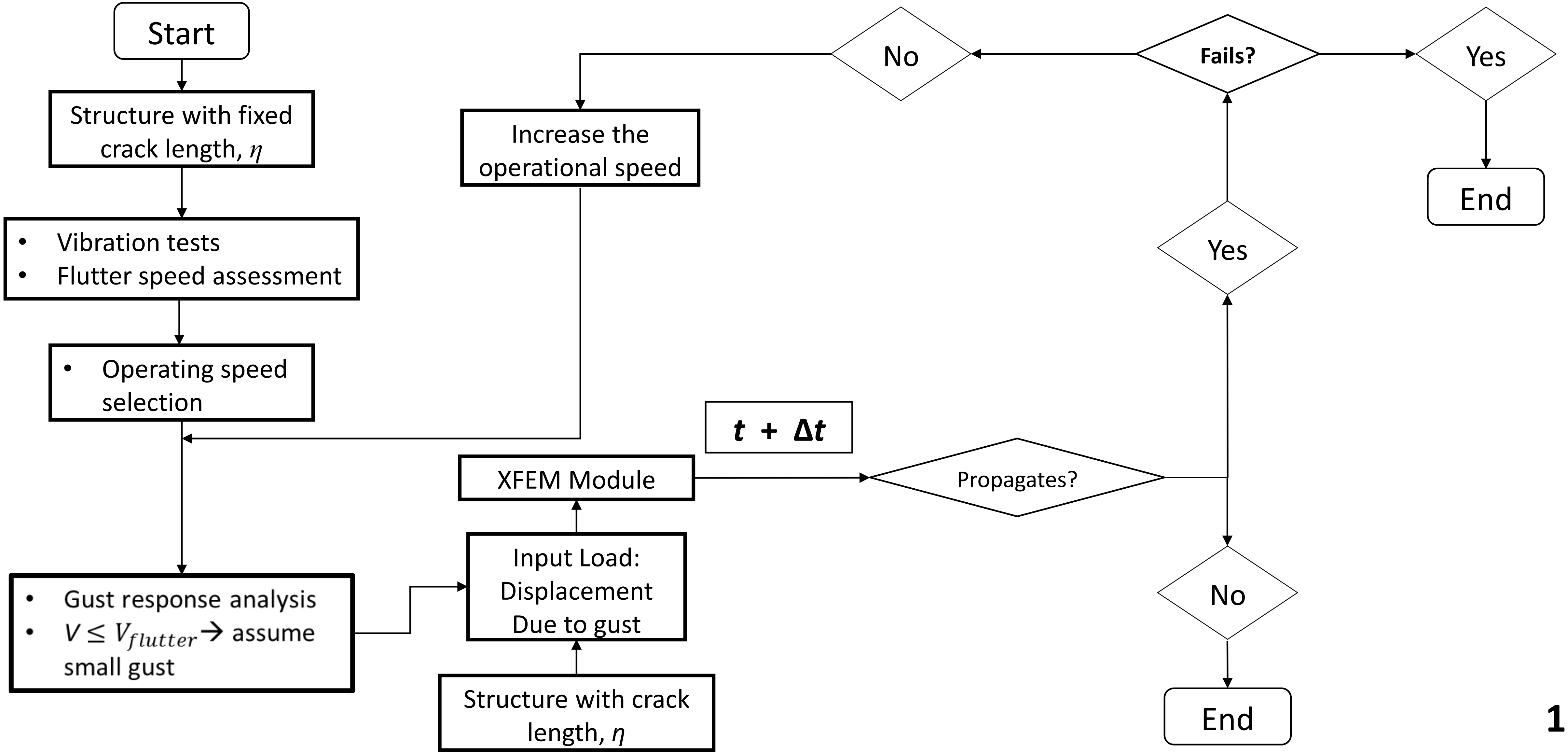
**3rd objective:**

To investigate the crack propagation subjected to aerodynamic loads at several specific flight regions before flutter is expected to occur.

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

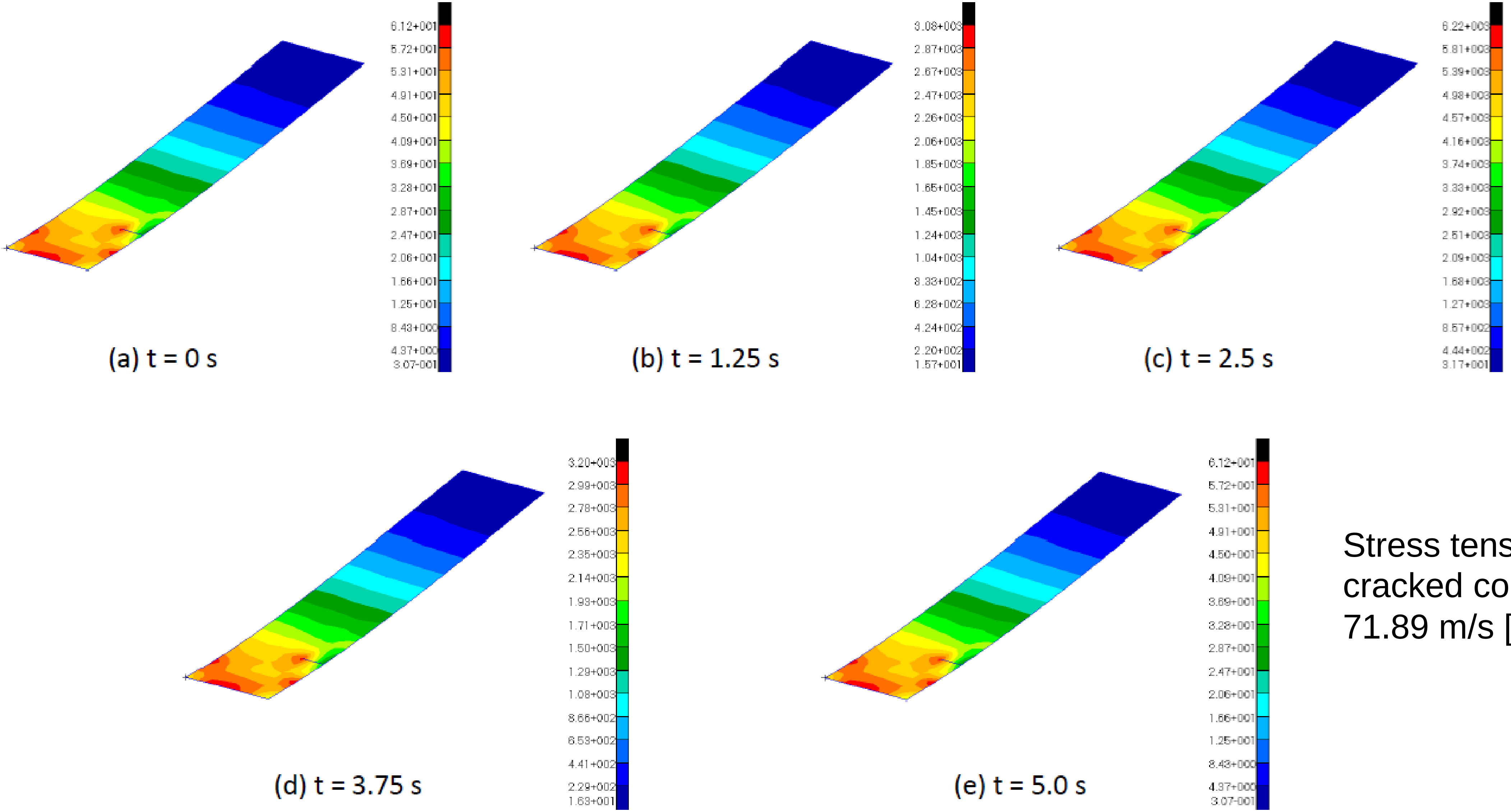


# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM



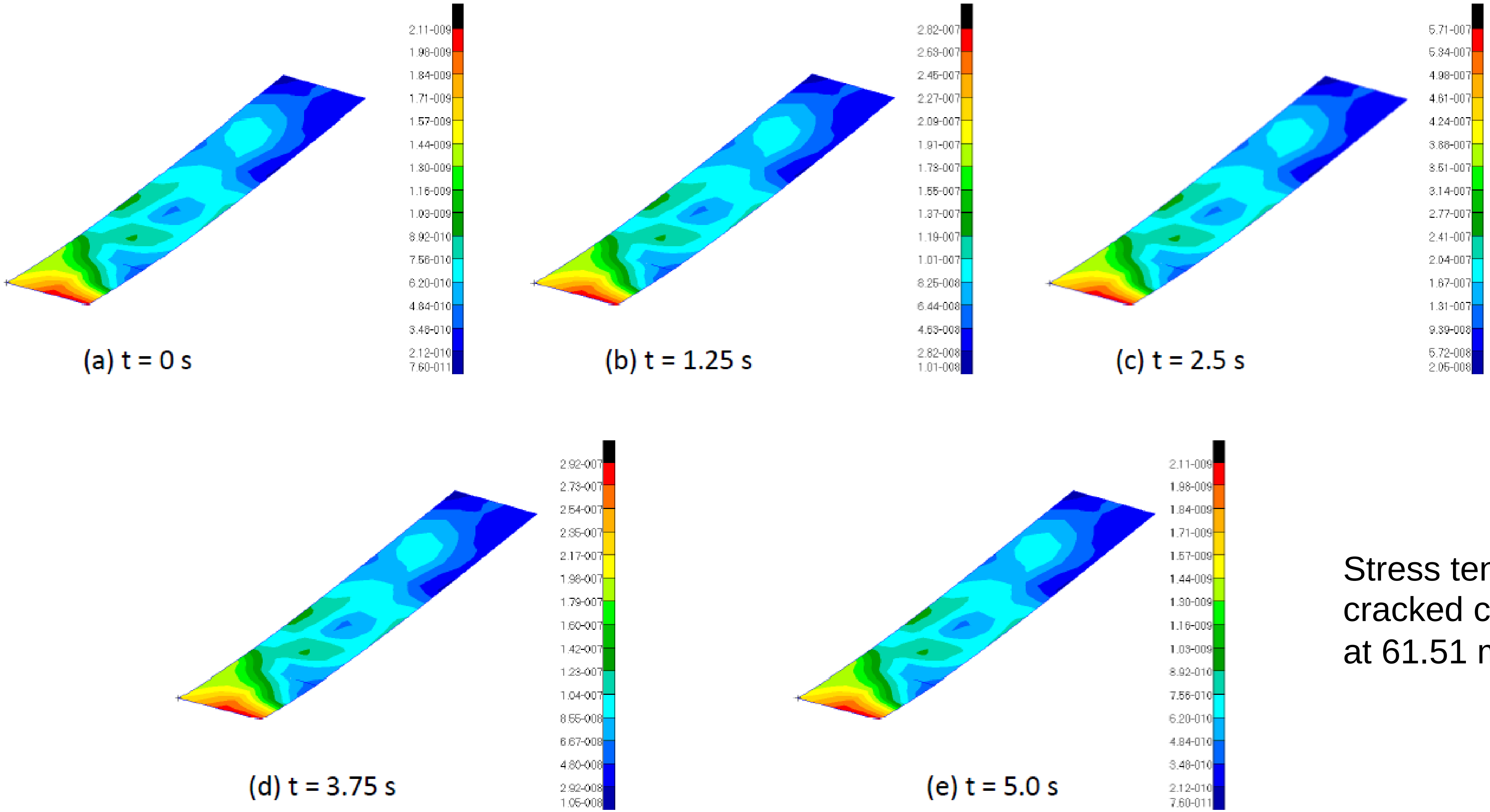
# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM






