

Efficient modelling of guided ultrasonic waves using the Scaled Boundary FEM towards SHM of composite pressure vessels

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Abstract

The Scaled Boundary Finite Element Method (SBFEM) is a semi-analytical method that shows promising results in modelling of guided ultrasonic waves. Efficiency and low computational cost of the method are achieved by a discretisation of the boundary of a computational domain only, whereas for the domain itself the analytical solution is used. By means of the SBFEM different types of defects, e.g. cracks, pores, delamination, corrosion, integrated into a structure consisting of anisotropic and isotropic materials can be modelled.

In this contribution, the SBFEM is used to analyse the propagation of guided waves in a structure consisting of an isotropic metal bonded to anisotropic carbon fibre reinforced material. The method allows appropriate wave types (modes) to be identified and to analyse their interaction with different defects. Results obtained are used to develop a structural health monitoring system for composite pressure vessels used in automotive and aerospace industries.

1. Introduction

Guided ultrasonic waves (GWs) have been shown to be particularly suitable for structural health monitoring (SHM) of such safety relevant components as oil and gas pipelines, and rails [1-3]. Techniques based on GWs are still under development for more complex applications considering wave propagation in structures made of fibre reinforced plastic materials only or in combination with metals [4-6]. Due to dispersion and multimodal character of GWs, development of a technique based on GWs requires careful modelling and analysis of wave propagation and defect-mode interaction. At first, a tool for calculation of dispersion curves and mode shapes is needed. Based on these curves appropriate modes depending on application can be selected for further analysis. At next, a tool for modelling of propagation of chosen GW modes is required. The Scaled Boundary Finite Element Method (SBFEM) is suitable for this purpose allowing for calculation of dispersion curves, mode shapes and modelling of GWs [7-9]. This semi-analytical method is highly efficient for geometries with a constant cross-section, which is the part to be discretised, see Fig. 1 (a) compared to the FEM discretisation in Fig. 1 (c) [9-10]. Another feature of the SBFEM is that an infinite domain can be modelled avoiding unwanted reflections, see Fig. 1 (b). Also, the method provides an elegant solution for modelling of a crack, describing a crack tip analytically and thus avoiding the singularity, see Fig. 1 (d) [9].

In this contribution, the SBFEM is used to analyse GWs propagation in a structure consisting of an aluminium plate bonded to carbon fibre reinforced plastics (CFRP). This structure corresponds to a structure of a Type III composite pressure vessel (COPV) used for storing either natural gas or hydrogen in automotive and aerospace applications. Results obtained are used to develop a structural health monitoring system for COPVs.

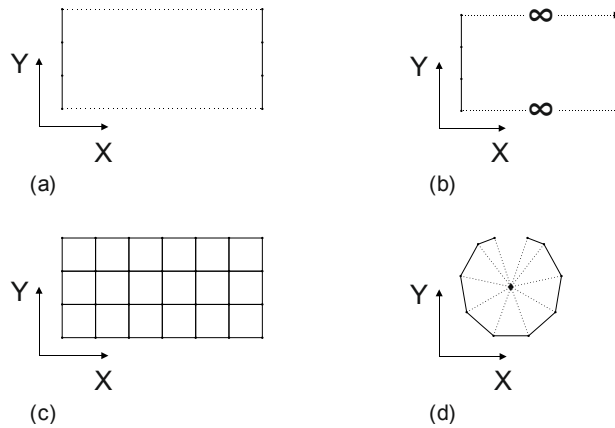


Figure 1. Schematic discretisation of (a) a plate (b) with an infinite domain in the SBFEM (c) a plate in the FEM and (d) an arbitrary domain with a crack in the SBFEM

2. Methodology

The pressure vessels are designed in a way that a failure mainly happens in its cylindrical part. There axial (longitudinal) cracks in the metal liner, as well as fibre breaks and epoxy matrix cracks in the CFRP occur. In this work wave propagation is modelled in the circumferential (hoop) direction. In terms of guided wave propagation, a cylindrical structure can be approximated to a plate, if the ratio of radius to thickness is greater than 10:1 [11]. All assumptions are summarised in Fig. 2.

