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Elastic constant determination of unidirectional composite via ultrasonic bulk wave through transmission measurements: A review

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ABSTRACT

The determination of the elastic constants of unidirectional carbon fibre composite via immersion based ultrasound is an established area with much literature. Existing literature reviews in this area discuss the extant literature but do not offer a deep review of the seminal publications during this period, but instead focus on reporting the contributions of the published literature. Thus, a gap in knowledge exists for a comprehensive literature review charting the evolution of how the elastic constants of uni-directional carbon fibre composite are determined via immersion based ultrasonic through transmission. This work addresses this. Building on previous literature, this paper reviews seminal publications in chronological order, with the benefits, drawbacks and contributions to knowledge of each reviewed publication identified within this work. This review is bounded from 1970 to 2015, (some 45 years of literature), and maps the progression of technological and scientific advancement of the through transmission technique; that is, seminal literature during this period is both identified and reviewed in chronological order thus demonstrating how each paper builds on previous work. This paper also documents two novel information tables, which for the first time allow the significant contributions to knowledge during this period to be quickly identified.

1. Introduction

Carbon fibre reinforced plastics (CFRP) are becoming increasingly common, with applications in industrial such as aerospace, wind turbine, automotive, sport equipment and construction [1]. Owing to increasing environmental and waste legislation [2–4] combined with the high cost of composites to manufacture, CFRP re-use, in particular CFRP recycling, is also field of on-going research [5–8].

With increasing application of CFRP, it is important to have testing methods suitable for both virgin and recycled materials. A wealth of existing literature on characterization of virgin materials, particularly in the field of non-destructive evaluation (NDE) may be found [9–11], with themes such as ultrasound, X-ray, thermography, eddy current analysis all featuring. This review focuses on one area of CFRP non-destructive evaluation, that of ultrasonic analysis.

The field of ultrasonic NDE is diverse with areas such as pulse echo, laser generated ultrasound, acoustic emission, through transmission, guided waves, bulk waves, surface waves, reflection and transmission analysis, point source point receiver techniques, air coupled analysis, elastic constant determination and defect detection found in literature. In terms of CFRP a similar argument is

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also made with many different CFRP structures able to be evaluated, i.e. anisotropic media, isotropic media, multi-layered structures etc.

This review therefore focuses upon a single area; elastic constant determination through non gas coupled bulk wave through transmission analysis of virgin uni-directional CFRP over the period of 1970–2014. This review will serve as a robust reference text for practitioners in the field of ultrasonic based testing of CFRP in that not only are there multiple contributions to knowledge identified within the text, along with identification of the relevant literature, the fundamental experimental arrangement of through transmission is identified in addition to the evolution of how this experimental arrangement evolved with time.

Additionally, given an absence of ultrasonic literature concerning the determination of elastic constants of CFRP manufactured using reclaimed fibres obtained via recycling this review will also serve to promote the effectiveness and process of ultrasonic based elastic constant determination to researchers involved in manufacturing and characterising these new materials.

Section 2 presents the methodology; scope of the research and an outline of how literature was selected for review. Section 3 presents a brief theoretical background on elastic wave propagation and elastic constant determination within anisotropic media. Section 4 presents the literature review with Section 5 presenting novel information tables documenting key findings, both in terms of authors and contributions to knowledge. Section 6 presents some additional reading with Section 7 presenting a conclusion.

2. Methodology

When conducting a review, the typical theme within literature is to report the results of a publication and refrain from giving each publication a detailed and rigorous review. Adopting this technique allows for very effective wide ranging reviews; findings from a large volume of literature in multiple areas can be presented efficiently. This paper limits the scope of the review however, thus allowing for a more in depth analysis of the available literature. Adopting this approach has three benefits, (1) drawbacks or concerns within literature are clearly identified, (2) not only a recap of findings but a full contribution to knowledge is able to be presented and (3) seminal works within the field are collated, organized and reviewed in a single document which may be used as a future reference text. This review goes deeper than a reporting of the results and presents a more in depth analysis of the available seminal works.

Existing substantial reviews of ultrasonic based analysis of composite material, such as [12,13], present a comprehensive discussion of the methods to ultrasonically determine the elastic constants of unidirectional composites. In terms of review novelty, a clear distinction between those works and this work can be made. Works such as, [12,13], focus more on the techniques used within industry and academia, with practitioners cited as references, and less on the contributions from individual authors (although in the case of [12] the authors of this text at times directly discuss their previous publications on the subject). This review is however more aligned with [11], in that, there is less focus on the theoretical and more on the practical findings arising from individual texts. Thus it is envisaged that this review may be used in conjunction with or to complement existing literature reviews [12,13].

Regards the boundaries of the research, Table 1 identifies the scope of literature reviewed.

Note that on occasion, one or more of the excluded research areas is discussed in this review. The rationale for discussing areas outside of the scope is made apparent from the context at that point.

The literature selected for this review was journal articles, conference papers and book publications. This literature was identified in part by searching through databases and also by reviewing the references cited in published journal articles. Lastly, book reviews such as [11–13] also helped identify further relevant literature.

It is important to emphasize that the decision to review a particular publication was at times taken on the opinion of the authors. For instance, Stijnman [14], employed an already existing method (at that point) to determine the elastic constants of a composite that was not either graphite composite or CFRP. As Stijnman used an existing technique to determine these elastic constants, reviewing this work served no real purpose and so the decision was taken not to review. Similar decisions taken on reviewable literature were at the discretion of the authors and as such, the reviewed literature presented here, while including most all seminal works, does not include every feasible publication associated with the through transmission technique.

2.1 Review structure

The review follows a chronological progression within literature, in that the review starts by reviewing earlier works in the field

Table 1
Identifies the boundaries and scope of the literature review.

