

## Numerical study of nonlinear guided waves in composite laminate with matrix crack

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**Abstract:** This work studies nonlinear guided waves for the detection of matrix cracks in composites. Finite element modelling is used to simulate a 2 mm-thick unidirectional GFRP with a 2 mm-long crack. The fundamental symmetric ( $S_0$ ) mode propagating perpendicular to the crack surface is investigated. The influence of different crack depths on the nonlinear guided waves is studied. Current results show that nonlinear responses only happen when a crack exists and that the nonlinear responses differ between a half-thickness and a through-thickness crack.

**Keywords:** Nonlinear guided waves, unidirectional composites, numerical study, matrix crack, through-thickness crack

### Introduction

The use of composite materials for safety-critical structures is increasing in various industrial sectors [1, 2, 3]. This poses an urgent challenge to non-destructive testing (NDT) and structural health monitoring (SHM) in assessing different defects and damage [1, 3, 4]. The nonlinear ultrasonic guided wave method [5, 6, 7] is an emerging SHM technique that has been shown to be effective in the detection of fatigue cracks in metals. The main sources of acoustic nonlinearity include material nonlinearity and contact acoustic nonlinearity (CAN). In recent years, the use of the CAN for manifesting damage such as closed cracks or delaminations in composites is receiving growing attention from researchers [8, 9]. This work aims to study the nonlinear guided wave response to a single matrix crack in a unidirectional composite laminate using finite element modelling (FEM). A 2 mm-thick unidirectional GFRP laminate with a 2 mm-long crack under symmetric excitation was modelled. The influence of various crack depths (i.e., no crack, half-thickness crack, and through-thickness crack) on nonlinear guided waves is investigated with a focus on primary frequency ( $1f$ ) and superharmonics ( $2f$ ,  $3f$ ).

### Material description and modelling scenarios

A  $300 \times 300 \times 2$  mm GFRP composite with a layup of  $[0]_8$  was modelled in Abaqus (Fig. 1). The material properties of the GFRP laminate for modelling are available in [10]. The fundamental symmetric  $S_0$  mode (10-cycle, 250-kHz Hanning windowed tone burst) was excited by applying in-plane concentrated forces on both the top and bottom surfaces of the laminate (at the edge of circular areas). Three crack depths, i.e., no

crack, half-thickness crack, and full-thickness crack, with a crack length of 2 mm, were simulated. The wave propagating perpendicular to the crack surface was investigated. The crack surface was parallel to the  $x$ -axis (fiber direction).

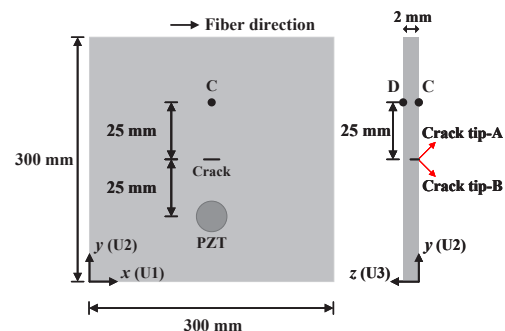


Fig. 1: Diagram of the unidirectional composite laminate. The crack is at the center of the plate along the  $x$ -axis (fiber direction). Wave propagating perpendicular to the crack surface was studied. Positions C and D are the corresponding sensing points.

### Dispersion characteristics by DLR Dispersion Calculator

Fig. 2 shows the dispersion curve of the unidirectional GFRP laminate obtained from the DLR Dispersion Calculator. The Dispersion Calculator (DC) is a specialized tool for calculating the dispersion characteristics of the guided waves in isotropic and anisotropic materials using the stiffness matrix method [11]. The phase velocities and the wavelengths at  $1f$ ,  $2f$ , and  $3f$  are summarized in Tab. 1. It is good to note that

