Nonlinear elastic waves in layered bars made of different materials

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Abstract. The paper presents experimental observation of strain solitary waves in layered waveguides with layers made of two glassy polymers, PMMA and polystyrene. It is shown that in delaminated structures solitons propagate in each layer independently with parameters typical for waves in each material. In bars with layers bonded with the glassy adhesive a combined wave is formed, propagating as a single one in both layers and exhibiting soliton properties.

1. Introduction

A wide variety of laminated composite materials are used nowadays for various applications, including aerospace and automotive industries. Laminated structural elements may be produced either of the same material or of different ones. Robust coupling of materials with different adhesive and mechanical characteristics is always a complicated task; and further in-service monitoring of their structural integrity becomes an important and challenging problem.

Recently we demonstrated the feasibility of strain solitary waves as a candidate approach for NDT of layered structural elements made of the same material \[1\]. This approach may be further applied to address the problem of delamination detection in structures made of different materials. In this paper we present experimental results on strain soliton evolution in bonded and delaminated bars with layers made of two glassy polymers, polystyrene (PS) and PMMA. Note that peculiarities of strain soliton formation in these materials and its behaviour in uniform waveguides made of them were studied in detail in our previous papers (see e.g. \[1,2\] and references therein).

2. Experimental arrangement

Experiments on generation and observation of bulk strain solitons in layered bars were performed using the experimental setup applied in our former research on nonlinear bulk elastic waves in various waveguides (see e.g. \[1,2\]). The experimental technique is based on laser generation and subsequent holographic recording of the waves under study. The strain soliton is formed in the uniform PMMA rod from the initial shock wave generated in water nearby its input cross section via laser evaporation of the metallic foil (see Fig. 1). The rod (10 mm in diameter, 50 mm long) is bonded to the two-layered bar (10x10 mm cross section) with layers (5x10 mm cross section) made of PS and PMMA. The two waveguides are used in experiments: one with delaminated (clenched) layers, and the other with layers perfectly bonded by the ethylcyanoacrylate (CA), “Super-Moment” adhesive. The initial
‘rod’ part of the waveguide provides optimal conditions for a soliton formation and ensures that it is definitely the soliton entering the layered part under study. Note that our previous experiments showed that the CA adhesive is close in linear elasticity to that of PMMA and PS (see Table 1 for elastic characteristics of both polymers and CA adhesive) and does not introduce any significant distortions in strain soliton behaviour ([1]). Wave patterns in the bar were recorded using the technique of classical ‘analog’ holographic interferometry, providing observation of bulk density waves in an optically transparent waveguide via wave-induced local variations of the refractive index of the waveguide.

**Table 1.** Elastic parameters of PS, PMMA and CA adhesive.

|        | Density | Young modulus | Poisson ratio | 3rd order elastic moduli (Murnaghan) | Nonlinearity coefficient | Sound velocity (rod) |
|--------|---------|---------------|---------------|--------------------------------------|--------------------------|----------------------|
|        | ρ g/cm³ | E GPa         | ν             | l GPa | m GPa | n GPa | β GPa | C_r m/s |
| PS     | 1.06    | 4.03          | 0.34          | -18.9 | -13.3 | -10.0 | -35.3 | 1870   |
| PMMA   | 1.16    | 5.27          | 0.34          | -10.9 | -7.7  | -1.4  | -15.9 | 2080   |
| CA     | 1.05    | 2.76          |               |        |       |       |       |        |

**Figure 1.** Experimental layout

3. **Interferogram processing**

The traditional interferogram processing procedure includes measurements of fringe shifts with consecutive calculations of wave amplitude and length. Various defects in interference fringes, discontinuities in particular, complicate or even preclude automatic fringe tracking and interferogram processing by means of known algorithms. We have recently demonstrated ([3]) the possibility to process classical holographic interferograms in finite width fringes using algorithms developed for reconstruction of off-axis digital holograms (e.g. [4-6]) and specifically those sustainable to fringe discontinuities, e.g. [6]. This latter algorithm was applied in the present work for processing of interferograms demonstrating strain soliton evolution in layered bars. The results obtained are shown in Figs. 2 and 3.
The soliton parameters can be directly obtained from the fringe shifts on interferograms or from the reconstructed arrays of phase shift values in the following way. In classical case the soliton amplitude can be calculated from the fringe shift by the formula:

\[ A = \frac{\Delta K \lambda}{h(n_1 - 1)(1 - \nu)} \]  