Boundaries on the literature reviewed	Examples of research areas falling outside boundaries (excluded research areas)
Bulk waves (waves treated as acting in an infinite medium)	Lamb waves, Rayleigh waves, guided waves
Unidirectional composite (with where possible polymer matrix)	Cross ply composite, isotropic composite, multidirectional laminates, thick composites, woven composites
Carbon fibre or graphite fibre (where possible)	Kevlar or Boron based fibres
Non gas coupled ultrasound through transmission (velocity based measurement)	Wave attenuation measurements, pulse echo techniques, point source point receiver technique, A-scans, B-scans, C-scans, Air coupled ultrasound, transmission – reflection coefficients
Elastic constant determination (mechanical properties) through experiment	Defect detection, porosity, fibre content, attenuation factor, theoretical modelling based on composite properties, mechanical tests, viscoelastic properties

and concludes with later works in the field.

To ensure efficiency, early works (1970s–1980s) are often given more attention in certain areas than later works. Rationale for this being (a) this period was a significant period for the development of the through transmission technique and (b) many of the techniques developed in this period are still used today and so there is no need to repeat their discussion in later papers. As such, from 1980s onward if no new knowledge was presented within literature relating to sample size, type of transducer, propagation direction etc. then these areas did not always necessarily require discussion. It should be stated that this decision did not prevent any work from being reviewed nor did it prevent specific works from receiving more attention than others. For instance, works that broach new measurement techniques may warrant more depth than publications that use existing measurement techniques.

Further, to assist the reader, the review itself is split in sections. The first section concerns the Zimmer and Cost approach and the Markham Method. These two powerful techniques highlight the root of the through transmission technique upon which all literature is ultimately based. Thus, these techniques are clearly highlighted for the reader in Sections 4.1 and 4.2 with Section 4.3, documenting the contributions to knowledge obtained using these techniques during the period 1970–1980.

Section 4.4 outlines an experimental breakthrough known as the double through transmission technique, develops group velocity and presents reconstruction algorithms developed during the 1980s through to the 1990s.

Given the more in-depth approach to the subject matter of this review, a critical examination of literature is obtained. This is however at the expense of scope. Thus, additional reading is presented for the reader in two places, the first place being Sections 4.5 and 4.6. Having by this stage identified various experimental techniques, Sections 4.5 and 4.6 identify pertinent literature which touches on the subject matter, developed in parallel with the subject matter at this point.

Keeping with the chronological progression within literature, Section 4.7 builds on 4.4. Section 4.7 presents modern literature and various contributions to knowledge concerning the determination of elastic constants via immersion based ultrasound through transmission.

Further, Section 5 documents for the first time within literature information tables outlining various contributions to knowledge from the period 1970–2014. Owing to the large amount of findings documented within this review. To ensure efficiency, more than one table exists; Table 9 documents the 1970s–1980s, with Table 10 documenting the 1980s – modern era. It of merit to note that Table 10 does not necessarily document findings that have already been documented in Table 9. For instance, Table 10 does not acknowledge whether publications from the period 1980 onward determined the full set of elastic constants as Table 9 demonstrates that determining elastic constants is achievable and so including this information in Table 10 would be of no merit.

Lastly, the second interjection of additional reading is given in Section 6. Given that the various experimental arrangements outlined in this review have application in air coupled ultrasound, Section 6.1 is presented. Benefits, drawbacks and pertinent literature is identified for the reader. Returning to a lack of literature on ultrasound through transmission of composite manufacturing using reclaimed fibres obtained via recycling, Section 6.2 is given. Pertinent literature outlining composite recycling and the processing structure property relationships are identified for the reader.

Prior to the literature review, Section 3 presents brief notes outlining elastic wave propagation through a solid.

3. Elastic wave propagation in solids

As ultrasonic waves (which are a type of elastic wave) propagate through a solid, the solid undergoes compression or shearing actions with particles deviating from equilibrium position. Thus, there exists a natural relationship between the phase velocity of propagating plane waves and the elastic constants of the solid. The relationship is given by the Christoffel equation.

$$|\Gamma_{ij} - \rho V^2 \delta_{ij}| = 0$$

With Γ_{ij} being the Christoffel matrix, ρ is the density, δ_{ij} is the Kronecker delta function and V^2 is the phase velocity squared. For the most general case of an anisotropic solid, with 21 constants, the Christoffel matrix is equal to,

$$\Gamma_{ij} = \begin{matrix} \Gamma_{11} & \Gamma_{12} & \Gamma_a \\ \Gamma_{21} & \Gamma_{22} & \Gamma_b \\ \Gamma_{31} & \Gamma_{32} & \Gamma_c \end{matrix}$$

With,

$$\Gamma_{11} = C_{11}n_1^2 + C_{66}n_2^2 + C_{55}n_3^2 + 2C_{56}n_2n_3 + 2C_{15}n_3n_1 + 2C_{16}n_1n_2$$

$$\Gamma_{22} = C_{66}n_1^2 + C_{22}n_2^2 + C_{44}n_3^2 + 2C_{24}n_2n_3 + 2C_{46}n_3n_1 + 2C_{26}n_1n_2$$

$$\Gamma_{33} = C_{55}n_1^2 + C_{44}n_2^2 + C_{33}n_3^2 + 2C_{34}n_2n_3 + 2C_{35}n_3n_1 + 2C_{45}n_1n_2$$

$$\Gamma_{23} = \Gamma_{32} = C_{16}n_1^2 + C_{26}n_2^2 + C_{45}n_3^2 + (C_{46} + C_{25})n_2n_3 + (C_{14} + C_{56})n_3n_1 + (C_{12} + C_{66})n_1n_2$$

$$\Gamma_{13} = \Gamma_{31} = C_{16}n_1^2 + C_{26}n_2^2 + C_{45}n_3^2 + (C_{45} + C_{36})n_2n_3 + (C_{13} + C_{55})n_3n_1 + (C_{14} + C_{56})n_1n_2$$

$$\Gamma_{12} = \Gamma_{21} = C_{16}n_1^2 + C_{26}n_2^2 + C_{45}n_3^2 + (C_{44} + C_{23})n_2n_3 + (C_{36} + C_{45})n_3n_1 + (C_{25} + C_{46})n_1n_2$$