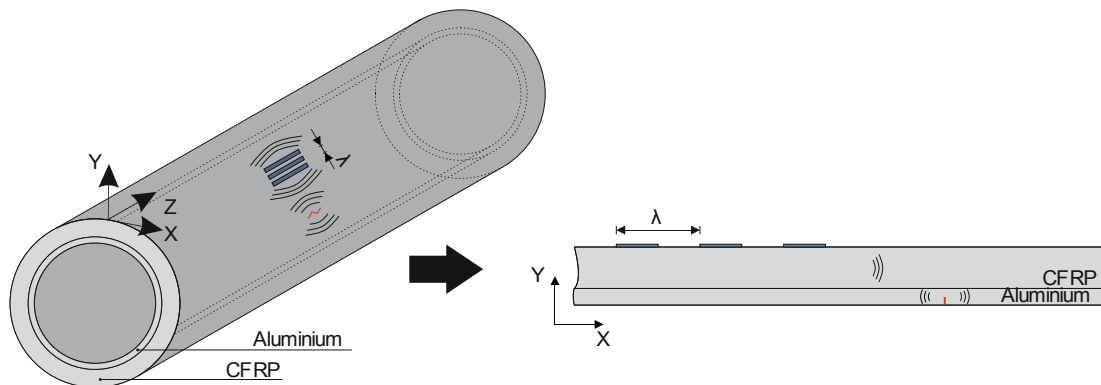


Figure 2. Sketch of a simplified structure of a COPV with corresponding sensor placement

A numerical model shown in Fig. 3 consists of a plate made of a 4 mm CFRP laminate with a [90/0/90/0] layup (from top to bottom), followed by a 2 mm aluminium layer. Modelling was performed under the two-dimensional plain strain assumption. The 0° and 90° CFRP plies correspond to circumferential (hoop) and axial (longitudinal) directions of the COPV. The CFRP plies were modelled separately being transversally

isotropic with a 1 mm thickness of each. Material properties used in the model are listed in Table 1, where ρ is density, E is Young's modulus, G is shear modulus, and ν is Poisson's ratio. Due to a production process of COPVs, a firm connection between the aluminium liner and CFRP overwrap is achieved, thus allowing considering a firm bonding between two parts of the structure. The excitation in space was performed by applying pre-calculated mode shapes of a desired mode at the plate edge. The excitation in time was a Hanning-windowed tone burst at the centre frequency of a desired mode. Data were recorded using 50 points with a 0.5 mm step. The modelling was performed in the frequency domain allowing using infinite domains and changing domain length without affecting computational time.

Table 1. Properties of an epoxy carbon ply (E_1 is in the fibre direction)

Property	ρ (kg/m ³)	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
Prepreg	1490	121	8.6	8.6	4.7	4.7	3.1	0.27	0.27	0.4