Stress tensor plots on cracked composite 0º at 71.89 m/s [unit: kPa]

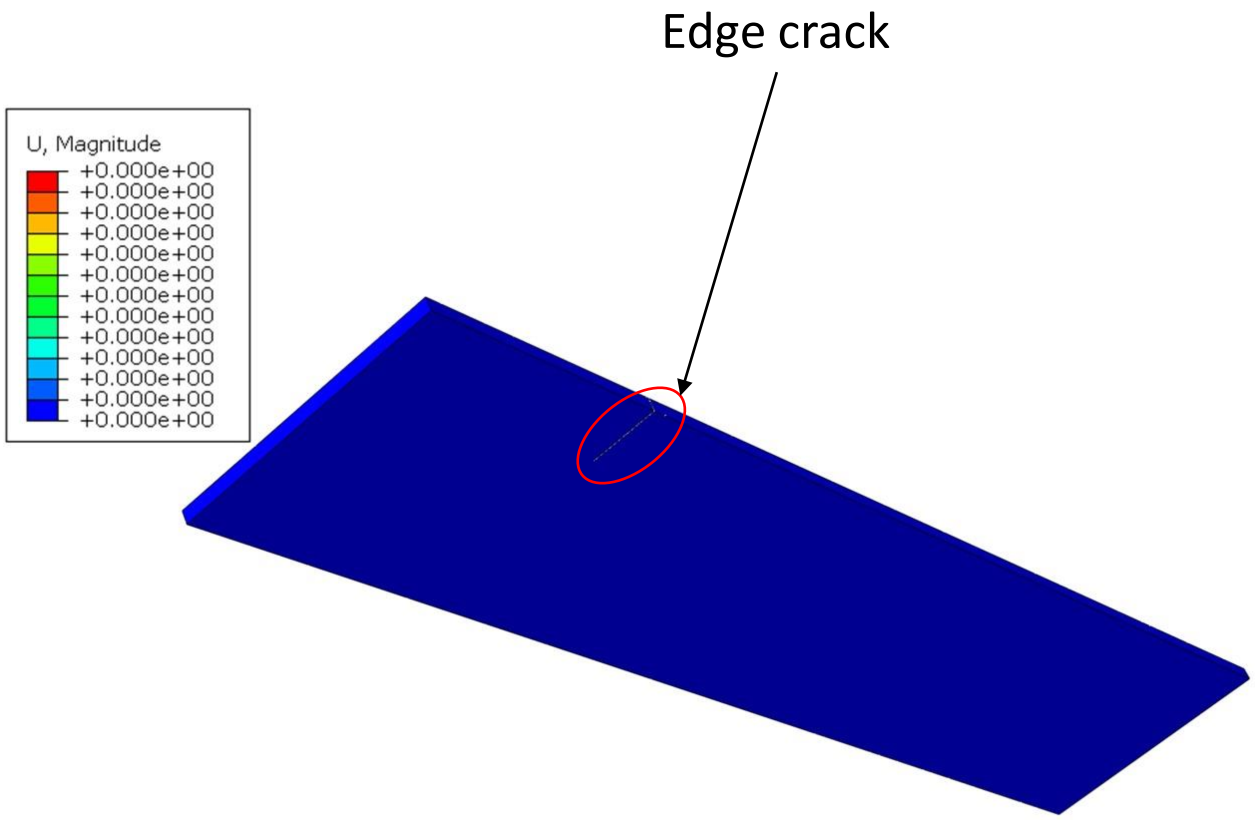
# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM



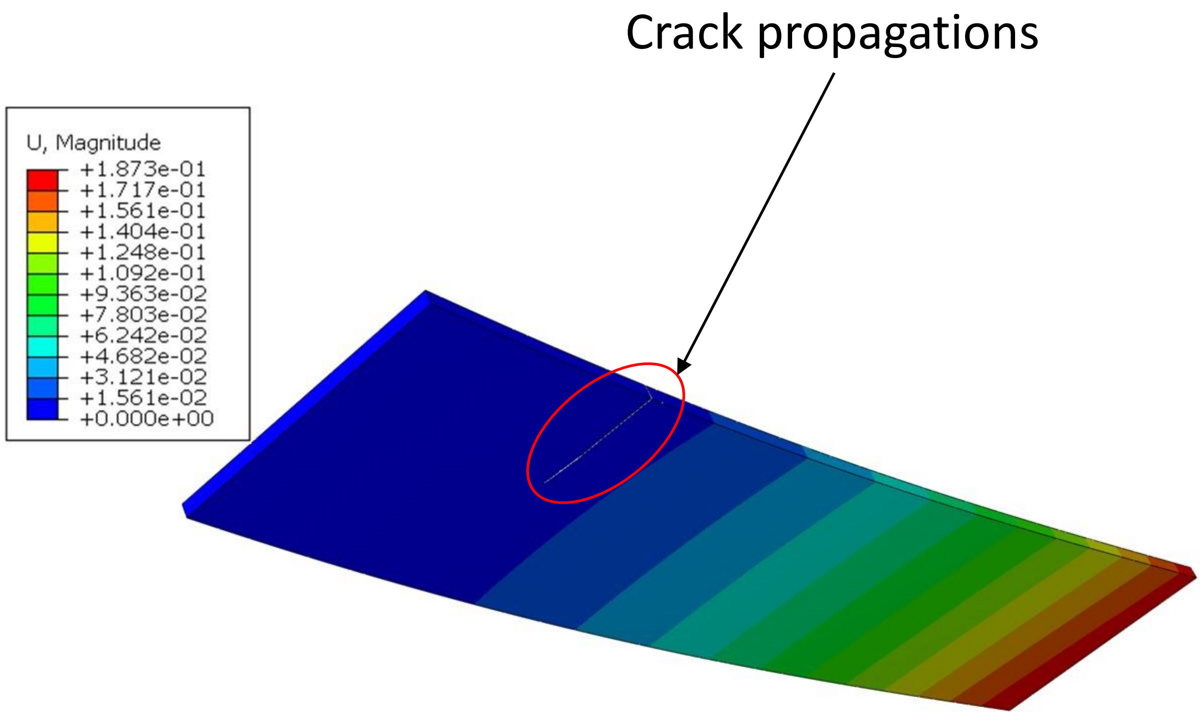

(a) t = 0 s
(b) t = 1.25 s
(c) t = 2.5 s
(d) t = 3.75 s
(e) t = 5.0 s

Stress tensor plots on cracked composite 135º at 61.51 m/s [unit: kPa]

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM




a) Bottom view: before interaction with aerodynamic loads




b) Bottom view: After interaction with aerodynamic loads

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

## Research highlights

- Establishment of a novel scheme in developing a fracture mechanism on a cracked composite plate under aerodynamic loads by means of XFEM.
- $0^{o}$ cracked composite plate has partially failed due to crack propagation first instead of the flutter failure.
- However, a contradict observation was found for the $135^{o}$ composite plate where it failed due to the flutter.

# Structural integrity of wing box dominated by aeroelastic gust loads



- Could the novel scheme applied to the real wing box?
- How about the crack on the wing box subjected to gust loads?

**4th objective:**

To develop a fracture mechanism on wing box subjected to aeroelastic gust loads.

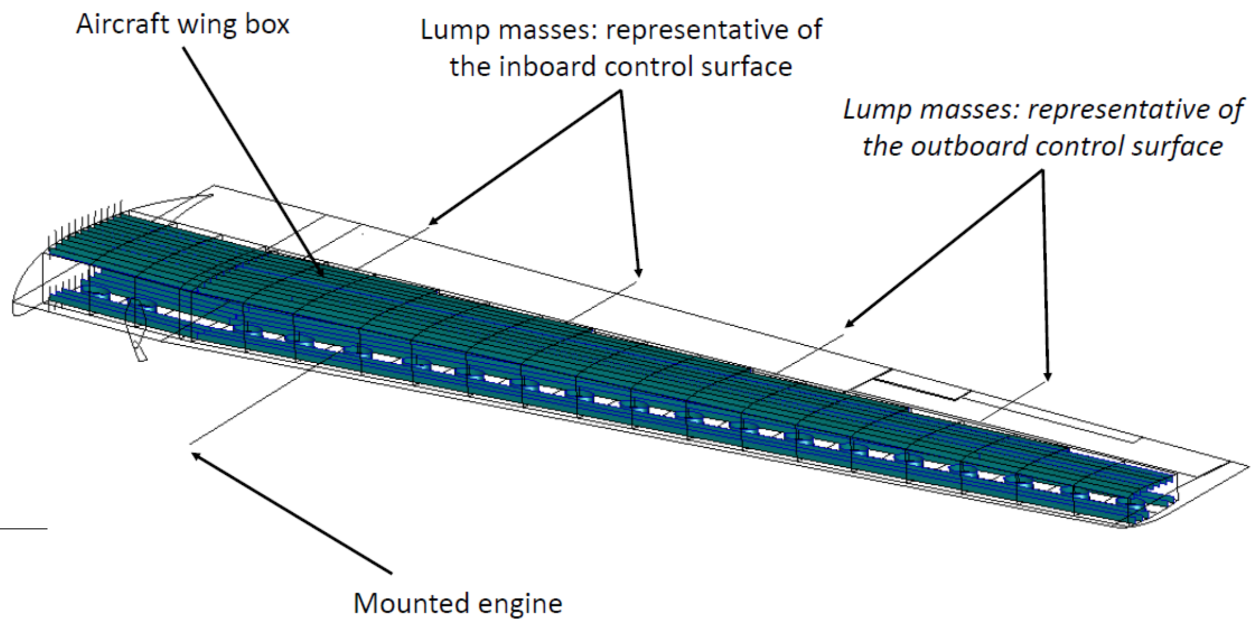
# Structural integrity of wing box dominated by aeroelastic gust loads

Indonesian N219 commuter aircraft

*photo retrieved from https://www.ndhi-bumn.id/product/n219

**Solid element**: wing skin

**Lump mass**: engine & control surfaces




Wing box model of N219

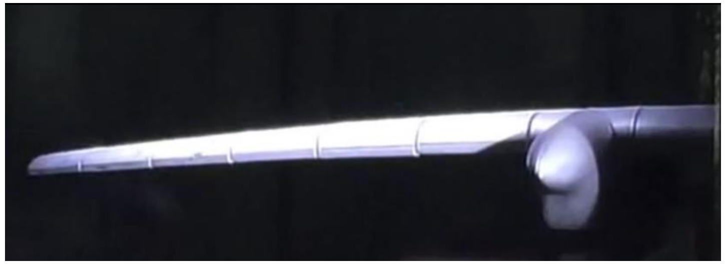
Flutter speed validations: Experimental and modelling

| Flutter results (Maximum take-off weight configuration) | | | |
|---|---|---|---|
| Parameter | Experimental (wind tunnel test) | Stick model (FE-Strip) | Shell plate (FE-DLM) |
| Vibration Mode | Torsion | Mode 4 Wing torsion | Mode 4 Wing torsion |
| Flutter speed | 40 m/s (1:10 true scale) | 767 KTAS (395 m/s) | 400 m/s |