With n_1, n_2, and n_3 representing the directional cosines of propagation direction for a given reference axis and C_{xx} the particular elastic constant. Given a propagation direction and a degree of anisotropy, the phase velocity can be expressed in terms of elastic

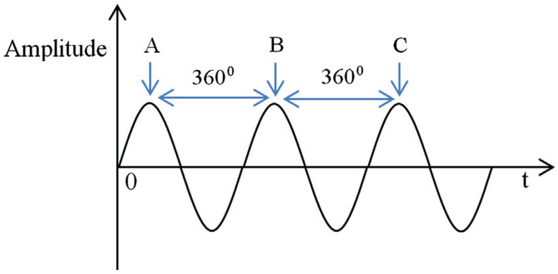

Fig. 1. Documents a plane wave. The points a, b and c are at equal phase with respect to each other as the wave propagates through space and time. In this example, the wave front could be stated as point a, point b and point c etc. The speed at which the wave leaves point a and reaches point b, or leaves point b and reaches point c is known as the phase velocity.

constants by finding the roots of the Christoffel equation.

The wave velocity/elastic relationship discussion is not taken further in this review owing to (a) most all publications reviewed identify the required wave type and direction required to determine the elastic constants and (b) additional texts take this process further while also providing examples, [12,13,15–18]. Additionally, Musgrave, [18] and Gold, [19], documented equations for the phase velocity in terms of the elastic constants (an output from the Christoffel process) for mediums of hexagonal symmetry. With unidirectional CFRP closely paralleling hexagonal symmetry, these equations are often quoted within literature.

An additional point concerns axis selection. As unidirectional composite is described in the reviewed literature, the choice to assign the fibre axis as 1, 2, 3 or x, y or z, is made by individual authors. As such, these often change from publication to publication with the choice of axis bearing on the denomination of elastic constant. That is, depending on how authors geometrically view a material, the denomination of an elastic constant may alter from publication to publication, for example, C_{11} in one publication may refer to C_{33} in another publication. Confusion is limited however as the elastic constants in relation to the material parameters cannot change even though denomination (or name) often does. Thus care should be taken.

3.1. Phase velocity and group velocity

Lastly, a distinction between phase velocity and group velocity prior to the literature review is made. For traveling plane waves, waves in which wavelength and frequency do not alter, the wave may be classed as having constant phase. That is, from a given phase reference point, say 90° the phase of the wave will travel through a complete cycle of 360° (one wavelength) through space and time and then return to the same reference point. The speed at which this process occurs is called the wave's phase velocity of a wave. Further, points of equal phase occurring in space and time are known as wave fronts. Fig. 1 is given to help reinforce the phase concept.

Group velocity is the variation of a given wave's envelope or amplitude as it propagates through space and time. More specially, in some circumstances the various frequencies which comprise an ultrasonic pulse may begin to travel at different velocities and so the direction of wave propagation, as measured via wave envelope may begin to deviate away from the direction of phase velocity and in the direction of what is known as group velocity. A representation of the group velocity effect is given in Fig. 2.

4. Literature review

Modern CFRP ultrasonic through transmission literature builds on two techniques outlined by Zimmer and Cost [20] and Markham [21]. Given that future research effectively refines and develops the techniques outlined by these authors, it is appropriate

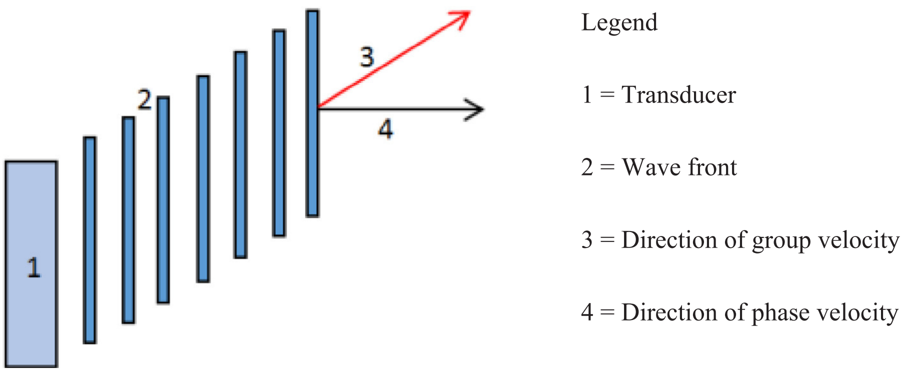

Fig. 2. The group velocity effect is shown. Path 4 is the direction of phase velocity, while path 3 is the direction of group velocity. Notice that group velocity causes the direction with respect to the transducer to deviate away from a normal.