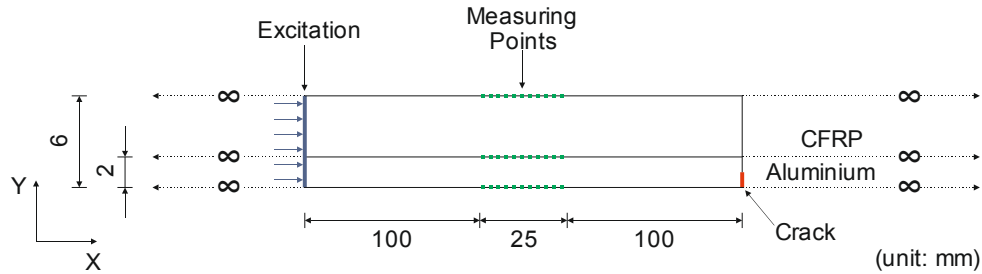


Figure 3. Schematic of a numerical model used in the SBFEM

To allow for damage detection in both aluminium and CFRP, one mode showing characteristic interaction with damage in different materials should be identified. For this, damage in the aluminium part was modelled by a crack of a 1 mm length and zero width, which was achieved by disconnecting boundaries of two SBFEM domains. However, damage in the CFRP cannot be represented by one crack. Usually, it is overall damage of a composite, which includes fibre breaks and matrix cracking. A way to model such overall damage is to reduce elastic constants of the material stiffness matrix. In this work all elastic constants of every CFRP layer are reduced and influence of this change on different GW modes is analysed.

3. Results and discussion

Dispersion curves for the infinite aluminium-CFRP plate are presented in Figure 4. The circles mark modes at their centre operation frequencies, as chosen for numerical modelling. These points were selected based on the minimal dispersion of the group velocity. All values from dispersion curves and number of cycles in a tone burst used for modelling are summarised in Table 2. The longest computational times on a standard desktop PC for the dispersion curves and wave propagation were 5 s and 5 minutes, respectively.

3.1 Damage in the aluminium liner

The signals obtained using the SBFEM were analysed by means of 2D FFT and an example of mode 3 excitation at the central frequency of 1 MHz is presented in

Figure 5. Fig. 5 (a) shows mode 3 propagating in the aluminium-CFRP plate. Fig. 5 (b) shows reflection of mode 3 and its conversion into mode 6 after interaction with a 1 mm crack in aluminium. Such characteristic interactions were analysed for all modes chosen and results are summarised in Table 2, with modes sensitive to the crack marked in bold.

Table 2. Modes used for numerical modelling. In bold are modes, which have shown characteristic interaction with a 1 mm crack in aluminium

Mode	1	2	3	4	5	6	7
Frequency (MHz)	0.14	0.5	1.0	0.4	0.48	0.7	0.87
Group velocity (m/s)	2090	2570	2880	4980	3180	4240	5440
Phase velocity (m/s)	1680	2510	2770	5840	7040	5430	9950
Wavelength (mm)	12	5	2.8	14.6	14.8	7.8	11.4
Number of cycles	10	40	60	30	40	60	60

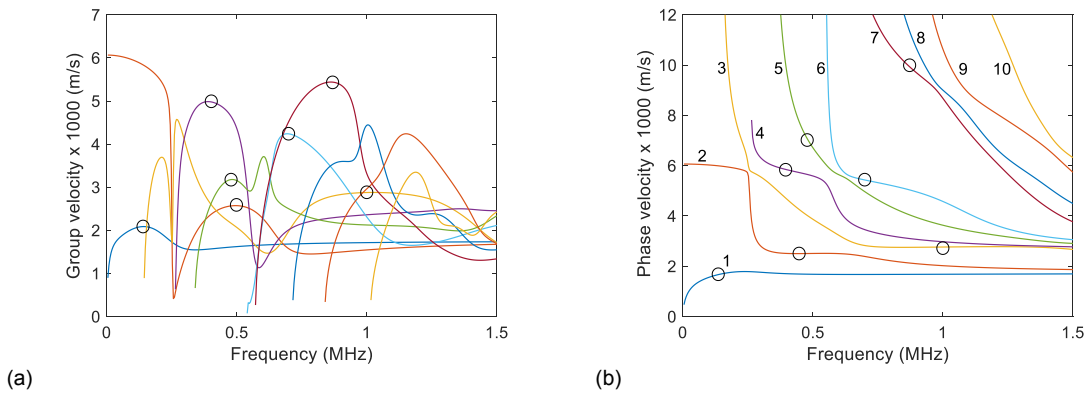


Figure 4. Dispersion curves for: (a) group velocity and (b) phase velocity, calculated for the infinite aluminium-CFRP plate using SBFEM. The first ten guided wave modes are numbered in numerical order. The circles mark modes, as chosen for numerical modelling