# Structural integrity of wing box dominated by aeroelastic gust loads

## Flutter speed validation: Exp. & Sim.

*CASR23, \CASR Part 23 Amdt. 2, Part 23. Airworthiness Standards: Normal, Utility, Acrobatic, and the Commuter Category Airplanes," tech. rep., Ministry of Transportation, Republic of Indonesia, 09 2014.*



Front view: Wing torsion mode at flutter speed demonstrated in wind tunnel as the right wing

| | Flutter results (Maximum take-off weight configuration) | | |
|---|---|---|---|
| Parameter | Experimental (wind tunnel test) | Stick model (FE-Strip) | Shell plate (FE-DLM) |
| Vibration Mode | Torsion | Mode 4 Wing torsion | Mode 4 Wing torsion |
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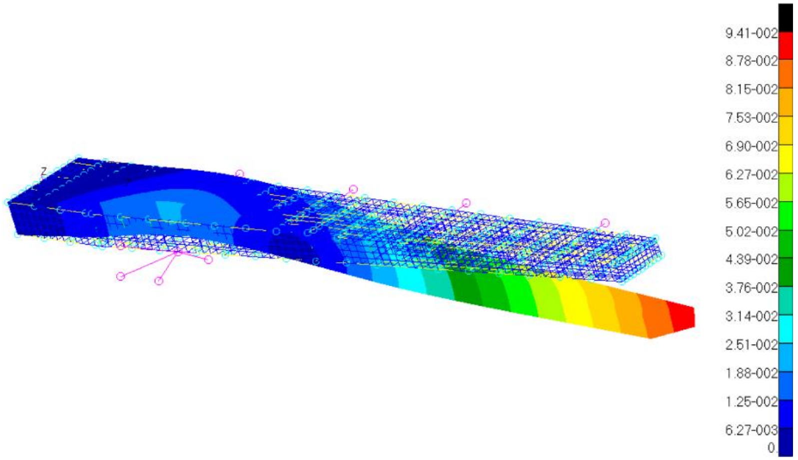
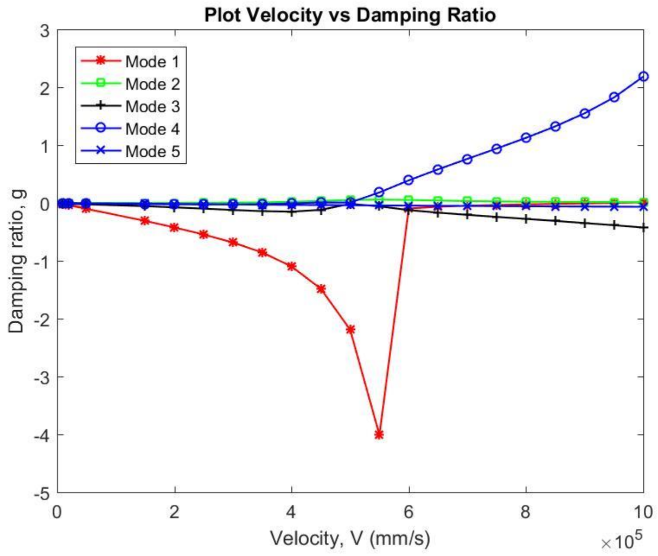
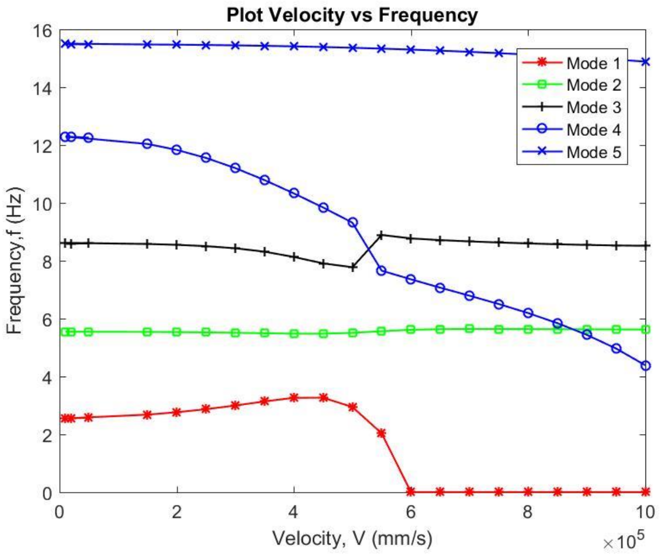