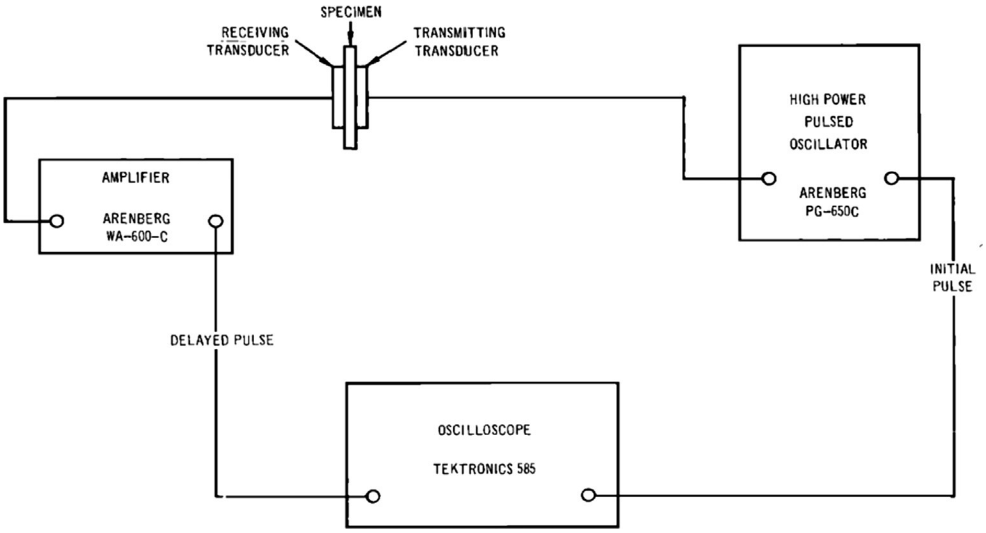

Fig. 3. Pulsed through transmission set up used by Zimmer and Cost. An ultrasonic pulse is transmitted through the material with the received pulse and sample width used to determine wave velocity (The time difference between initial pulse and received pulse was found using time delay function on oscilloscope). *Reprinted with permission from Zimmer JE, Cost JR. Determination of the elastic constants of a unidirectional fibre composite using ultrasonic velocity measurements. Acoust Soc Am; 47: 795–803. Copyright 1970, Acoustic Society of America.*

to clearly identify the root of the through transmission technique for the reader. Thus, discussion of [20,21] is presented in isolation of the remainder of the review, in Sections 4.1 and 4.2. The review of these works is now given, with the review of [20] presented first.

4.1. Zimmer and Cost (1970)

One of the earliest instances of ultrasonic wave velocity measurements being used to determine the elastic constants of a fibre composite was by Zimmer and Cost in 1970, [20]. Alongside determining the complete set of elastic constants for a unidirectional composite the authors also sought to validate earlier theoretical predictions developed by previous authors.

The type of sample used in this study was Scotchply 1002, a glass reinforced epoxy (‘E’ glass fibres with a 1002 epoxy resin) with density, average fibre diameter and fibre volume fraction recorded as 1.9 g cm^{-3}, 0.011 mm and 0.49 respectively. The authors also reported that while the unidirectional composite had a random fibre array (fibres were somewhat randomly orientated per volume area), large areas were recorded as tending towards hexagonal symmetry and so the material was considered transversely isotropic; only 5 elastic constants were required to determine the mechanical properties.

Determination of the elastic constants was through a technique known as the ultrasonic pulsed through transmission technique. In this arrangement a test piece is placed between two transducers and the length of time taken for a pulse to leave one transducer and arrive at the second transducer is recorded and used along with sample width to determine wave velocity. The system used by the authors is given in Fig. 3.

To determine the five independent constants the authors propagated both longitudinal and transverse waves through various samples in different directions and polarizations relative to the fibre direction. To facilitate this requirement, the authors used samples, cut from a larger piece of composite (0.31 in. thick), in which the fibres had angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° to the sample sides. It is of merit to note that although 7 samples were created, only 3 were required to allow for the determination of elastic constants. The four remaining samples, 15°, 30°, 60° and 75° were used by Zimmer and Cost to validate the ultrasonic velocity method. The transducers used were stated as being quartz, and were bonded to the test piece using Salol (phenyl salicylate). The frequency of operation was 5 MHz with the authors stating this was chosen to reduce interactions between the wave and the fibre (for a wavelength approximately equal to fibre diameter unwanted interactions can occur) and also because attenuation increases with frequency – although quite high attenuation was still recorded in each sample. The samples were of various thicknesses and this was shown not to have a large effect on the velocity measurements.

To determine C_{33} and C_{11} the authors propagated longitudinal waves in the fibre direction and at right angles to the fibre direction respectively. To determine C_{44} and C_{66} (noting that C_{66} is not independent but instead relies on C_{33} and C_{23}) transverse waves were propagated perpendicular to fibre direction and polarized in and normal to the plane of the fibre respectively.

Additionally C_{44} was determined by propagating a transverse wave in the direction of the fibres. However, this proved to be an inaccurate method for measuring C_{44} and so the value for C_{44} was taken from perpendicular measurement. The last elastic constant, C_{12} was quoted as being determined through propagating a longitudinal or transverse wave at 45° to fibre direction. This process resulted in quasi-wave propagation (particle deviation from equilibrium is not parallel or perpendicular with propagation direction) with wave polarization for quasi-transverse waves recorded in the plane of the fibre and propagation direction.

Table 2
The elastic constants of on Scotchply 1002 (Glass fibre composite) and associated experimental error derived via pulse ultrasound through transmission, adapted from [20].

Elastic constant	Experimental error (%)
C_{11}	6
C_{12}	100
C_{23}	15
C_{33}	6
C_{44}	6

The authors documented results from theoretical models (outside the scope of this review) and found close agreement with the theoretical values and ultrasonically measured values. In relation to elastic constant error, which resulted from a 2.5% and 1% error in velocity and density measurements, the elastic constants accuracy varied. These results are recorded in Table 2.

It is also the case that Zimmer and Cost recorded both a positive and negative value C_{12}; the explanation provided by the authors was that the equation for C_{12} contained a square term, and so there is no way to know from the experiments conducted which value to select. The authors opted for the positive value, noting that this value provides a more accurate result in relation to the theoretical predictions for material of hexagonal symmetry.

The penultimate area investigated by Zimmer and Cost was dispersion effects, making use of the additional samples which recorded angles of fibre direction to the side of test piece of 15°, 30°, 60° and 75°. When discussing shear waves polarized at right angles to the plane of the fibre, the authors state that a straight line will be produced if the stiffness associated with propagating a shear wave from 0° to 90° (with respect to fibre direction) is plotted against the squared sine of the angle of propagation (again with respect to fibre direction). Zimmer and Cost outline that the straight line relationship is not recorded by experiment and deviates owing to dispersion effects – they state that from 0° the dispersion effects increase until a maximum at about 15° from fibre direction is reached. After 15°, a decrease in dispersion effects was recorded until the angle of 90° was reached. The authors also demonstrate that when the angle of propagation to fibre reaches 45°, dispersion effects are approximately 30% (noting that C_{12} is determined using wave propagating at 45°) and for the samples of 60° and 75° dispersion caused the phase velocity to be increased by less than 15°. These results are documented in Fig. 4.