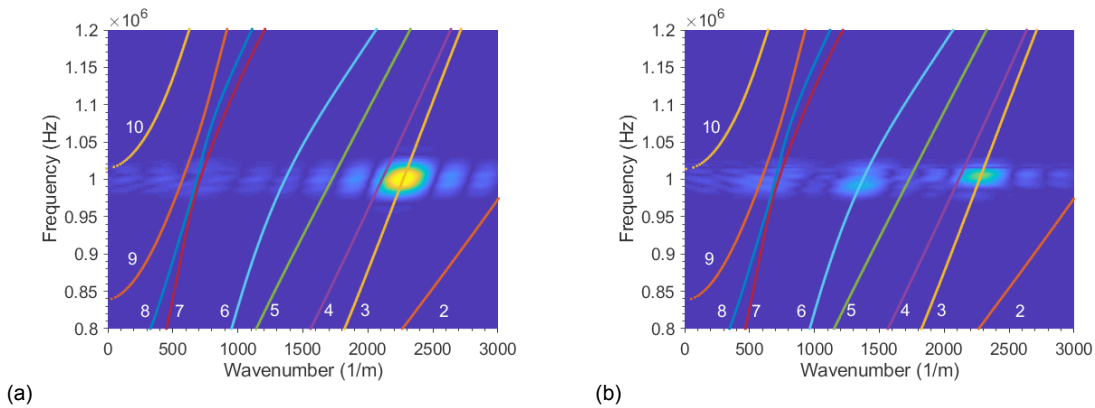


Figure 5. 2D FFT spectra of out-of-plane displacements obtained from the aluminium-CFRP interface overlapped with frequency-wavenumber curves; everything calculated using SBFEM. Excitation of mode 3 at f=1 MHz: (a) propagating modes and (b) reflected modes from a 1 mm crack in aluminium

Analysis has shown that mode 5 and mode 7 did not interact with the crack in aluminium. To understand this behaviour, the 6 mm aluminium-CFRP plate was considered as two separate parts: a 2 mm aluminium plate and a 4 mm CFRP plate. In Figure 6 dispersion curves of these three structures – the aluminium plate, the CFRP plate and the coupled aluminium-CFRP plate – are compared. The grey squares

represent three guided wave modes in the 2 mm aluminium plate for the frequency range chosen. The modes existing in the 4 mm CFRP plate are marked with dashed lines. The combination of these two structures produces set of guided wave modes shown with solid lines. Modes of the combined structure are either CFRP or aluminium dominated, or both; so that energy (displacement) is concentrated either within CFRP layers or in aluminium, or uniformly distributed within both parts. For instance, first two modes of the coupled structure (solid lines) up to the frequency of 0.2 MHz are yielded from both aluminium and CFRP plate modes. The higher the frequency the more modes of the CFRP plate come into play and thus influencing modes of the aluminium-CFRP plate. Up to the frequency of 0.8 MHz there are just two aluminium modes, but six CFRP modes. Thus, there are some combinations of frequency and phase velocity ranges on the dispersion curves, where modes of the whole structure are dominated by the CFRP modes. For example, for phase velocities below 2000 m/s, between 3000 and 5000 m/s, and above 6000 m/s in the frequency range from 0.2 to 0.8 MHz. So, the modes in this frequency range appear at their cut-off frequencies as CFRP modes, approach an aluminium mode, in the phase velocity range from 5000 to 6500 m/s, and change their behaviour to both aluminium and CFRP dominated. Going further up in frequency, modes change their behaviour to CFRP dominated again till the next aluminium mode is reached at around 3000 m/s. The modes with phase velocities laying between 2000 and 3000 m/s, show combined behaviour, changing to CFRP dominated below the phase velocity of 2000 m/s. Only the modes positioned near aluminium modes and having combined behaviour showed characteristic interaction with a crack in the aluminium, see filled circles in Fig. 6. Modes, marked in red, are CFRP dominated in the centre operation frequencies, as chosen for numerical modelling, and were not influenced by the crack in aluminium. This can be observed by analysing mode shapes, for example compare mode shapes of mode 5 and mode 6 in Figure 7. Mode 5 has a very little displacement in the aluminium part compared to the CFRP part; see Fig. 7 (a). In contrast, mode 6 shows combined behaviour of CFRP and aluminium modes; see Fig. 7 (b). Such behaviour, when carefully analysed and understood can be advantageous, allowing for damage detection in different constituent parts of a component.