Front view: Flutter response on torsional mode modelled as the left wing



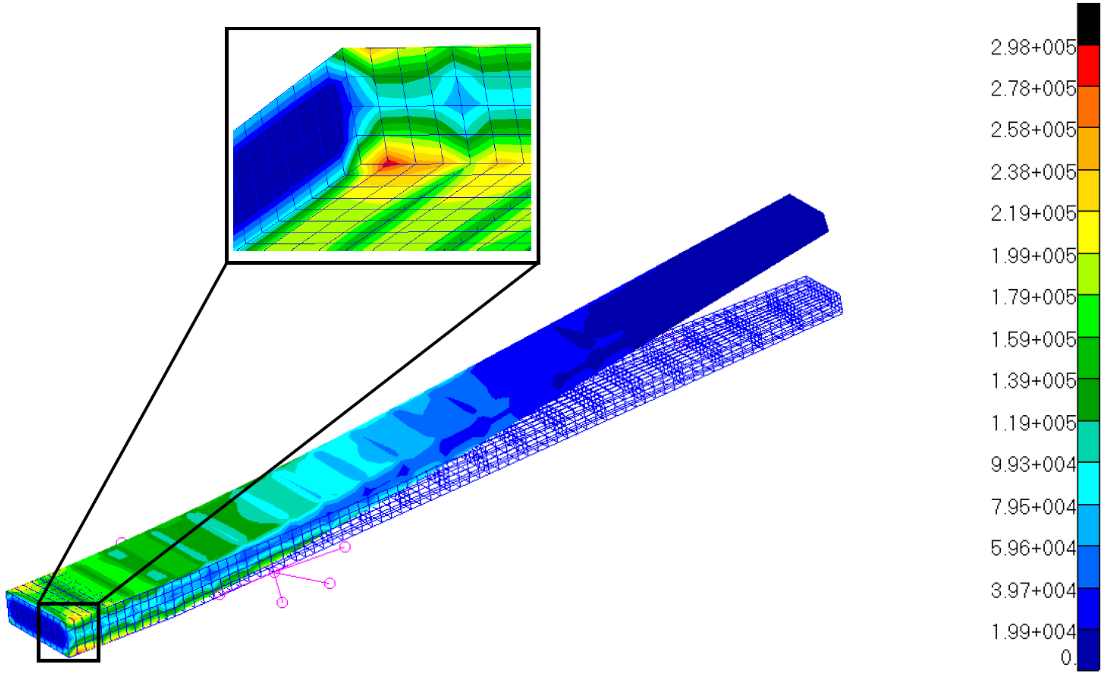

V-*g* plot of the commuter aircraft wing



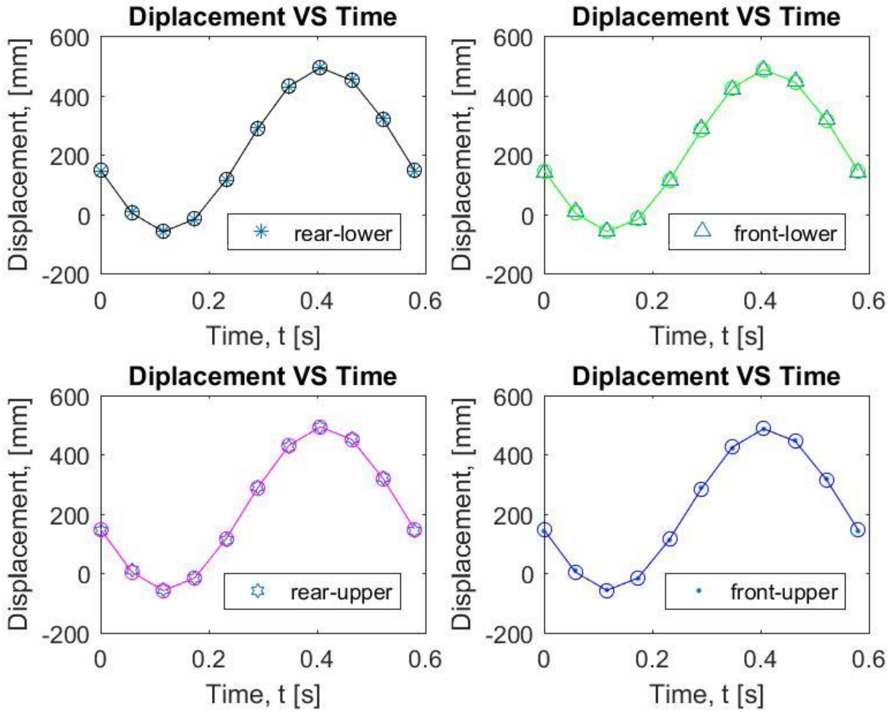

V-*f* plot of the commuter aircraft wing

# Structural integrity of wing box dominated by aeroelastic gust loads

## Stress analysis and FSF

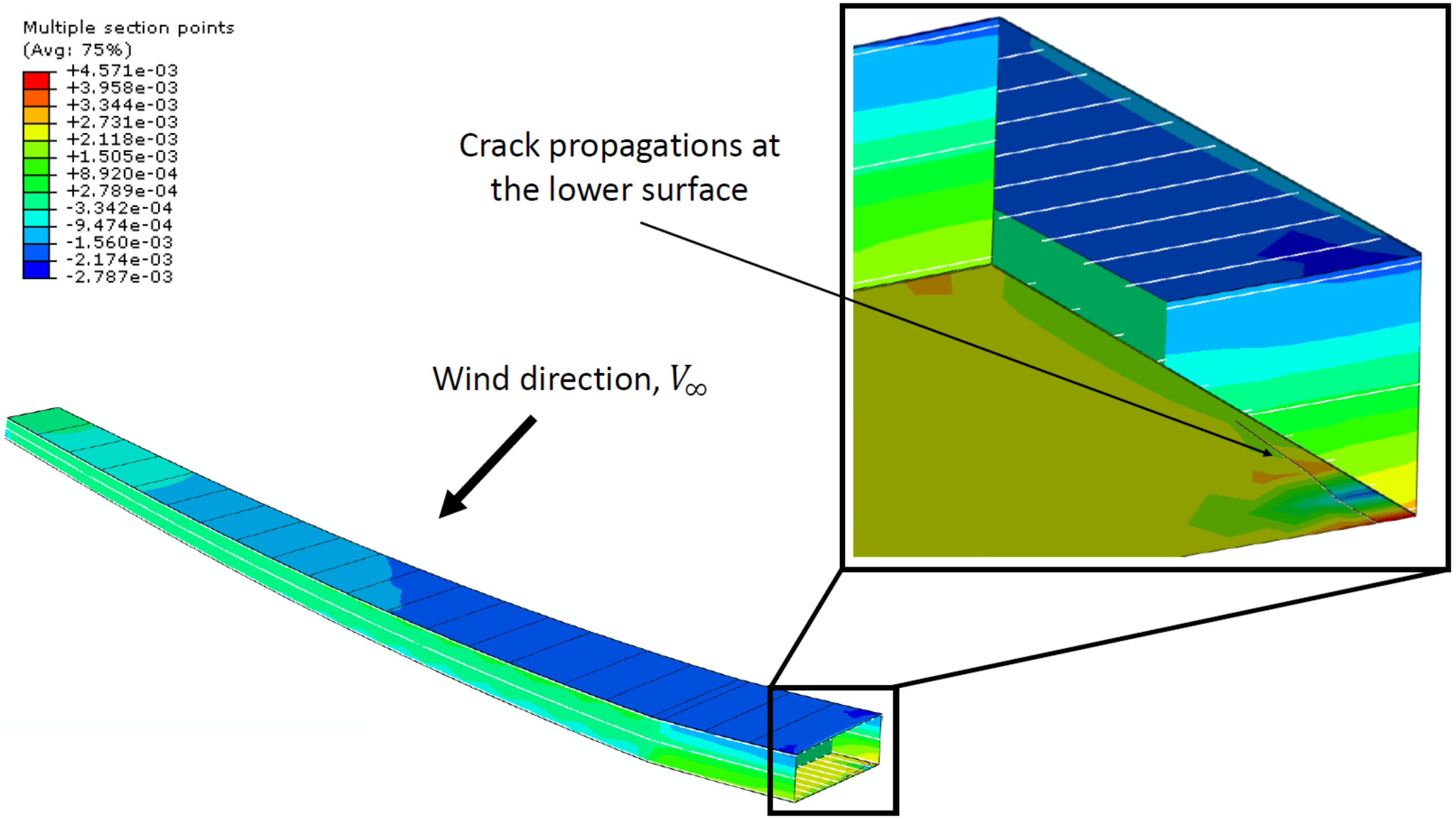



Focus view: stress tensor under gust loads for $V_B$ = 140 KEAS [unit: kPa]




Wing tip periodic motions represent via Fourier Series Function at $V_B$ = 140 KEAS

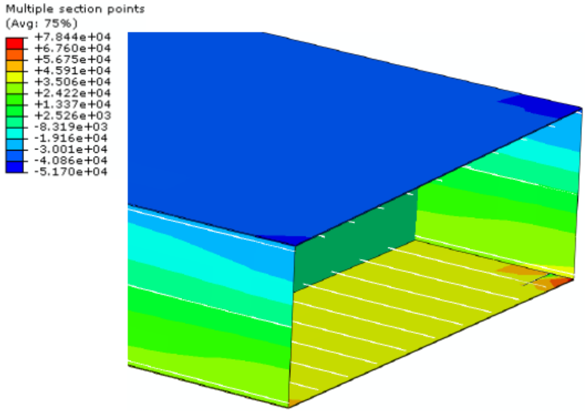
## Fracture assessment – stress contour



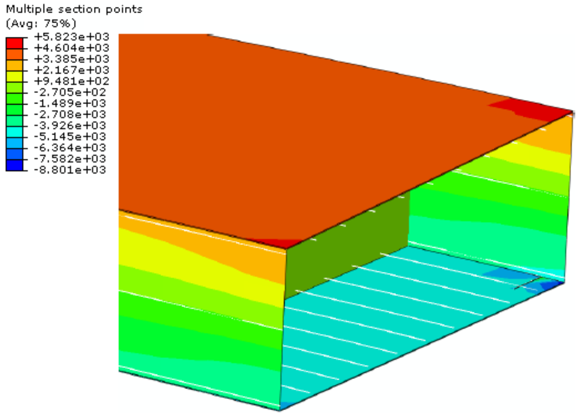

Final state: near wing root (lower-front skin) results on fracture behavior via XFEM [unit:kPa]

# Structural integrity of wing box dominated by aeroelastic gust loads

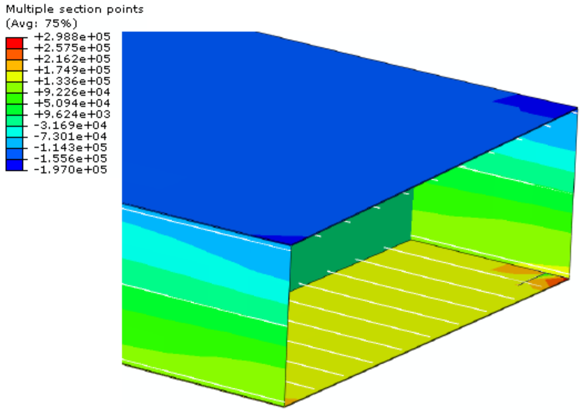
## Fracture assessment – stress contour



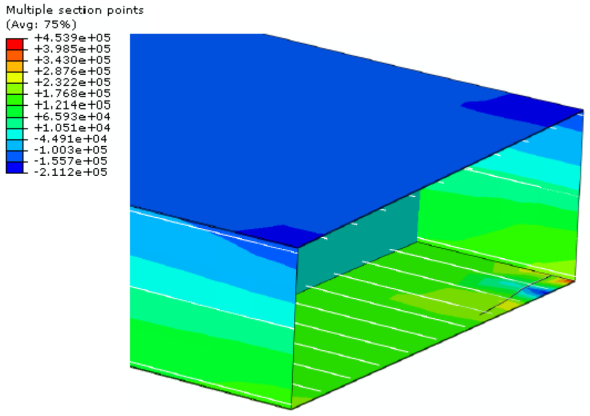

(a) t =0.001 s



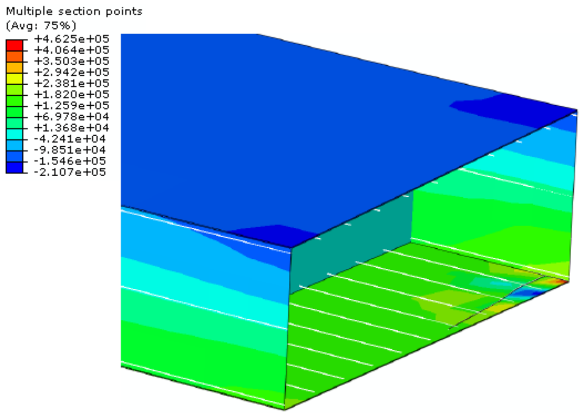

(b) t =0.16 s



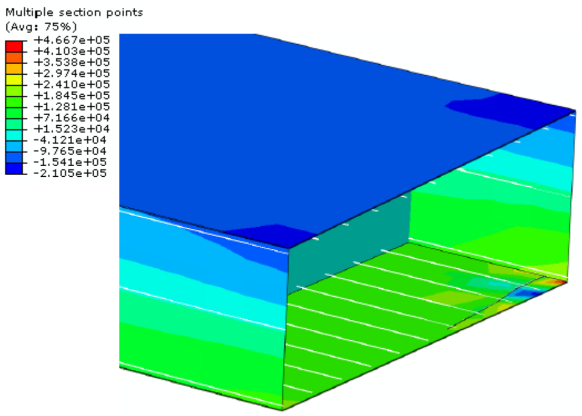

(c) t =0.41 s




(d) t =0.46 s




(e) t =0.51 s




(f) t =0.58 s

Stress plot: near wing root (lower-front skin) results on fracture behavior via XFEM [unit:kPa]

# Structural integrity of wing box dominated by aeroelastic gust loads

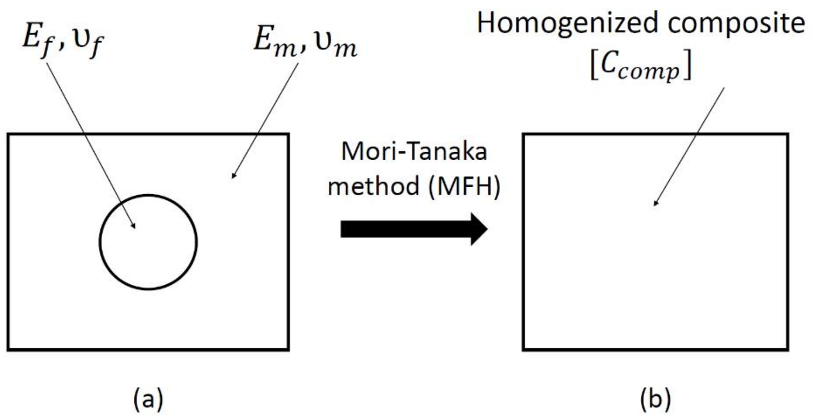


## Research highlights

- The fracture study was applied to the modelled wing box, which is quite complicated.
- This is the first time that the crack propagations successfully demonstrated under the influence of gust loads via XFEM.

# THANK YOU
# for your
# ATTENTION

# Structural Modelling – Mean Field Homogenization




Mean field homogenization by Mori-Tanaka Method

# Current progress

% difference of expected strength & experimental results by M. R Wisnom et al. (2008)

| Case | Lay-up | Expected strength (MPa) | Experimental (MPa) | Difference % |
|---|---|---|---|---|
| 1 | $(45/90/\text{-}45/0)_s$ | 1074 | 842 | 21.6 |
| 2 | $(45_2/90_2/-45_2/0_2)_s$ | 642 | 660 | 2.8 |
| 3 | $(45_4/90_4/-45_4/0_4)_s$ | 454 | 541 | 19.2 |

%difference the expected strength by M.R Wisnom et al. (2008) & failure stress - present work

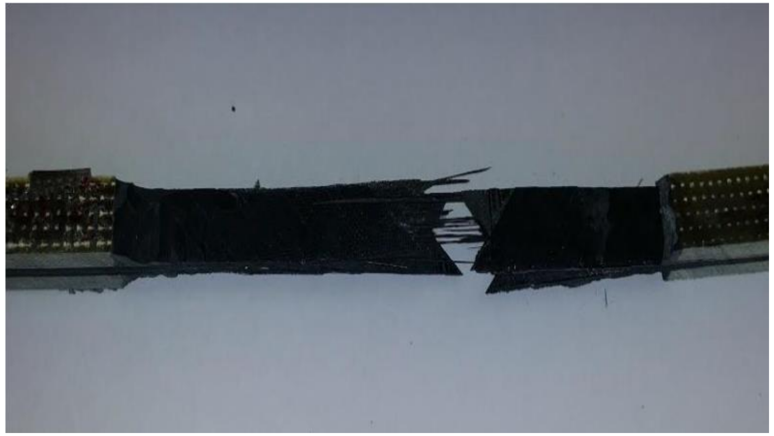
| Case | Lay-up | Expected strength (MPa) | Failure stress-present work (MPa) | Difference % |
|---|---|---|---|---|
| 1 | $(45/90/\text{-}45/0)_s$ | 1074 | 1076.36 | 0.2 |
| 2 | $(45_2/90_2/-45_2/0_2)_s$ | 642 | 692.47 | 7.86 |
| 3 | $(45_4/90_4/-45_4/0_4)_s$ | 454 | 546.59 | 20.39 |