The authors record a similar analysis when examining dispersion effects associated with longitudinal waves and found that dispersion was less severe (around 5% for velocity), noting that generally velocity increased for angles $< 20°$ and decreased for angles $> 20°$. Note also, when quantifying dispersion effects for shear and longitudinal waves, the two values of C_{44} (the accurate one obtained via propagation at 90° to fibre axis and the one obtained via 0° to fibre axis) were used by the authors.

Lastly, Young's modulus as a function of fibre angle was also studied noting that the theory discussed was based on a single crystal material. Zimmer and Cost found that Young's modulus, derived from experimental elastic stiffness constants and equations found in single crystal theory, was within 15% of theoretical values calculated using existing models thus further verifying ultrasonic velocity

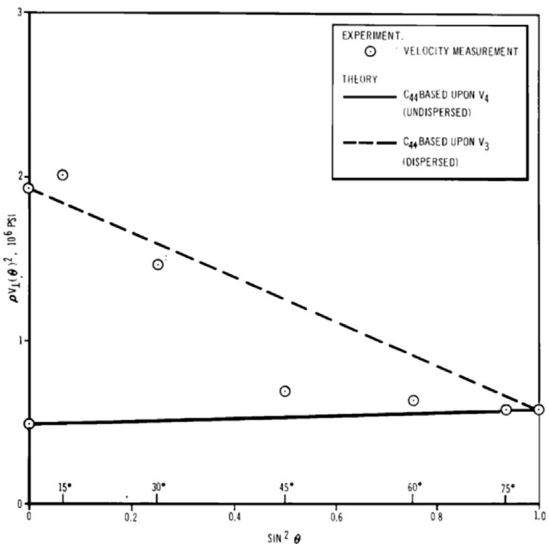

Fig. 4. Dispersion effects recorded by Zimmer and Cost when propagating shear waves polarized at right angles to the fibre. At angles of propagation with respect to fibre direction of less than 45° (excluding 0°) noticeable dispersion was recorded. *Reprinted with permission from Zimmer JE, Cost JR. Determination of the elastic constants of a unidirectional fiber composite using ultrasonic velocity measurements. Acoust Soc Am; 47: 795–803. Copyright 1970, Acoustic Society of America.*

as a viable method to determine the elastic constants of glass fibre composite.

It was for the first time demonstrated by Zimmer and Cost that using an existing ultrasonic velocity technique (previously used to investigate single crystal materials), the full set of elastic constants for a transversely isotropic glass fibre composite could be determined. Further, the authors also documented the associated stiffness when propagating both shear waves and longitudinal waves through material with fibre angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° and that Young's Modulus could be determined using the experimentally derived elastic constants. Thus, ultrasonic velocity measurements were presented as an effective way to determine the elastic properties of a material. While this work is held in high regard and precedent setting, there were issues with the publication. Problems such as (a) glass fibres (opposed to carbon fibres) were used, (b) the accuracy of result was good but could be better (C_{12} was recorded as has having uncertainty of 100%) and (c) multiple samples of composite were required to conduct these test. Looking specifically at the last concern, it can be said that even though the test is non-destructive (test piece not destroyed) the original larger section of composite was required to be cut into smaller sections to create multiple test pieces, ergo there was still a large degree of destructive testing in this system.

4.2. Markham (1970)

Developed at approximately the same time, circa 1970, was an alternative system devised by Markham, [21]. Published in the same month, Markham presented a system in which the elastic constants of a uni-directional fibre composite were determined using critically only one sample. Markham's study uses carbon fibres, as opposed to glass fibres, with the sample specifics, other than a density quote of 1671 kg m^{-3}, not referred to; the sample is referred to as only a 'typical carbon fibre-epoxy resin composite'.

Looking now at Markham's method. Similar to [20], the ultrasonic velocity principle is again adopted as the basis for determining the elastic constants. The novelty in Markham's work is by the rotation of a single sample (immersed in a body of coupling fluid) around one or two axis's thus allowing waves from a transducer of fixed position to impact the surface at varying degrees of incidence. Thus through Snell's laws, both longitudinal and transverse waves may be propagated in various directions through the sample. That is, similar to Zimmer and Cost, the pulse transmission system is deployed but critically the sample is not held rigid but is instead mounted on a turntable with both transducers and turntable immersed in a coupling medium, typically water.

The apparatus used by Markham is documented in Figs. 5 with 6 documenting a simplified version of the rotatable turntable system.

To avoid (as much as possible) aforementioned interactions between the wave and the fibre and to allow for the assumption of an infinite medium, similar to [20], Markham states that wavelength should be larger than fibre diameter but significantly smaller than thickness of the sample. He develops this argument further than [20] and states that given transverse and longitudinal waves having potential to travel at different speeds (Markham quotes that the potential exists for speeds to range from 1600 m s^{-1} to 12000 m s^{-1}) then to satisfy bulk wave conditions transverse and longitudinal propagation should be examined at different frequencies. The frequency for operation in this case ranged from 1.25 MHz to 5 MHz.

