Identifying Impact Fatigue Damage in Carbon Fiber Composites Using Infrared Deflectometry and the Virtual Fields Method

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Abstract. Composite structures are often subject to repeated impacts of low energy, resulting in sub-structure damage that is often difficult to observe on its surface, but can substantially influence its structural integrity. As such, this study investigates sub-surface damage due to cyclic low-energy impact loading identified using infrared (IR) deflectometry and the Virtual Fields Method (VFM). The method is implemented both experimentally and numerically using finite element analysis. Specifically, numerical models are created with simulated delaminations using ABAQUS software, while experiments consist of rectangular composite laminate plates subjected to low-velocity impact fatigue cycling at 1.6 J. IR deflectometry is then performed to extract full- field kinematic maps over the surface of the plate. Using VFM, global and local constitutive properties of the plate are calculated, revealing "equilibrium gaps" that are used as a quantitative damage indicator.

Introduction

Naval aircraft are required to decelerate from over 200 kph to 0 in under one second upon landing, resulting in intense launch and recovery cycles, leading to an impact fatiguing effect on the structure. These impulsive loading cycles make carbon fiber-reinforced polymer (CFRP) composites susceptible to sub-structure damage that cannot easily be observed on the surface with the naked eye. This vulnerability makes it imperative to understand and quantify sub-surface damage accurately, including its functional relationship with the impact energy, number of cycles and reduction in stiffness parameters of the composites for more robust impact fatigue life predictions.

A unique identification method is considered here: infrared (IR) deflectometry, a full-field optical method that has a high sensitivity to surface defects. Coupled with the use of VFM, this method of damage identification is explored both numerically through finite element ABAQUS simulations, as well as experimentally.

IR Deflectometry. Deflectometry is extremely sensitive to surface slopes, making it a high-resolution full-field imaging technique [3]. IR deflectometry is a modification of the optical deflectometry technique, which normally uses the reflection of visible light [1,2]. However, using visible light imposes strict requirements on the surface finish of the specimen. A surface is classified as "specularly reflective" through the Rayleigh criterion in Eq. 1 below:

$$\frac{\lambda}{\sigma \cos \theta} > 8 \qquad (1)$$

where λ is the light wavelength, σ is the surface roughness of the sample, and θ is the angle of incidence. The wavelength of visible light is ~500 nm, thus in normal incidence, a surface roughness of < 60 nm is required to meet the specular reflection definition. IR light has a wavelength of ~10 µm, allowing a surface roughness of up to 1.25 µm, which is compatible with several "as-manufactured" engineering surfaces [4] and relaxing the need for a mirror-like finish that is a challenge for CFRP plates.

Virtual Fields Method. VFM is an inverse method that utilizes full-field kinematics to extract constitutive properties, and a book detailing its history and applications can be found in [5]. For an orthotropic material, specifically a symmetrical composite laminate under pure bending, the principle of virtual work can be rewritten as such in Eq. 2:

$$-\int_S D_{11}\,\kappa_1\kappa_1^* dS - \int_S D_{22}\,\kappa_2\kappa_2^* dS - \int_S D_{66}\,\kappa_6\kappa_6^* dS \qquad (2)$$
$$-\int_S D_{12}(\kappa_1\kappa_2^* + \kappa_2\kappa_1^*) dS - \int_S D_{16}(\kappa_1\kappa_6^* + \kappa_6\kappa_1^*) dS - \int_S D_{26}(\kappa_2\kappa_6^* + \kappa_6\kappa_2^*) dS + \sum_{j=1}^{n} F_j \cdot w_j^* = 0$$

where *D* are the bending stiffness terms, *F* is the applied force to induce deflection, *κ* are the curvature fields obtained from deflectometry experiments, *κ** are the virtual curvature fields, and *w** is the virtual deflection. With the selection of six virtual fields, a linear system can be built where the unknowns are the bending stiffness values, *D.* These values can be solved for as demonstrated in [6].

Methodology

The use of VFM in identifying sub-surface damage in CFRPs was first investigated numerically through finite element analysis. ABAQUS/CAE software was used to create an 8-ply unidirectional laminate, with the material properties of Hexcel IM7-8552 UD carbon fiber pre-preg [7] and relevant model parameters found in Table 1. Simulated delaminations were inserted in a small region of the plate between the 4th and 5th ply of the 3D model (circled in red in Fig. 1a). A point load was applied in the center of the plate in the positive-Z direction (circle in yellow in Fig 1b), effectively bending the plate. A difference in strain fields between the undamaged and damaged plate models were observed as seen in Fig. 1c and 1d, respectively. From here, the strain fields can be converted to curvature fields, and used as input for the curvatures (κ) in Eq. 2. Using VFM, a map of stiffness loss for plates in bending can be generated, resulting in a damage indicator [3]. This method is currently being verified using the simulated damage in the current model, then will soon be investigated experimentally using IR deflectometry on physical CFRP samples loaded with low-energy repetitive impacts.

Software	ABAQUS/CAE 2021
Plate material	Hexcel IM7-8552 UD CF pre-preg
Plate dimensions	127 mm x 127 mm x 3 mm
Element type	C3D8 (8-noded linear brick)

Table 1. Parameters used in finite element ABAQUS model

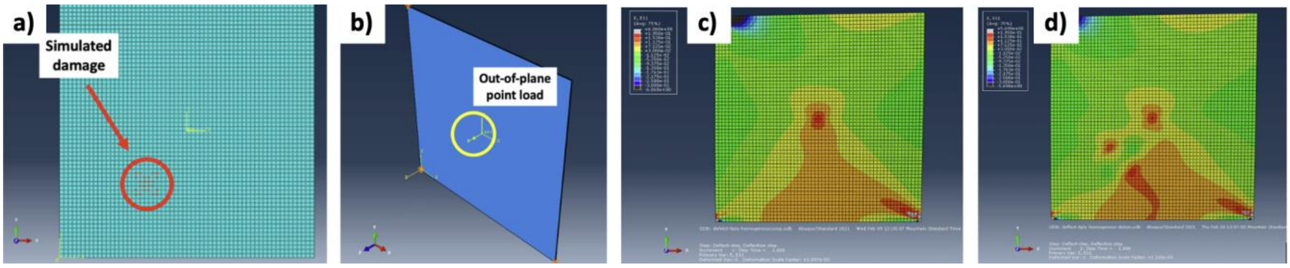

Fig. 1. a) Finite element model of CFRP with location of sub-structure damage highlighted in red, b) concentrated point load applied in center of plate in +Z-direction, c) ε_{xx} strain field of undamaged specimen and d) ε_{xx} of specimen with simulated damage (right)

Conclusion

The study explores the application of IR deflectometry and VFM as a damage indicator in CFRP laminates under repetitive impact loading conditions. We have numerically demonstrated that the strain field on the surface of the undamaged CFRP plate under deflection loading is different than that of a simulated sub-surface damage CFRP plate to help validate our replicated experimental approach. Next steps include applying the equilibrium gap method to find local gaps in equilibrium on the surface of the FE modeled laminate to fine-tune the damage tolerancing process. The numerical model will also be used to aid in the design of the experiments that will be leveraging infrared deflectometry and VFM to quantify damage under low-energy repetitive impacts.

References

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