% difference of experimental by M.R Wisnom et al. (2008) & failure stress-present work

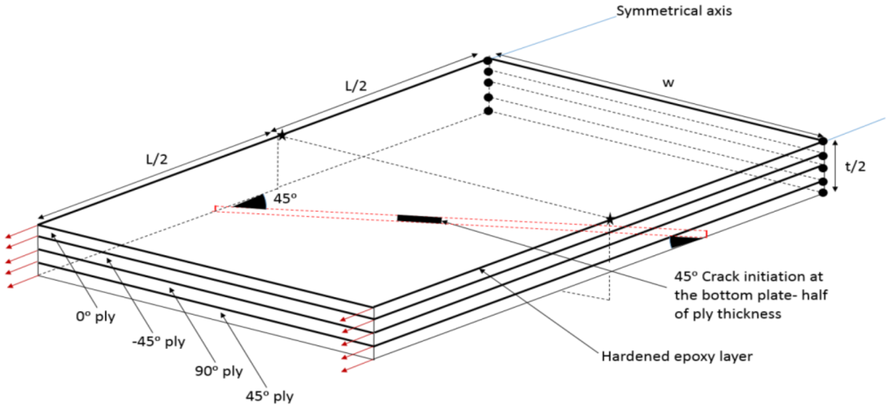
| Case | Lay-up | Experiment (MPa) | Failure stress-present work(MPa) | Difference % |
|---|---|---|---|---|
| 1 | $(45/90/\text{-}45/0)_s$ | 842 | 1076.36 | 27.83 |
| 2 | $(45_2/90_2/-45_2/0_2)_s$ | 660 | 692.47 | 4.92 |
| 3 | $(45_4/90_4/-45_4/0_4)_s$ | 541 | 546.59 | 1.03 |

# Transversal crack and delamination of laminates using XFEM

## Fracture study



Experimental results of crack and delamination




Symmetrical model of present composite structure

Carbon fiber composite elastic properties used in the XFEM analysis

| Parameter | Value |
|---|---|
| $E_1$ | 161 GPa |
| $E_2 = E_3$ | 11.38 GPa |
| $G_{12} = G_{13}$ | 5.17 GPa |
| $G_{23}$ | 3.98 GPa |
| $\upsilon_{12} = \upsilon_{13}$ | 0.32 |
| $\upsilon_{23}$ | 0.436 |

Yield stress used in XFEM analysis taken from Corum et al. (2000) and Ibtihal-Al-Namie et al. (2011)

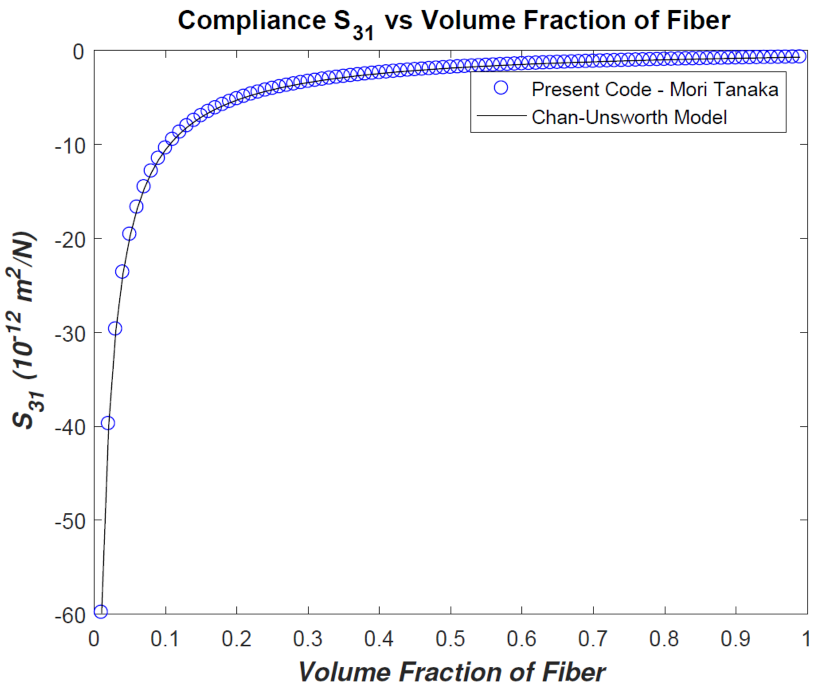
| Material | Angle | Maximum principal stress (MPa) |
|---|---|---|
| ICMF | 0 | 476 |
| ICMF | 45 | 149 |
| ICMF | 90 | 476 |
| ICMF | -45 | 149 |
| Epoxy | NIL | 50.2 |

Fracture toughness value of carbon fiber composite laminate by Pinho et al. (2006) and Ibtihal-Al-Namie et al. (2011)

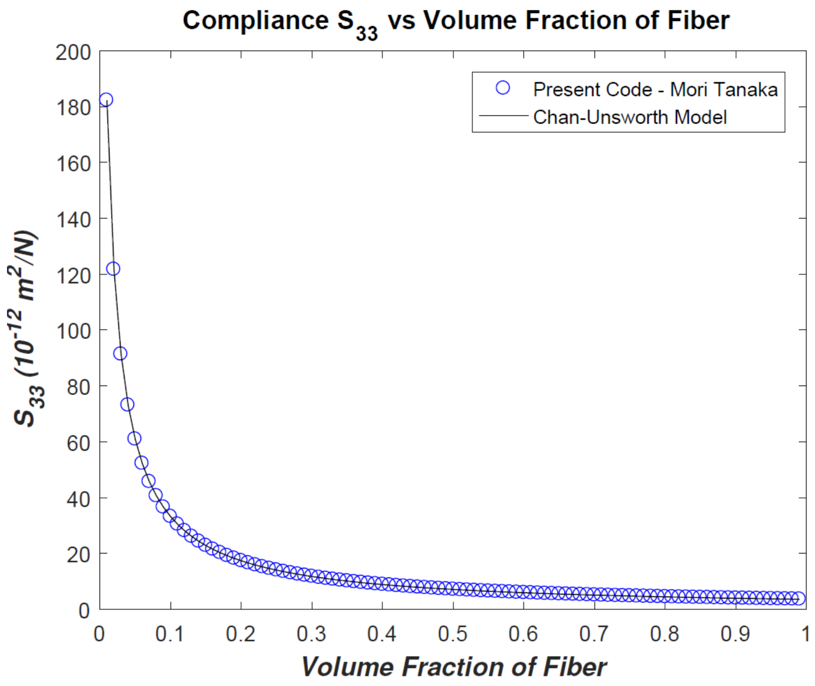
| Layer | $G_{Ic}$ (J/m$^2$) |
|---|---|
| Carbon fiber | 91.6 |
| Epoxy matrix | 1.7 |

# APPENDIX

## Structural Modelling



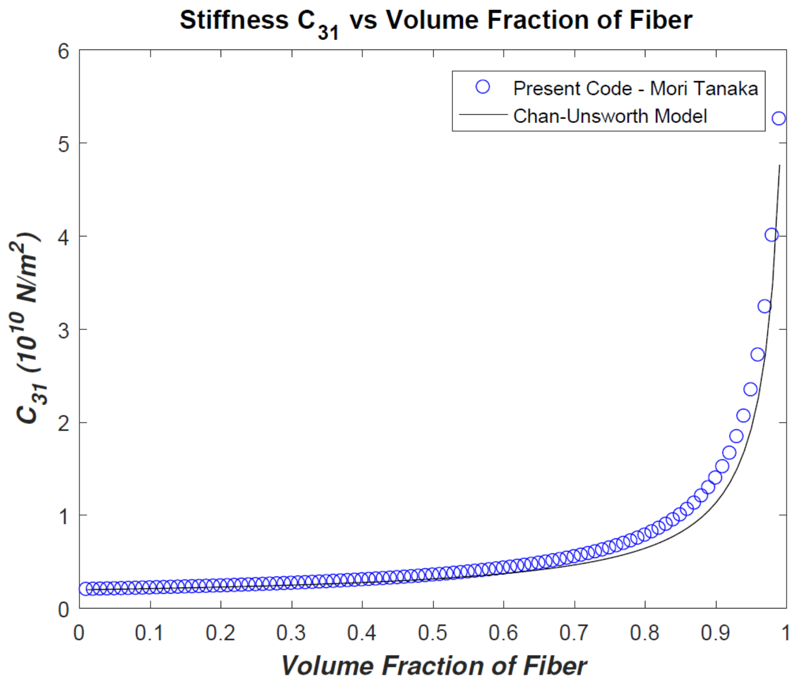

Effective stiffness matrix component of $S_{31}$



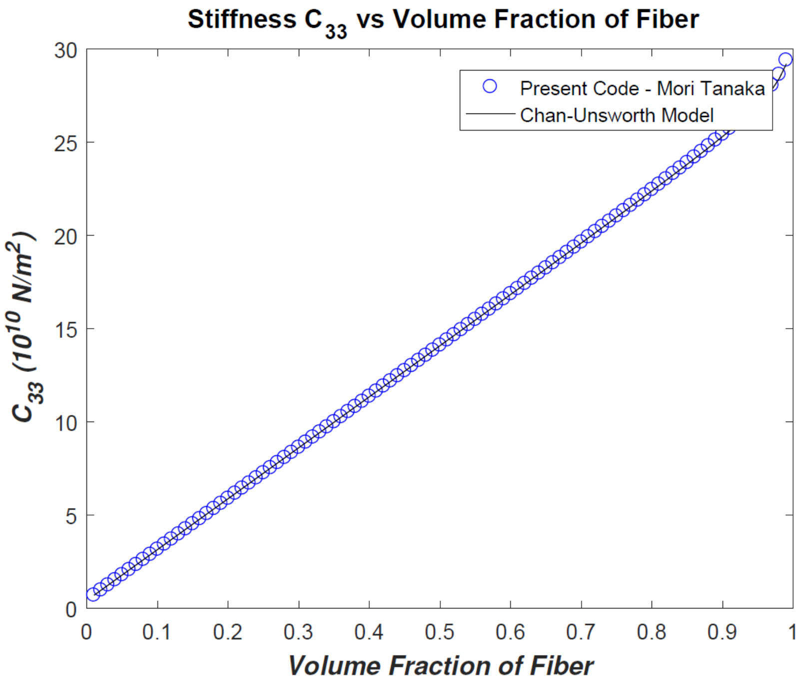

Effective stiffness matrix component of $S_{33}$

# APPENDIX

## Structural Modelling




Effective stiffness matrix component of $C_{31}$




Effective stiffness matrix component of $C_{33}$

# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

## Vibrational analysis

*Abdullah, N.A et al., Composite Structures (2018)*

Material properties of graphite- fiber reinforced polyimide composite

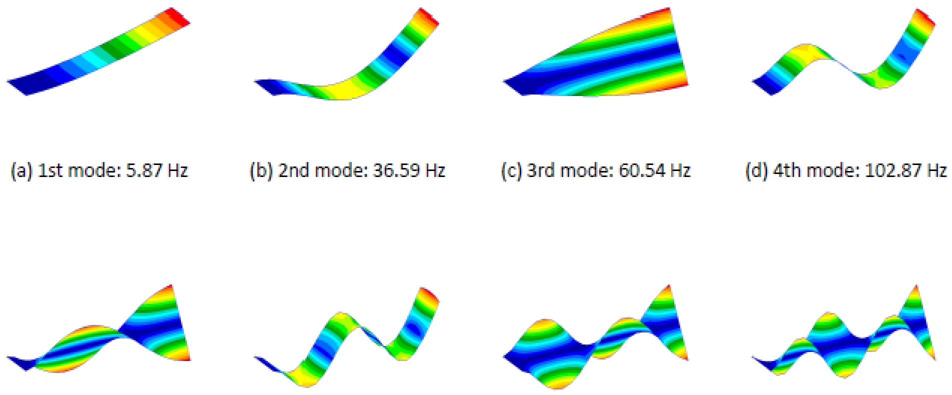
| | | |
|---|---|---|
| Modulus of elasticity | $E_m = 2.76$ GPa | $E_f = 275.6$GPa |
| Poisson's ratio | $\nu_m = 0.33$ | $\nu_f = 0.2$ |
| Shear modulus | $G_m = 1.036$ GPa | $G_f = 114.8$ GPa |
| Mass density | $\rho_m = 1600\ kg/m^3$ | $\rho_f = 1900\ kg/m^3$ |
| Fiber volume fraction | $V = 0.5$ | |