A pulse of 1 μs with a repetition rate of 1 kHz was selected along with a digital delay timing system, accurate to $\pm 1 \times 10^{-9}$ ns, to

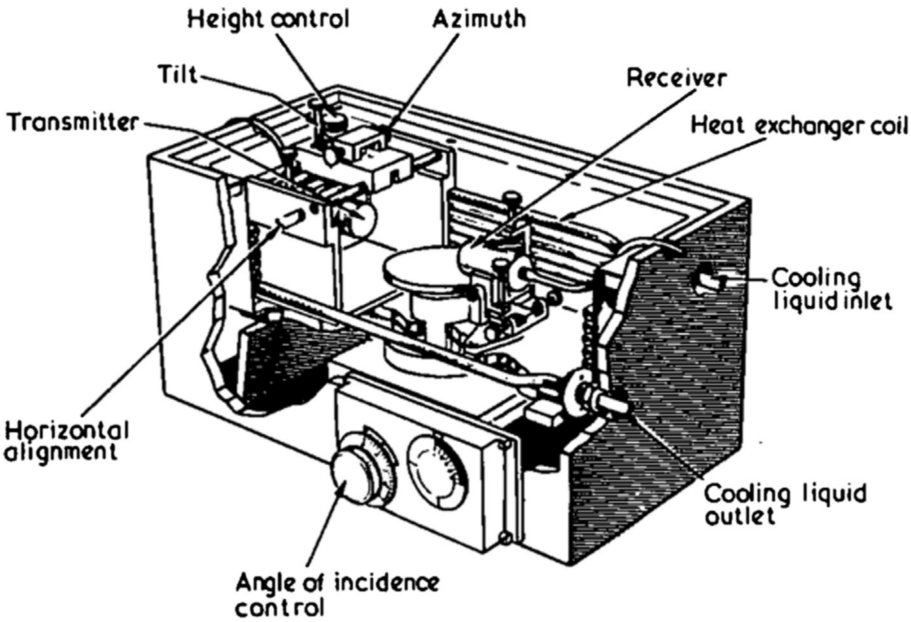

Fig. 5. General representation of the immersion based through transmission system used by Markham. *Reprinted from Composites, Vol 1/edition number 3, Markham, M. F., Measurement of the elastic constants of fibre composites by ultrasonics, Pages No 145–149., Copyright (1970), with permission from Elsevier.*

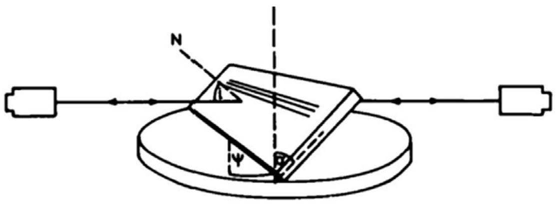

Fig. 6. General representation of transducer placement and rotatable turntable used by Markham. The sample may be rotated on two axis's to allow for waves to strike samples at varying degrees of incidence thus inducing mode conversion. *Reprinted from Composites, Vol 1/edition number 3, Markham, M. F., Measurement of the elastic constants of fibre composites by ultrasonics, Pages No 145–149., Copyright (1970), with permission from Elsevier.*

record time of flight measurements between transmitter and receiver (both with and without a sample in between). Similar to [20], the nature of the waves required in this study were (a) two longitudinal waves propagating along fibre direction and perpendicular to fibre direction, (b) two transverse waves propagating perpendicular to the fibre direction and (c) a longitudinal or transverse wave propagating at 45° to fibre direction with polarization in the plane of the fibre.

Markham also puts forward an additional technique to allow for transverse waves to propagate through a composite at normal incidence. A prism with a 90° angle is situated on the turntable with the sample bonded to one of the sides of the prism, Markham calls this side AB. When a longitudinal wave is incident at around 18° from the normal at the opposite side, Markham denotes this as BC, a transverse wave will propagate in the direction towards the bonded sample at AB. When the wave reaches the sample/prism interface, it continues (approximately) and a transverse wave is thus propagated through the sample. Under this system, the transmitting transducer doubles up as a receiving transducer given a liquid boundary being completely reflective of transverses waves. This system is shown as Fig. 7.

Along with determining the 5 independent elastic constants of the CFRP sample, via Snell's laws and the equipment in Fig. 5, Markham also investigated the variation in velocity of both transverse and longitudinal waves. When propagating both types of waves at varying angles to the fibre direction, he found that the maximum transverse and longitudinal velocities occur at about 75° and 0° to the fibre axis respectively. Note however, that further dispersion analysis following in the same vein as that considered by [20] was not conducted.

In this work, Markham demonstrated that for a single piece of unidirectional CFRP exhibiting transverse isotropic symmetry that the full set of elastic constants could be determined using ultrasound velocity measurements. Using the pulse transmission technique,

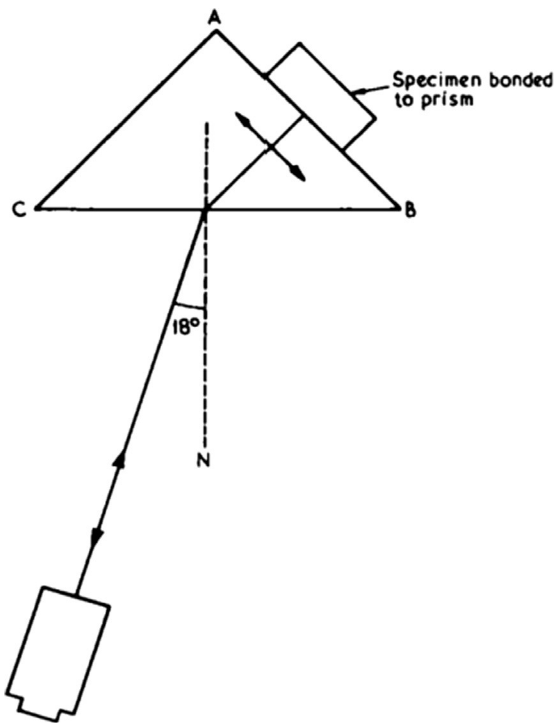

Fig. 7. A method for generating transverse waves normal to surface of a sample via a bonded prism. *Reprinted from Composites, Vol 1/edition number 3, Markham, M. F., Measurement of the elastic constants of fibre composites by ultrasonics, Pages No 145–149., Copyright (1970), with permission from Elsevier.*

the novelty in this work was through immersing both the transducers and sample in a water tank while rotating the sample. Markham also presented a method to generate transverse waves at normal incidence to the test piece using a prism.