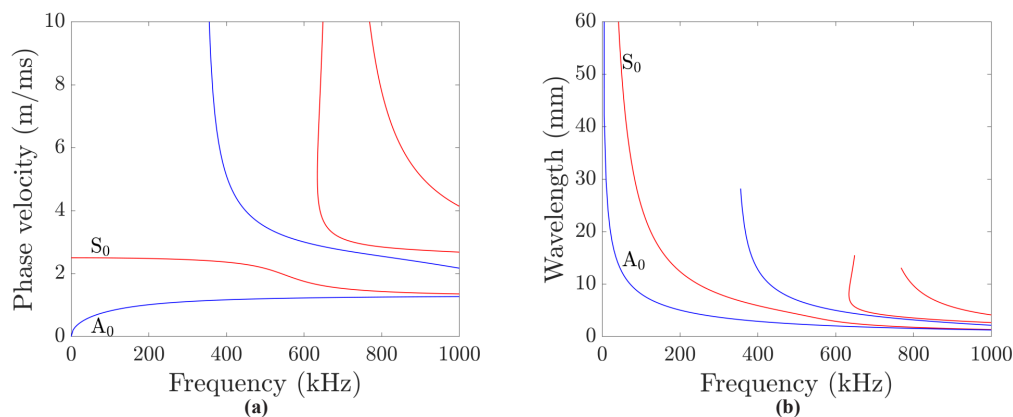


Fig. 2: The dispersion curve of the unidirectional GFRP laminate from the DLR Dispersion Calculator. (a) phase velocity, (b) wavelength. Wave propagation perpendicular to the fiber direction.

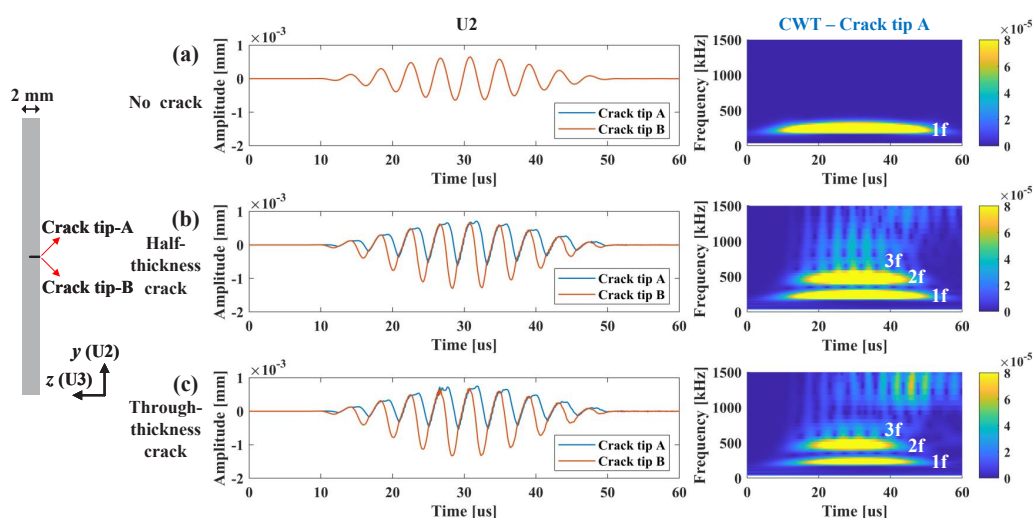


Fig. 3: The simulation results show the crack-wave interaction in the unidirectional composite. (a-c) are the displacements of crack tips A and B in the  $y$ -axis direction ( $U_2$ ) and the continuous wavelet transform (CWT) of the displacement  $U_2$  at crack tip A for no-crack, half-thickness, and through-thickness crack cases, respectively.

the ratio between the crack length ( $L=2$  mm) and the wavelength of the excited fundamental  $S_0$  mode ( $\lambda=9.86$  mm at  $1f=250$ kHz) is around 0.2. To verify the FEM model, the phase velocities from FEM ( $1f$ ) were calculated and compared with the DC, and their difference is 0.1%–0.2%.

Tab. 1: The phase velocities and the wavelengths of the guided waves in the unidirectional GFRP laminate obtained from the Dispersion Calculator.