First eight frequencies from modal analysis by Wang et al. (2005) for θ = 0º

| Mode | 1st (Hz) | 2nd (Hz) | 3rd (Hz) | 4th (Hz) |
|---|---|---|---|---|
| Bending | 6.94 | 43.47 | 121.71 | 238.49 |
| Torsion | 62.81 | 197.45 | 329.08 | 460.71 |

First eight frequencies from modal analysis by present work for θ = 0º

| Mode | 1st (Hz) | 2nd (Hz) | 3rd (Hz) | 4th (Hz) |
|---|---|---|---|---|
| Bending | 5.87 | 36.59 | 102.87 | 203.02 |
| Torsion | 60.54 | 184.23 | 315.74 | 460.00 |



(a) 1st mode: 5.87 Hz (b) 2nd mode: 36.59 Hz (c) 3rd mode: 60.54 Hz (d) 4th mode: 102.87 Hz

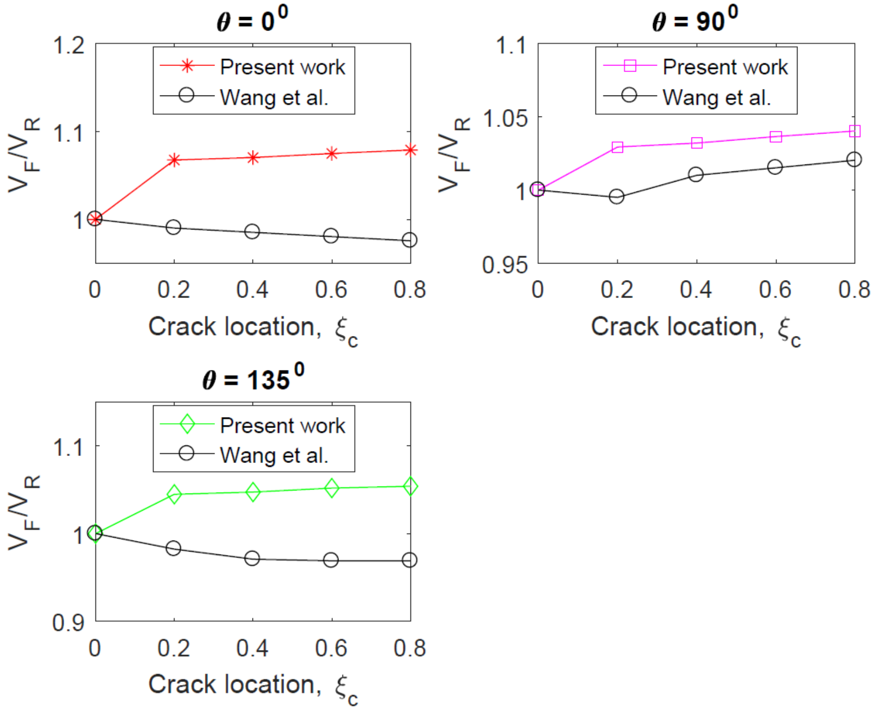
(e) 5th mode: 184.23 Hz (f) 6th mode: 203.02 Hz (f) 7th mode : 315.74 Hz (g) 8th mode: 460.00 Hz

First 8 vibration modes for $\theta$ = 0 º

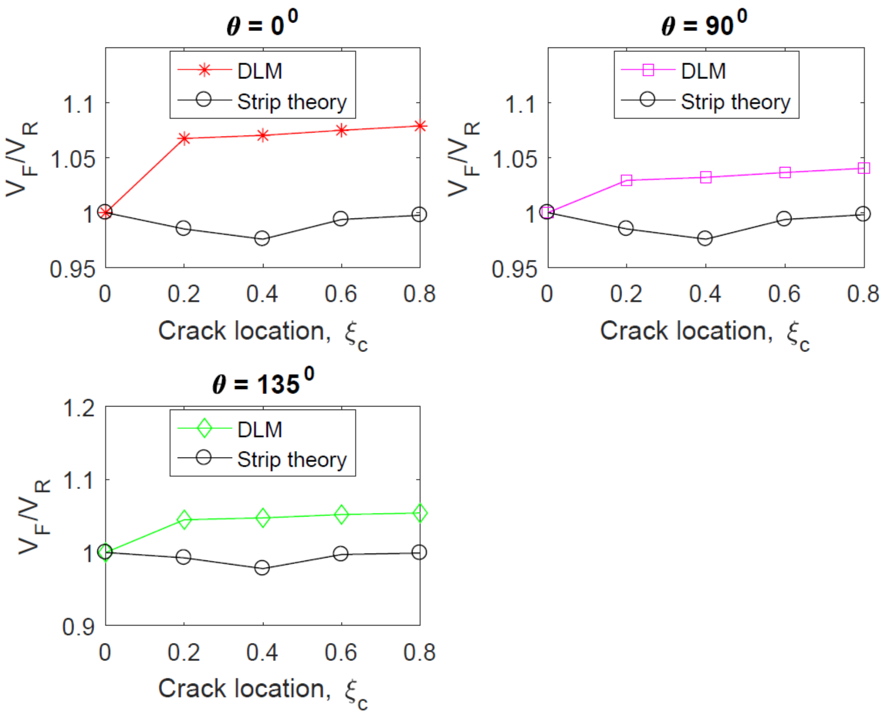
# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

## Flutter speed plot – crack location analysis

*Abdullah, N.A et al., Composite Structures (2018)*




Normalized flutter speeds with respect to the crack location ($\eta$ = 0.2) for case $\theta$ = 0 º, $\theta$ = 90 º and $\theta$ = 135 º

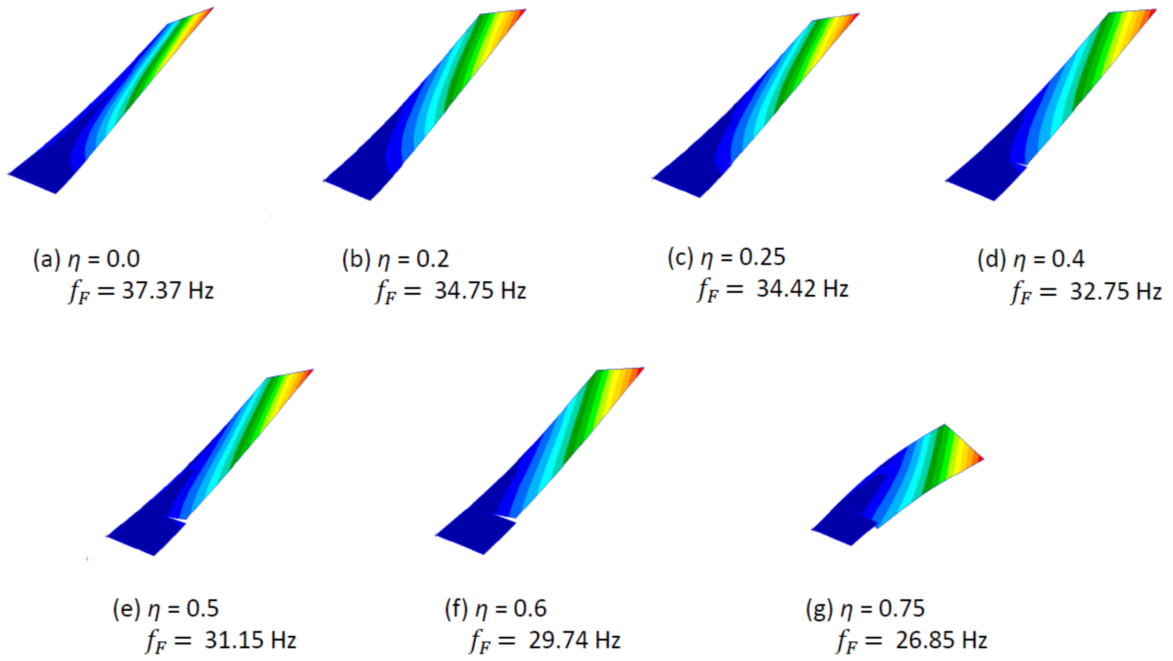



Comparison of DLM and Strip theory ($\eta$ = 0.2) for normalized flutter speeds with respect to the crack location for case $\theta$ = 0 º, $\theta$ = 90 º and $\theta$ = 135 º

# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

## Flutter response modes – crack ratio analysis

*Abdullah, N.A et al., Composite Structures (2018)*

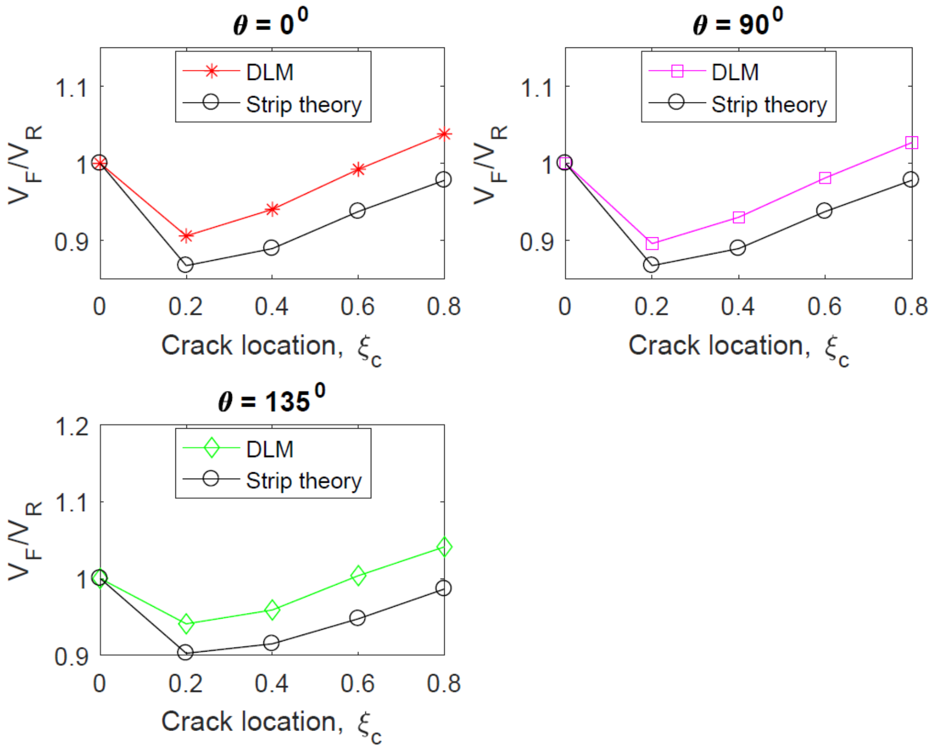



Flutter response modes for case $\theta$ = 0 º with variation of crack ratio

# Aeroelastic assessment of cracked composite plate by means of fully coupled FE and DLM

## Flutter speed plot – crack location analysis

*Abdullah, N.A et al., Composite Structures (2018)*



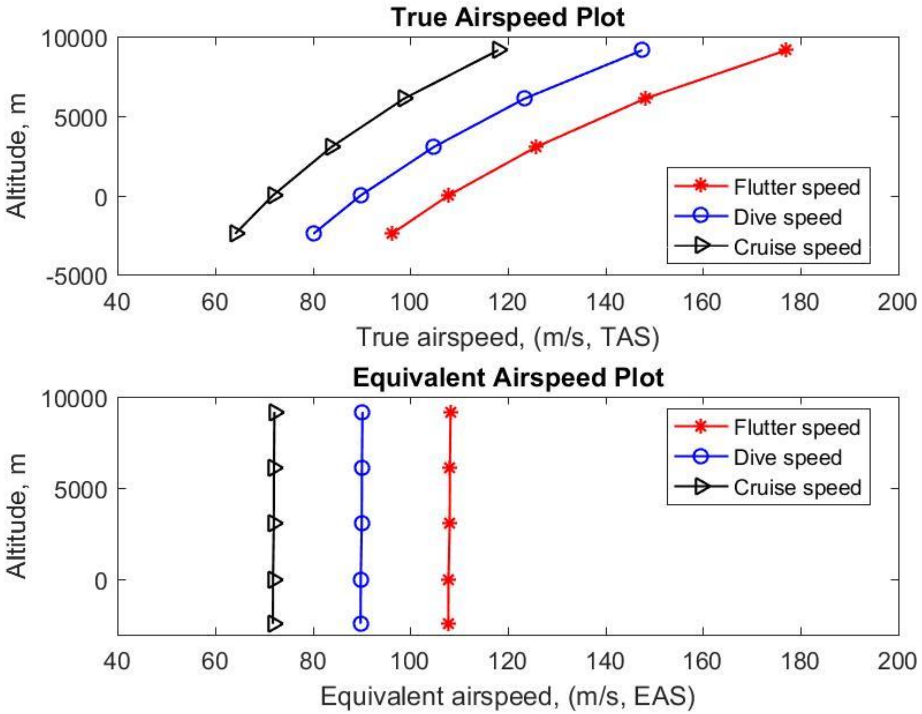

Comparison of DLM and Strip theory ($\eta$ = 0.6) for normalized flutter speeds with respect to the crack location for case $\theta = 0$ º, $\theta = 90$ º and $\theta = 135$ º

## Spline Method- Coupled FE & DLM

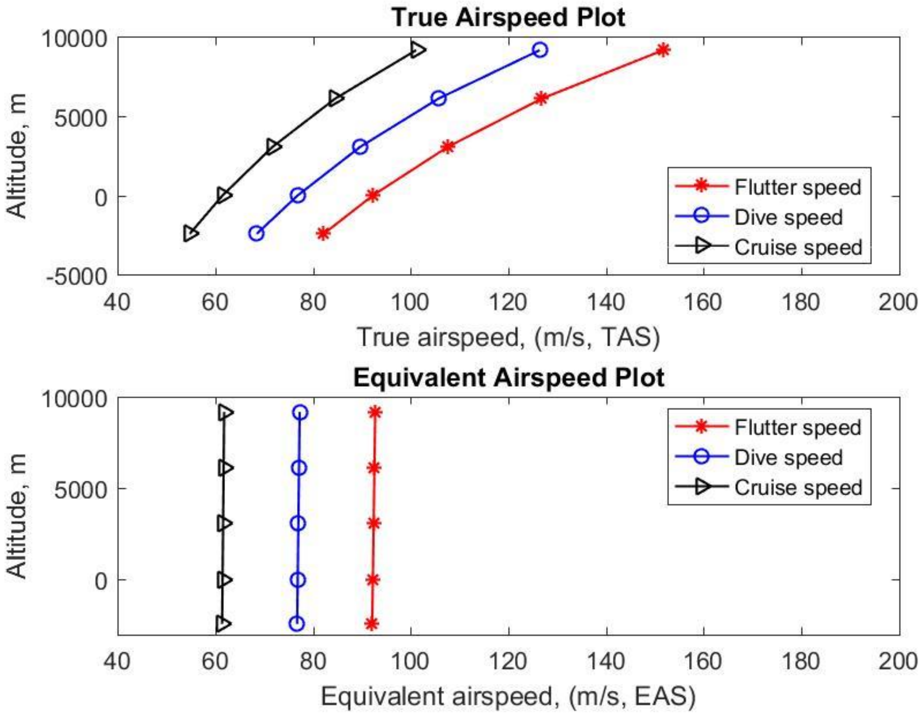
$$C = \begin{bmatrix} 6.8503 & 3.1437 & 0 \\ 3.1437 & 6.805 & 0 \\ 0 & 0 & 2.646 \end{bmatrix} \text{ X } 10^3 \text{ MPa}$$

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

## Designed flight envelope diagram based on FAR 23



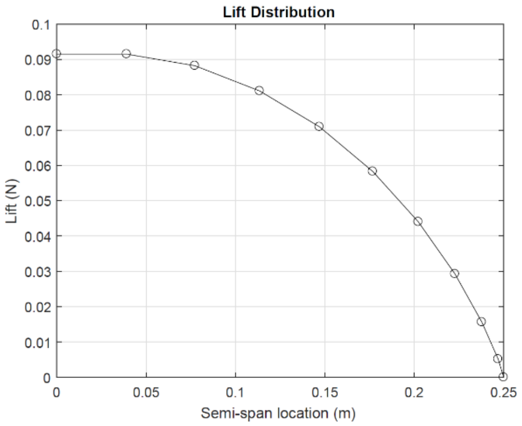

Unidirectional cracked composite plate 0$^o$



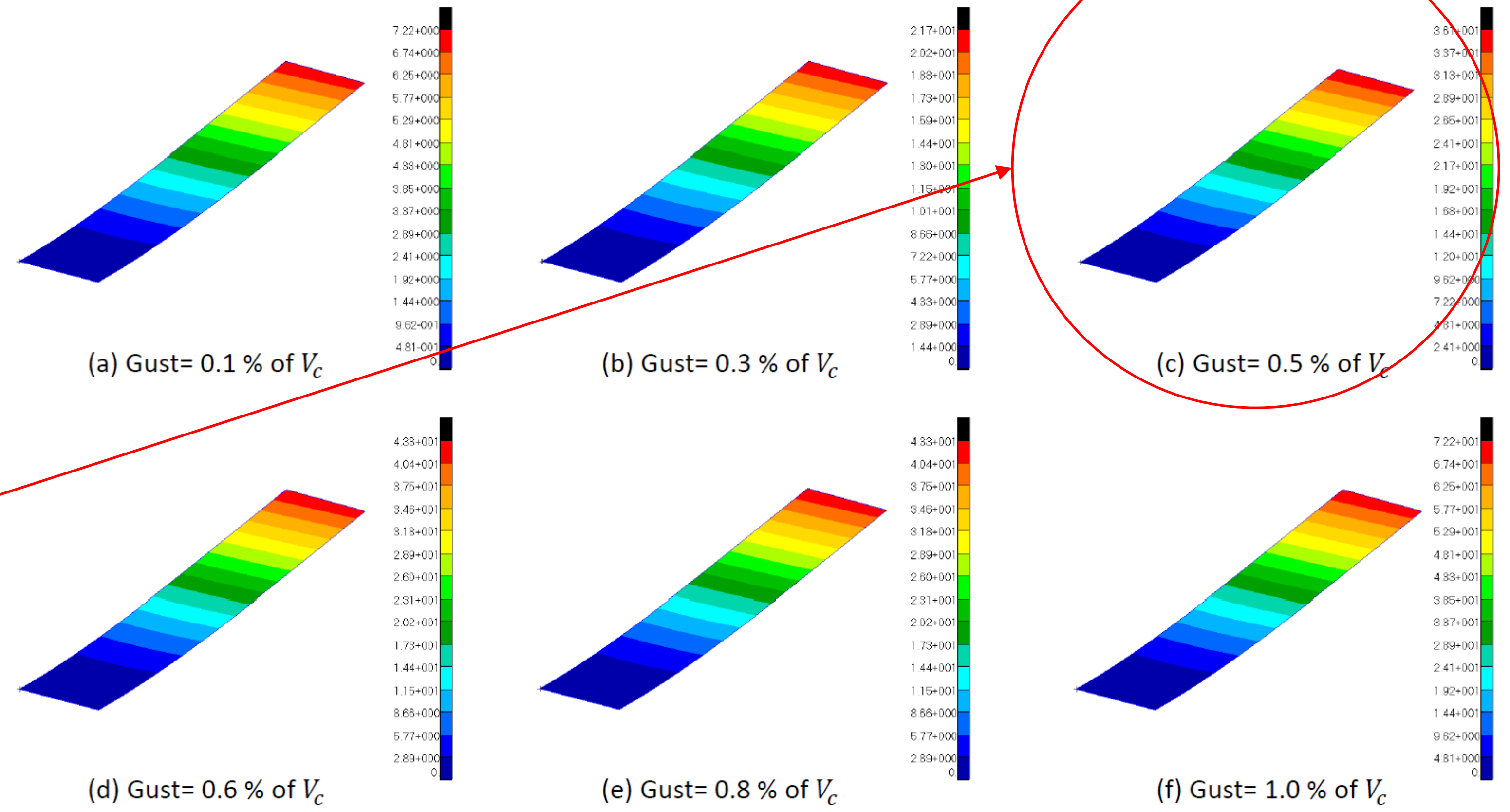

Unidirectional cracked composite plate 135$^o$

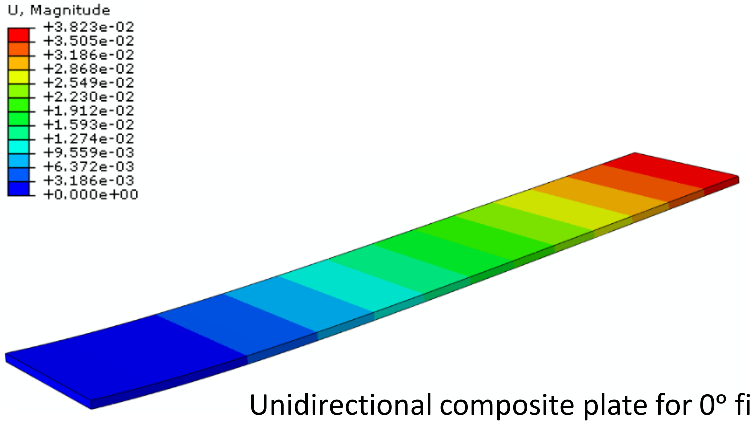
# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