Despite this work being trend setting, widely accessible and providing an excellent contribution to knowledge, there are drawbacks with it; (a) the specifics of the sample are not stated, (b) the specifics of angle rotation to create transverse waves are not presented (although the required equations for calculations are), (c) the equation for C_{13} is not included (the reader is left to calculate it), (d) dispersion effects are generally not considered, (e) the equipment or apparatus used is generally not discussed and (f) the values for elastic constants obtained were not cross referenced with mechanical based testing or theoretical modelling. As such, while trend setting, areas to build upon were evident.

Both Zimmer and Cost [20], and Markham [21], demonstrate the applicability of the pulse based transmission approach in determining the elastic constants of unidirectional CFRP with the techniques still used today. The remainder of this review effectively charts the progression within literature of how these methods are used to determine elastic constants and factors relating to the determination of elastic constants (for instance wave dispersion). Moving forward, this review refers to these methods as the Zimmer and Cost approach, and the Markham method (or the immersion technique).

4.3. Early works using Zimmer and Cost approach and Markham method (1970s–1980s)

Having developed the Zimmer and Cost approach and the Markham method, the next major experimental breakthrough was not until the late 1980s/early 1990s, courtesy of a technique denoted as the double through transmission technique. However, between the period 1970 and the development of the double through transmission technique, various contributions to knowledge, using both [20,21], are able to be found. These contributions are presented in this section, starting with Smith 1972, [22].

As with [21], Smith investigated the elastic properties of uni-directional CFRP (both carbon and graphite fibres used) via the pulse transmission technique. The composite properties sought by Smith being the five independent elastic constants C_{11}, C_{12}, C_{13}, C_{33}, C_{44}, the variance in the elastic constants of both graphite based fibre composite and carbon based fibre composite (noting that graphite fibres are isotropic but carbon fibre are only isotropic in direction of the fibre), the variance of elastic constants with regard to strength of fibre-matrix bond, Poisson ratio of fibres and the variance of elastic constants with fibre density and thus composite density. Table 3 outlines some general characteristics of the 13 different samples used by Smith.

Reviewing both the Zimmer and Cost approach and the Markham method, Smith opted for the Markham method to conduct this study. Smith states that although the number of modes able to be generated using the immersion technique is limited, it is still preferable to the lack of accuracy caused by alignment of the faces in relation to the fibre direction and the assumption of sample uniformity present in the multiple sample method.

The immersion technique presented is almost identical to the Markham method with the main difference being that additional transmitting and receiving transducers are arranged in parallel with the standard set up and were used to trigger the oscilloscope just prior to arrival of wave propagating through the sample. The arrangement used by Smith alongside a representation of waves propagating through CFRP is shown in Fig. 8(a) and (b).

The turntable is able to be rotated on an axis perpendicular to the ultrasonic beam with the angle of incidence variable to a resolution of 0.1°. For the immersion medium, Smith opts for distilled water, noting that a large body was used to promote thermal inertia – temperature was recorded constant to about 0.1° over several hours. Similar to previous works the frequency used in this study was in the region of 5 MHz and a Tektronix 555 oscilloscope was also used. Unlike previous works however, when selecting a transducer to act as the receiver, Smith states that a higher frequency transducer (compared to transmitting transducer) was chosen to combat fringe or resonant effects – the transmitting transducer was ¾″ in diameter and the receiving transducer was 10 MHz and ½″ in diameter.

Similar to previous work the waves used to determine C_{11} and C_{33} were both longitudinal and propagated with the ultrasonic beam both normal to and parallel to the fibre direction. The wave required to determine C_{66} was a transverse wave created in part by placing a principle axis (in this case fibre direction axis) perpendicular to ultrasonic beam direction and then rotating the sample on this axis. The propagation direction and polarization direction is not explicitly stated by Smith, however, it can be said that principle axis propagation is mentioned (angle to fibre direction stated as being 90°) and that judging by previous work and geometry of the samples, this will be in the 1–2 plane with polarization at a right angle. The two remaining constants, C_{44} and C_{13}, are said to have been created from rotating the 2 axis. Smith does not explicitly state what angle of propagation to fibre direction is used, however, it

Table 3
Adapted general characteristics of the fibre composite samples used by Smith [22].

Sample property	Information
Fibre origin	Rayon or Polyacrylonitrile (PAN)
Brands of fibre (Yarn)	'WYB', 'Thornel 25, 40, 50, 50s, 75s and 400', 'VYB', 'Courtaulds HTS' and experimental based
Sample symmetry	Samples are unidirectional transversely isotropic
Young's modulus (Fibre)	Varies from 6 to 80 × 10^6 psi
Composite density	Varies from 1.28 to 1.61 $g\,cm^{-3}$
Torsional shear strength	Varies from 4.5 to 13.8 × 10^3 psi
Fibre volume fraction (uncertainty recorded at 2%)	Varies from 0.53 to 0.64
Sample geometry	Face 10 cm^2, thickness 3–5 mm (0.5% accurate)