3.2 Damage in the CFRP overwrap

It was shown by Castaings *et al.* [5] that damage induced by micro cracking in a carbon-epoxy plate leads to a decrease in all elastic constants of the stiffness matrix. This assumption was used to analyse the influence of the material properties change on guided wave modes in the aluminium-CFRP plate. All elastic moduli of the CFRP were reduced by 10%, 20% and 30% and results on the example of mode 3 are presented in Figure 8. In the frequency range starting from 0.6 MHz there is an abrupt change in the group velocity dispersion curves, see Fig. 8 (a). In the frequency range from 0.8 to 1.2 MHz the group velocity decreases by 30% with the 30% reduction of elastic constants, whereas the phase velocity decreases by 14%, see Fig. 8 (b). The change in the group velocity is directly connected to the change in time needed for the wave to travel from one transducer to another. This feature can be used as an indication of damage in the CFRP.

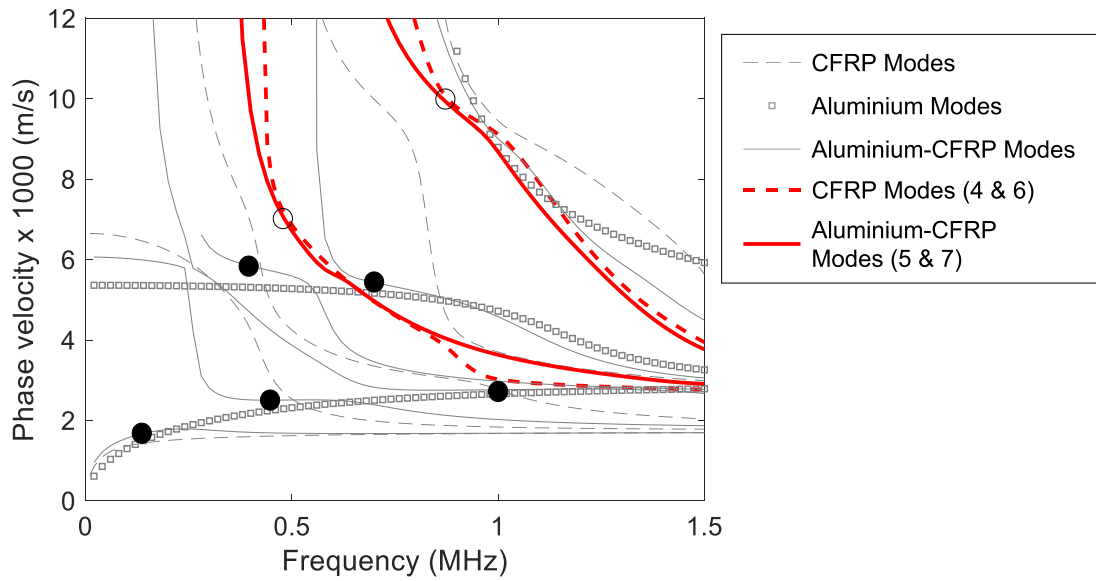


Figure 6. Combined phase velocity dispersion curves. The dashed lines mark modes for a 4 mm CFRP plate with a [90/0/90/90] layup. The squares mark modes for a 2 mm aluminium plate. The solid lines mark modes for the 6 mm aluminium-CFRP plate. The hollow and filled circles mark modes, which did not and did interact with a 1 mm crack in aluminium, respectively