## Validation – benchmark for 0$^o$




Unidirectional composite plate for 0º fiber direction: Lift coefficients for 10 segments on the plate at cruise = 71.89 m/s

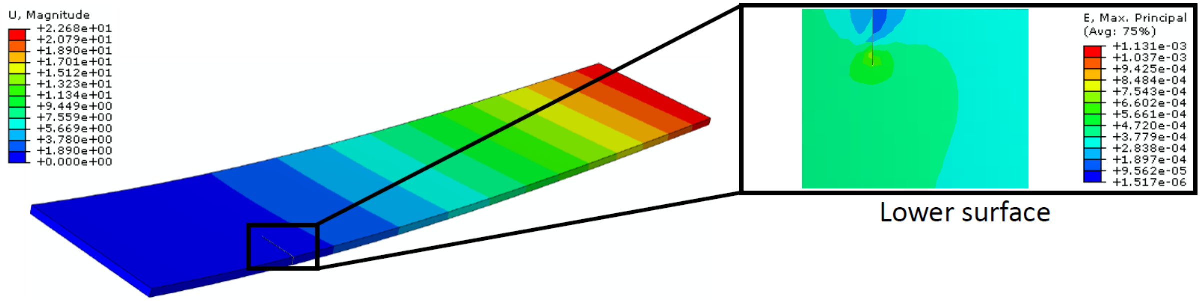


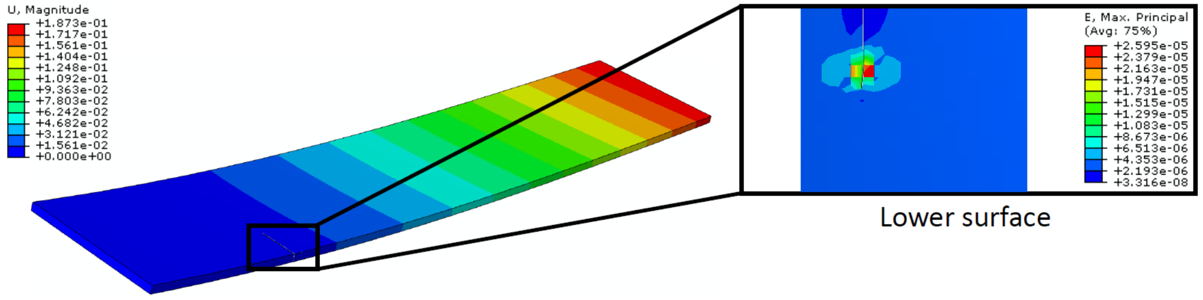

Unidirectional composite plate for 0º fiber direction: Displacement plots on cracked composite under aerostatic load cruise = 71.89 m/s [unit:m]

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

## Fracture assessment for $0^o$ composite plate

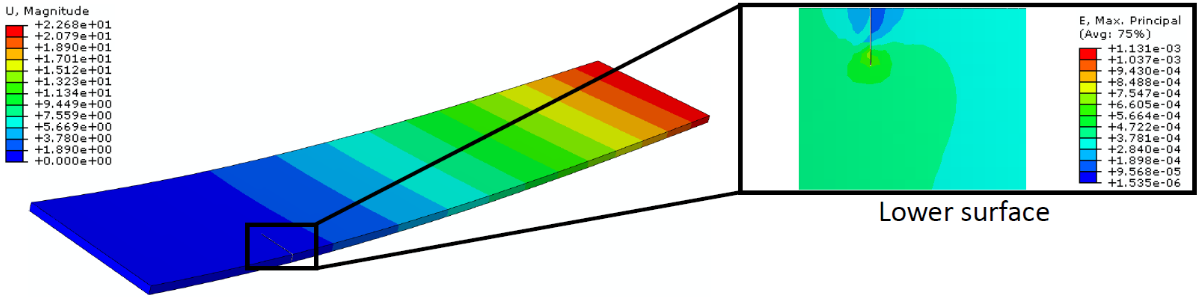


(a) Crack propagation at t = 1.59 s

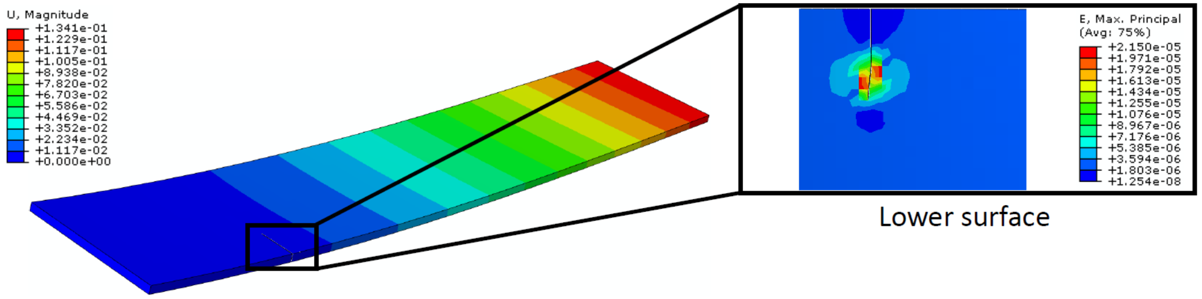


(b) Crack propagation at t = 5.0 s

Crack modelling by means of XFEM at 71.89 m/s [magnitude unit:mm]



(a) Crack propagation at t = 1.55 s

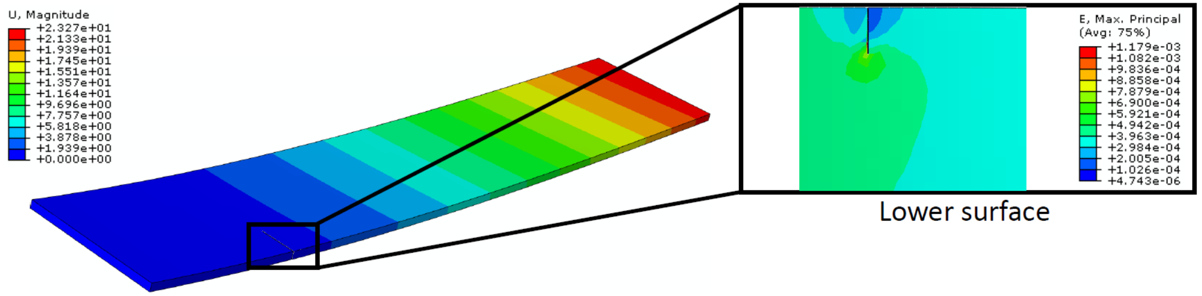


(b) Crack propagation at t = 5.0 s

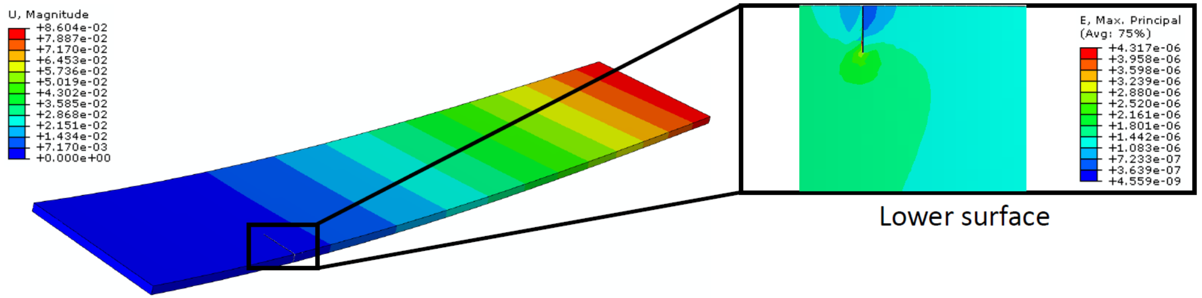
Crack modelling by means of XFEM at 107.84 m/s [magnitude unit:mm]

# Structural integrity of cracked composite plate subjected to aerodynamic loads using XFEM

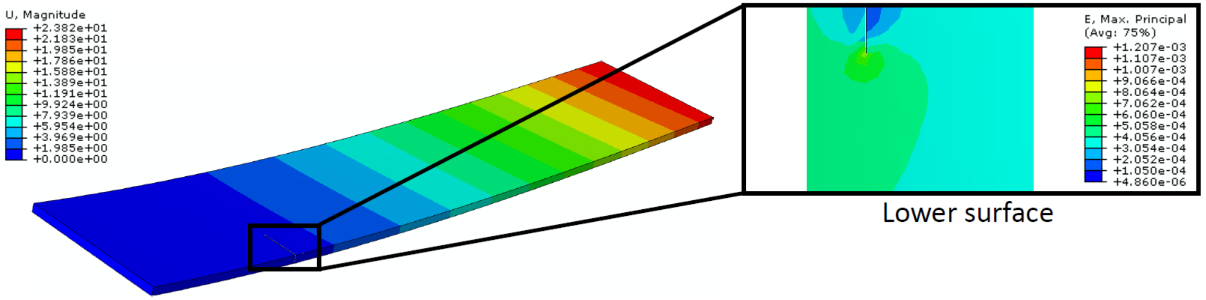
## Fracture assessment for 135$^{o}$ composite plate



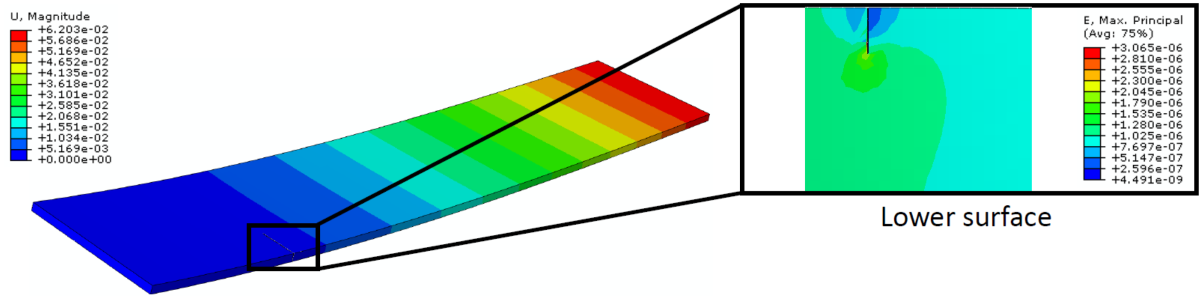

(a) At t = 2.5 s




(b) At t = 5.0 s




(a) At t = 2.5 s




(b) At t = 5.0 s

Crack modelling by means of XFEM at 61.51 m/s [magnitude unit:mm]

Crack modelling by means of XFEM at 92.27 m/s [magnitude unit:mm]