		1f–250kHz	2f–500kHz	3f–750kHz
Phase velocity (m/ms)	$S_0$	2.47	2.16	1.47
	$A_0$	1.07	1.20	1.25
Wavelength (mm)	$S_0$	9.86	4.33	1.96
	$A_0$	4.28	2.40	1.67

## Results

Fig. 3 shows the FEM results of the crack-wave interaction in the unidirectional composite. The in-plane displacements of the crack tips A and B in the  $y$ -axis direction ( $U_2$ ) are given for no-crack, half-thickness crack, and through-thickness crack cases, respectively. The corresponding continuous wavelet transform (CWT) of the displacements  $U_2$  at the crack tip A indicates the initial generation of nonlinearity due to the crack-wave interaction. It shows that for the no-crack case (Fig. 3(a)), only the primary frequency exists, and no super harmonics appear; for half- and through-thickness crack cases (Fig. 3(b-c)), the crack open-close phenomena are captured, resulting in nonlinear phenomena such as higher harmonic generation ( $2f$  and  $3f$  components in the CWT maps).

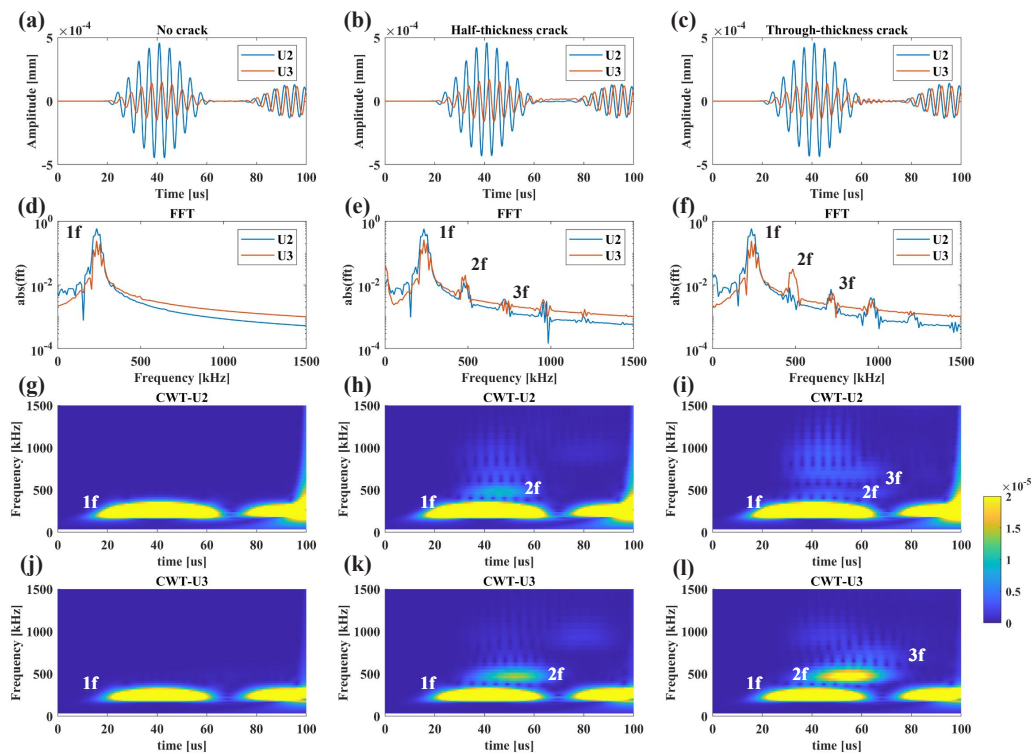


Fig. 4: The amplitude, FFT, and CWT plots (U2 and U3) at the sensing position C for no crack, half-thickness crack (crack depth 1 mm) and full-thickness crack (crack depth 2 mm) scenarios.

Fig. 4 shows the FEM results of a wave propagating at the sensing point C for no-crack, half-thickness and through-thickness crack cases. The position of point C is in Fig. 1. As the wave propagation is perpendicular to the crack surface, the deformations of U2 and U3 are dominant compared to U1. So here we focus on U2 and U3. The modelling results show that nonlinear responses (2f, 3f) happen when a crack exists (half- and through-thickness crack cases in Fig. 4(e, h, k) and 4(f, i, l), respectively); while for the no-crack case, it shows no nonlinear response (Fig. 4(d, g, j)). It also shows that the nonlinear responses differ between the half-thickness crack and the through-thickness crack.