(1)

where \( \Delta K \) is the fringe shift, \( \lambda \) is the recording laser wavelength (0.694 μm), \( n_1 \) is the refractive index of the material, \( h \) is the waveguide thickness along the recording laser beam (10 mm), \( \nu \) is the Poisson ratio. Since \( \Delta K = \varphi / 2 \pi \) (where \( \varphi \) is phase), we obtain for the case of digital hologram reconstruction algorithm:

\[ A = \frac{\varphi \lambda}{2 \pi h(n_1 - 1)(1 - \nu)} \]

(2)

4. Results and discussion

The experiments were performed using two specimen in the form of two-layered waveguides with layers made of PMMA and PS. Layers of the first specimen were completely delaminated and clenched together. Layers in the second specimen were bonded by the CA adhesive. In both configurations the layered part of the waveguide was bonded to the initial part (PMMA rod) by the CA adhesive.

![Image](Figure 2. Holographic interferograms (a, b) and results of their processing (c, d) for the strain solitons in a bar with delaminated layers made of PS and PMMA at the distance 20-70 mm from the layered part input. Waves move from left to right. The upper layers (PS) on the interferograms (a, b) correspond to the front curves on the processed phase distributions (c, d).)
Figure 2 presents interferograms of wave patterns and results of their processing in a waveguide with delaminated layers at the same distance from the input of the layered part of the waveguide (20-70 mm) but at two succeeding time moments. Obviously wave patterns in the layers differ quite noticeably, solitons in the materials propagate with different velocities, characteristic for each material. Their amplitudes are remarkably different. Moreover in the PMMA layer one can observe the formation of a soliton train, which is in close correspondence with our previous experiments and developed theory [2]. We can conclude that in this case the initial soliton enters two separate layers of PS and PMMA and then two individual solitons propagate along them independently. Due to the difference in velocities (1870 m/s in PS and 2080 m/s in PMMA) the soliton in the upper layer (PS) lags behind the soliton in the lower layer (PMMA). The soliton amplitude in the PS layer is much lower than that in the PMMA layer. This difference is due to two factors. Firstly, at the transverse junction of the PMMA rod and PS layer a part of the soliton energy is reflected back due to the difference in acoustic impedances of the materials. And secondly, it is a consequence of the difference in refractive indices of the materials (1.49 for PMMA and 1.59 for PS) resulting in a slightly different fringe shift for the same density variation (see eq. 1).

The wave patterns shown in Figure 3, where the PS and PMMA layers are bonded with the CA adhesive, are quite different: a combined solitary wave is formed propagating in the layered structure with the resultant velocity, amplitude and shape. Note that the waveguide area covered by the two interferograms in Fig. 3 (a,c) comprises 100 mm which equals to three soliton widths and would be sufficient to detect soliton separation in the layers, if any.

![Figure 3](image.png)

**Figure 3.** Holographic interferograms (a, b) and results of their processing (c, d) for the strain soliton in a bar with bonded layers made of PS and PMMA at the distance 20-70 mm (a, c) and 70-120 mm (b, d) from the layered part input. Waves move from left to right. The upper layers (PS) on the interferograms (a, b) correspond to the front curves on the processed phase distributions (c, d).
5. Conclusions
Thus it was shown that wave patterns representing strain soliton behaviour in bonded and delaminated waveguides with layers made of different materials are substantially distinctive. In delaminated layers solitons propagate independently exhibiting parameters specific for each material. In CA-bonded layers a single combined soliton is formed which propagates in the layered waveguide as a whole with some resultant parameters. The effect observed can be applied for in-operation delamination detection in layered structural elements.

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