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The effect of fiber content on the ultrasonic wave velocity in glass/polyester composites

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Properties

ABSTRACT

Purpose: The primary purpose of the present study was to find relationship between ultrasonic wave velocity and the fiber content in glass/polyester composites. In addition, further tests were conducted to determine how other factors can affect the ultrasonic wave velocity.
Design/methodology/approach: Experimental data have been obtained using ultrasonic wave velocity measurements and standard destructive analysis. For ultrasonic non-destructive testing, through-transmission technique was used.
Findings: Experimental results have shown that the longitudinal wave velocity increases almost linearly with an increase of the fiber content in investigated specimens.
Research limitations/implications: The propagation velocity of the ultrasonic waves can be affected, apart from fiber content, by interfacial stresses and changes of elastic modulus in polymer matrix during long-lasting conditioning. These factors overlap and which of the two can affect the ultrasonic wave to a higher degree is yet to established. Further work is needed in this area.
Practical implications: Ultrasonic wave velocity measurement seems to be an effective method of fiber content evaluation, but for any different composites, distinct relationships should be determined.
Originality/value: The results obtained would be of considerable importance in industrial applications to achieve a first estimate of fiber content variations in composite materials.
Keywords: Non-destructive testing; Ultrasonic wave velocity; Glass/polyester composites; Fiber content

1. Introduction

Fiber reinforced polymer composites have a number of advantages when used as components for the aerospace, navel, automotive or construction industries. Due to their high strength-to-weight and stiffness-to-weight ratios as well as their fatigue and corrosion resistance, it is possible to produce components that exhibit significant weight savings and improved service-time performance over that of more traditional materials (steel and aluminium alloys) [1]. It is known that the mechanical properties of fiber reinforced composites, among others, highly depends on fiber content variations. There are many research works directed towards understanding the influence of reinforcement content on the selected characteristics of composites [2÷5]. Local reinforcement variations arising during production process decide about out-of-control variations of strength and stiffness in a given component, which is of a great importance in the case of products with a high failure-free requirements. To improve manufacturing quality it is necessary to develop methods which are suitable for the purpose of reinforcement content determination. Traditionally, the fibre content is measured by three basic methods, including solvent extraction, burn-off and acid digestion [6]. These methods, due to their destructive character can not be applied when components are subjected to a hundred-percent inspection. The observations above suggest that there is a need to develop the non-destructive methods to be applicable for presented purpose. From a wide range of non-destructive techniques, ultrasounds

seem to be the most promising for this purpose, because the mechanical wave propagation highly depends on elastic properties and density of the medium [7, 8]. It is also known that propagation of ultrasonic waves is sensitive to the variations in the microstructure and mechanical properties. Therefore, establishing a relationship between the microstructural (fiber content) and ultrasonic evaluation results could be very useful for improving the process parameters and controlling the quality of the products [8]. So far, ultrasounds has found many applications in non-destructive testing of composite materials [9÷18].

Previous research results [19] showed that the inhomogeneous distribution of glass fibers, which significantly degrades mechanical properties, is detectable by ultrasonic measurements [19, 20]. It was presented that the local fiber content and ultrasonic wave velocity are closely related, and second chosen parameter of the ultrasonic wave, namely attenuation coefficient, was not correlated with the fiber content [19].

The primary objective of this research is directed towards understanding the microstructure properties - ultrasonic wave velocity relationship in glass/polyester composites. Special attention was given to the fiber content, interfacial stresses and time-degradation of polymer matrix. For this purpose, a group of nine specimens were ultrasonic tested; first after manufacturing and then again twelve months after first testing.

2. Experimental

2.1. Procedure

The ultrasonic testing and destructive analysis was conducted to investigate the effect of fiber content and other parameters on the ultrasonic wave velocity in glass/polyester specimens. For destructive analysis and ultrasonic measurements, the specimens were prepared with the variation of glass content (30 ÷ 70%) by conventional hand lay-up. The specimens were twice investigated using ultrasonic measurements; before and after twelve months of conditioning under ambient conditions. Previous, as well as current ultrasonic investigations were performed with the use of the same apparatus.

2.2. Materials and specimens preperation

The investigated specimens were made of cross - ply plain weave [0/90] E-glass fabric (Saint Gobain Vetrotex Europe), polyester resin „Aropol M 105 TB" (Ashland Finland) and initiator „Butanox M-50" (Akzo Nobel Polymer Chemicals). The details about materials are summarized in Table 1.