The influence of the sensing points at the front and the back surface on the obtained nonlinear responses is also investigated. The amplitude, FFT, and CWT plots (using the out-of-plane displacement U3) at the sensing positions C ( $z=0$  mm) and D ( $z=2$  mm) for no crack, half-thickness crack (crack depth 1 mm) and full-thickness crack (crack depth 2 mm) scenarios are given in Fig. 5. It shows that for the no-crack and through-thickness crack cases, the out-of-plane displacement U3 of the sensing points at the front and back surfaces is symmetrical, so only symmetrical S mode waves exist; while for the half-thickness crack case, the U3 at the two sensing points is asymmetrical, which means that the new asymmetrical A mode

waves also appear and propagate in the specimen.

## Conclusions

This paper studied the nonlinear guided waves for the detection of a single matrix crack in composite laminates. Finite element modelling was used to simulate a 2 mm-thick unidirectional GFRP composite with a 2 mm-long crack. The fundamental symmetric (S0) mode propagating perpendicular to the crack surface was investigated. The influence of no crack, half-thickness crack, and through-thickness crack scenarios on the nonlinear guided waves was studied. The results show that the crack of 2 mm length in the composite laminate is possible to be detected using the nonlinear guided wave method, where the crack length is 1/5 of the primary guided wave's wavelength; the nonlinear responses only happen when a crack exists and that the nonlinear responses differ between a half-thickness crack and a through-thickness crack. Future work is to study different crack lengths and different composite layouts on the nonlinear ultrasonic guided waves for matrix crack and microcrack detection.

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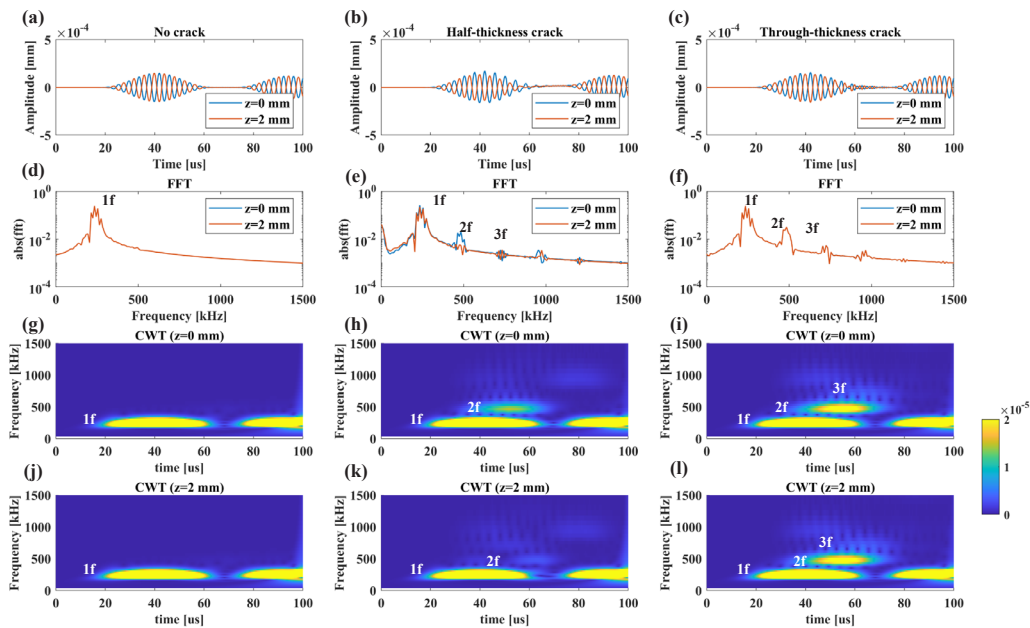


Fig. 5: The amplitude, FFT, and CWT plots (the out-of-plane displacement  $U_3$ ) at the sensing positions C ( $z=0$  mm) and D ( $z=2$  mm) for no crack, half-thickness crack, and full-thickness crack scenarios, respectively.

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