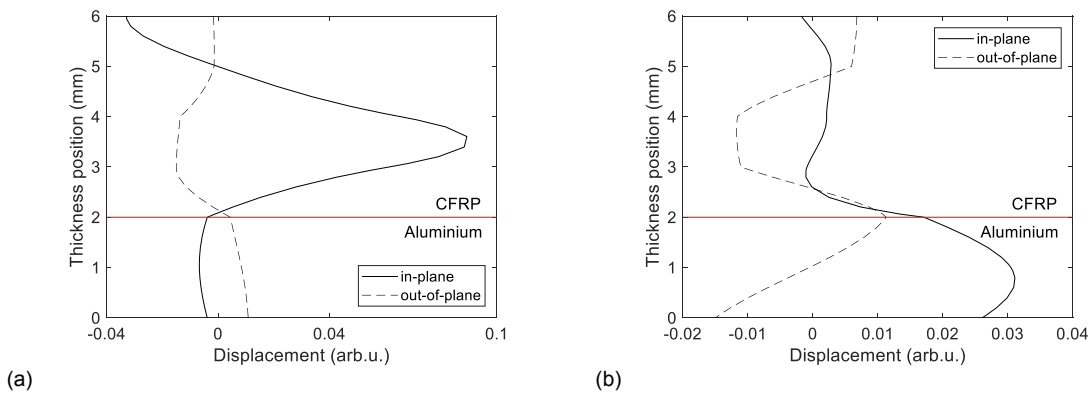


Figure 7. Mode shapes of: (a) mode 5 at $f=0.48$ MHz and (b) mode 6 at $f=0.7$ MHz

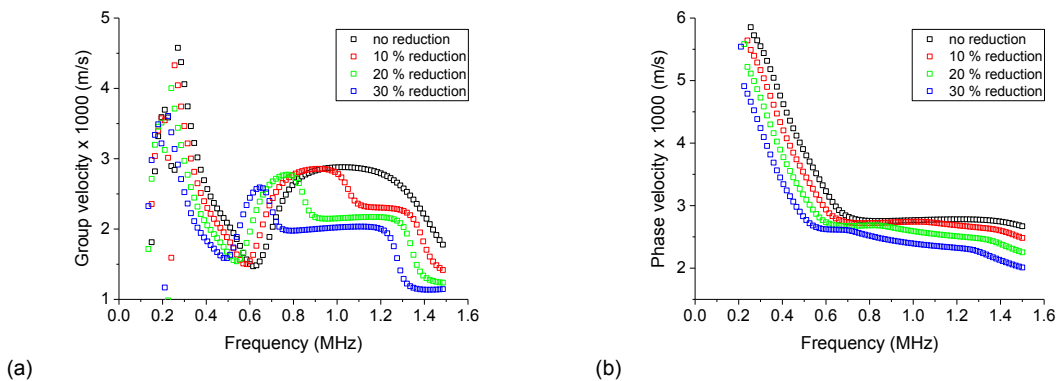


Figure 8. Influence of elastic moduli reduction on: (a) group velocity and (b) phase velocity of mode 3, calculated for the infinite aluminium-CFRP plate using SBFEM

3.3 Summary

By means of numerical modelling using the SBFEM it was possible to identify mode 3 as a mode sensitive to the damage both in aluminium and CFRP parts of the component. A defect in aluminium led to the reflection of mode 3 and its conversion into mode 6, whereas damage in the CFRP showed a strong influence on the group velocity of the mode.

4. Conclusions

In this contribution, the SBFEM was used to calculate dispersion curves, mode shapes and to analyse the propagation of guided waves in a structure consisting of an isotropic metal bonded to anisotropic carbon fibre reinforced material. The method allowed to identify appropriate modes and to analyse their interaction with different damage types. Results obtained are used to develop a structural health monitoring system for composite pressure vessels used in automotive and aerospace industries.

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