Glass fiber reinforced polyester composites were fabricated by hand lay-up, with variation of glass content. The polyester resin was cold-cured under ambient conditions (~20 ºC). The composites prepared in such a way had a glass content from 30% to 70% by weight and with 10 mm average thickness. The variation of glass content was achieved using different number of glass layers with the same total thickness of the specimens. Polyester matrix, after curing process was thermally hardened at 50 ºC for 24 hours.

Table 1.
The properties of constituent materials

Parameter	Unit	E-glass	Polyester resin
Density	g/cm^3	2,58	1,10
Tensile strength	MPa	3500	55
Elastic modulus	GPa	75	3,6

2.3. Ultrasonic velocity measurement

Ultrasonic velocity in the specimens was measured using a MG 2000S ultrasonic thickness meter (AZ Industry Supplier, Warsaw, Poland). The schematic view of ultrasonic investigation is shown in Fig. 1.

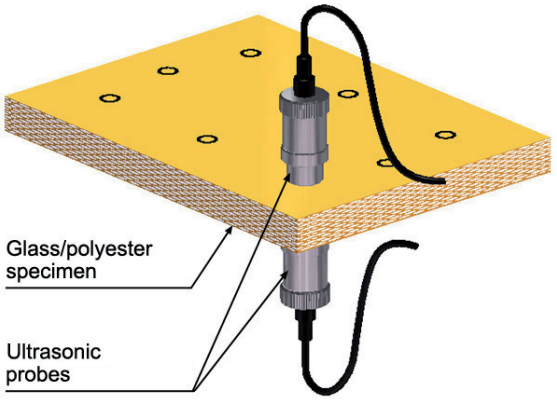

Fig. 1. Scheme of the ultrasonic testing

The device has a build-in function to measure the propagating time. The ultrasonic instrumentation was operated in the time-of-flight mode using through-transmission technique. For longitudinal velocity measurements, two standard probes of 2 MHz frequency was used. The accuracy of velocity measurements was within ±1 ms^{-1}. Eight measurement points were chosen on the surface area in such a way that there would be no side-wall effect on ultrasonic wave. For longitudinal velocity, eight measurements were made and the average values have been reported (Tab. 2.). As a coupling medium at the probes-specimen interface, the USG-gel (Centrum Medicum Poland) was applied. The ultrasonic velocity (c) was calculated dividing the specimen thickness (h) by the time-of-flight (τ) of ultrasonic wave on the basis of well-known formula 1:

$$c = h / \tau. \quad (1)$$

2.4. Destructive analysis

The destructive analysis was performed according to the method described in ISO 1172:2002 [21]. The whole population of specimens were tested in order to achieve the information about actual glass content from every specimen. In accordance with the standard, two test specimens were cut from location on

the composite to be representative of the material. It was performed with the use of a diamond circular saw blade in such a way that their weight was within the range of 2÷10 g. The next step was to dry the specimens to evaporate moisture and weighted with the use of a precision balance. Then, each specimen was put in a melting pot and baked in the temperature of 600 ºC for approximately 1 hour. That time was determined experimentally as weight of the specimens did not change after subsequent bakings. The glass content M_{glass} in each examined specimen was determined in accordance with the standard as a fraction of the initial weight and expressed by formula 2:

$$M_{glass} = (m_3 - m_1) / (m_2 - m_1) \cdot 100, \quad (2)$$

where:

m_1 – initial weight of the melting pot in [g],
m_2 – initial weight of the melting pot with a sample in [g],
m_3 – final weight of the melting pot with calcination residue in [g].

Results of the destructive examination of the glass content and densities of each specimen as well as average ultrasonic wave velocities were put into Table 2.

Table 2.
Densities and other determined properties of investigated glass/polyester specimens

No.	Density [g/cm^3]	Percent glass by weight [%]	Average speed of sound [m/s]
1.	1,40	30,74	2627
2.	1,45	36,46	2659
3.	1,51	41,00	2786
4.	1,54	48,34	2804
5.	1,70	59,90	2810
6.	1,72	60,88	2841
7.	1,74	64,09	2910
8.	1,74	64,31	2925
9.	1,80	68,10	2963

3. Results and discussion

Comparing the values of fiber content and ultrasonic wave velocity in investigated materials it became clear that these two properties are closely related. The results show that in general the ultrasonic velocity increases with an increase in glass content. This is in agreement with the findings of other researchers [7, 8]. Considerable dispersion of data in the wave velocity (Fig. 2. and 3.) can be attributed to the glass content in examined specimens and possible local absence of glass on the path of ultrasonic wave.

Figure 2 gives a comparison of the relationship between glass content and the ultrasonic wave velocity for glass/epoxy and glass/polyester composites. The longitudinal wave velocity for epoxy matrix reaches the value of polyester matrix for higher glass contents, and for these values the effect of resin type is negligible. However, as reinforcement content decreases, the discrepancy between wave velocities increases (Fig. 2.).

Figure 3 shows the same relationship, but in the case of glass/polyester composites which were subjected to a long-lasting, room temperature conditioning. It was observed from Figure 3 that there was a little variations in ultrasonic velocity obtained after twelve months of conditioning and that indicates that degradation processes of polymer matrix could take place. This can be also attributed to the relaxation of interfacial stresses which can occur with the aid of resin matrix shrinkage during curing process.

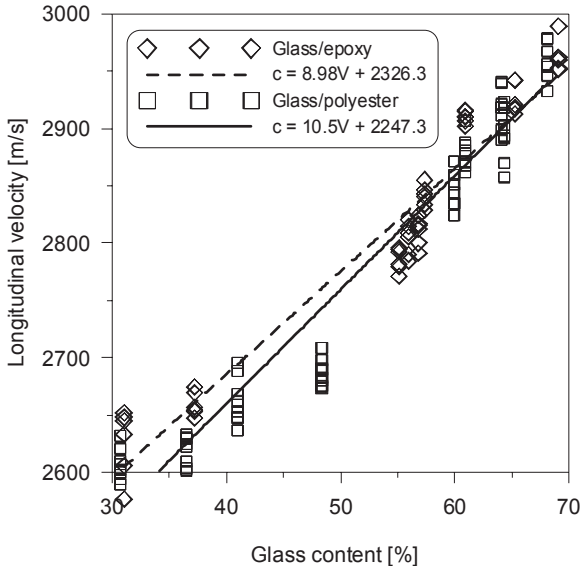

Fig. 2. Relationship between the ultrasonic wave velocity and the glass content for glass/epoxy and glass/polyester composites [19]

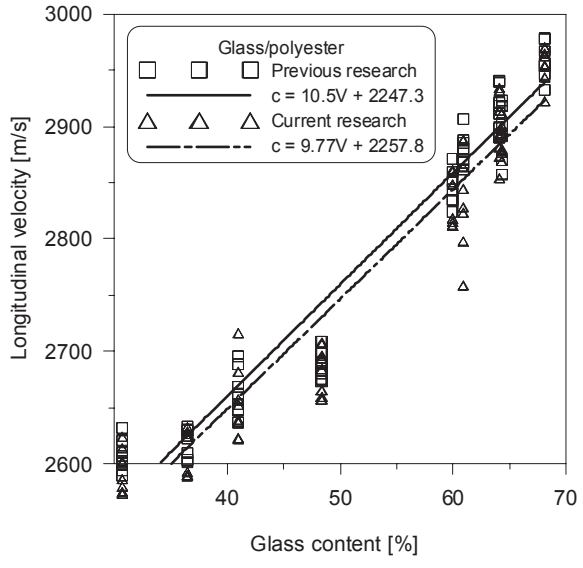

Fig. 3. Relationship between the ultrasonic wave velocity and the glass content for glass/polyester composites; comparison with the previous [19] and current investigations

These two, described above, factors can overlap and which one affect the ultrasonic wave to a higher degree should be explain in further research works. Due to the complexity of the problem, further investigations should be conducted, but achieved results provide a good starting point for any theoretical investigations.

4. Conclusions

In the present study, ultrasonic testing and destructive analysis were carried out on the group of glass/polyester specimens, fabricated by conventional hand lay-up. The specimens were prepared with variations of reinforcement content. The obtained results showed that increasing fiber content leads to an increase in ultrasonic wave velocity. The wave velocity increases almost linearly with the increase of glass content. The effect of long-lasting conditioning was investigated and it was concluded that the changes in the wave velocities can be attributed to the changes in elastic modulus of the polymer matrix. Due to the second considered factor, interfacial stress, which can overlap on time-changes in elastic modulus, and also can affect the ultrasonic wave velocity, further investigations are needed in this area.

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