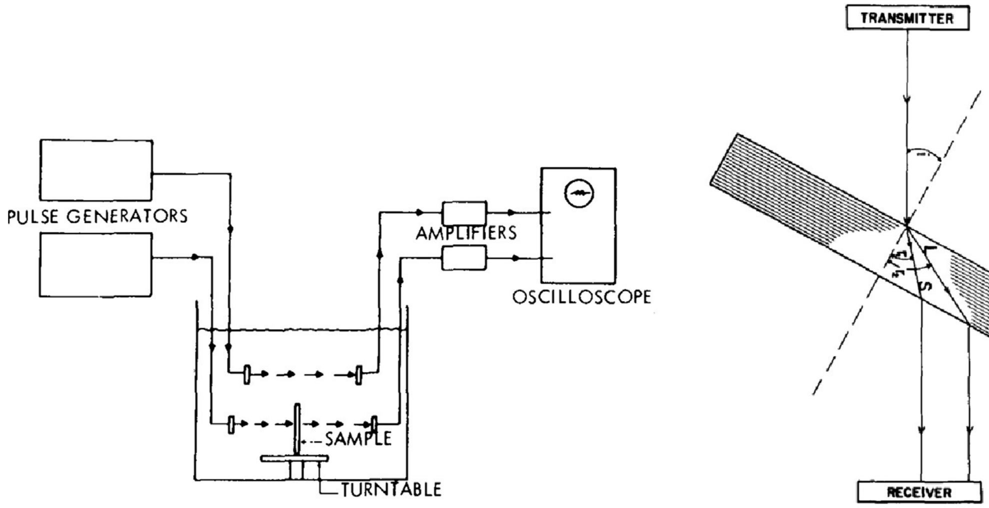

Fig. 8. Figure (a) documents the experimental arrangement as used by Smith, figure (b) documents the mode conversion process allowing both a longitudinal and shear wave to propagate through the sample when incident waves strike the surface at oblique angles. *Reprinted from Smith RE. Ultrasonic elastic constants of carbon fibers and their composites. J Appl Phys; 43: 2555–2561 with the permission of AIP Publishing.*

can be said that the equations do not allow for this angle to 90°; in the case of 90° the equations cited in text force C_{44} and C_{13} to equal 0. None the less, the full set of elastic constants was able to be determined with the equations required to do so presented in the text. Key findings recorded by Smith are presented in Table 4.

Additionally, using the composite ultrasonic velocity measurements and modelling techniques, Smith studied individual fibres and was able to determine the Poisson ratio and Young's modulus of the fibres. Smith also used small scale X-ray analysis to average the porosity for certain carbon fibre samples and sought to correct the fibre properties accordingly. Attention can be turned to text for the various findings regarding the specific differences between carbon fibres and graphite fibre elastic constants.

Further, Smith also investigated the validity of theory and essentially repeated the same experiment as conducted by Zimmer and Cost [20]; the determination of the curve associated with propagating transverse waves at angles of 0–90° to fibre direction. Note, that in reality propagation excluded 0° and 90° and only covered the angles of approximately 15–75°; it is presumably the case that accurate measurements of below 15° and above 75° were not able to be made using the immersion technique, however the author does not generally elaborate on this point. Smith confirmed the observations from [20], that C_{44} obtained from propagating a transverse wave at 90° to the fibre direction allows for better agreement between the experimental and the theoretical. Smith's experimental and theoretical result for an equation for C'_{55} (a variable presented in the text), is given as Fig. 9.

It is of merit to note however that Smith uses either a carbon fibre or graphite fibre composite (Smith does not clarify) to investigate C_{44} while Zimmer and Cost used a glass fibre composite.

With regards to the values of C_{44} not arising from 90° wave propagation, Smith, in the opinion of the current authors, is slightly ambiguous. When describing the theoretical predictions associated with using the other values of C_{44}, he states that the good agreement between the theoretical and the experimental would not have resulted if the angle of deviation changed by as much as 5° between 0° and 90°. To understand this statement, two questions are required to be answered, (1) is the value of C_{44} determined from the 90° measurement the same as the one recorded from measurement at 0°? And (2) is the value of C_{44} calculated from wave propagation at 90° successively altered by introducing progressive steps of 5° all the way from 90° to 0°, thus forcing the most accurate and inaccurate method of determining C_{44} to be 90° and 0° respectively? Going by the work of both [20] and [21], for the large part the probable answer to question (1) is no and the probable answer to question (2) is in general yes (note, that the most

Table 4
Key findings on the composite level, adapted from results by Smith [22].

Key findings (composite level)	
Accuracy of result	C_{11}, C_{33}, C_{44} and C_{66} recorded as ± 3%, C_{13} recorded as ± 20%
Impact of fibre Young's modulus	C_{11}, C_{33} and C_{66} dependent on Young's modulus. C_{13} and C_{44} independent of fibre modulus but varied with fibre type for graphite fibres and were unclear for carbon fibres
Impact of shear strength (used to evaluate fibre-matrix bond)	Constants do not greatly depend on shear strength
Differences between constants of graphite fibres and carbon fibres[a]	C_{11} and C_{66} differ greatly for graphite and carbon fibres. Carbon fibres being 10s of percent higher than graphite counterparts

[a] When elastic constants normalised to the same fibre loading, the difference between elastic constants was found to be as a result of the difference in properties of fibres and not through loading effects.

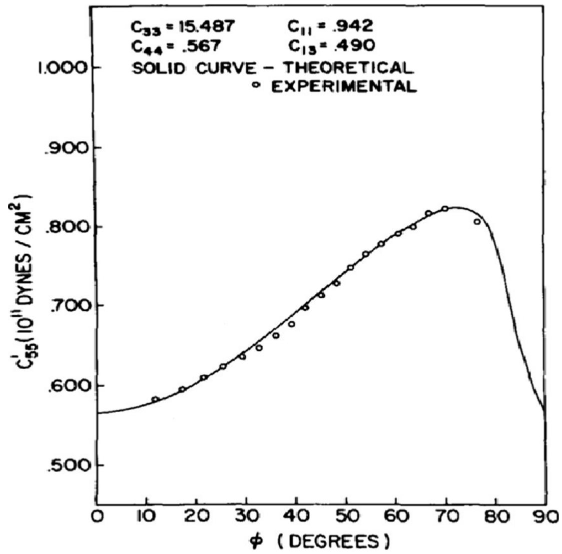

Fig. 9. Documenting the findings from Smith that a close relationship to the theoretical is recorded using the C_{44} value obtained from propagating a transverse wave at 90° to fibre direction. Note that the variable C'_{55} used by Smith was dependent C_{11}, C_{13}, C_{33} and C_{44}. *Reprinted from Smith RE. Ultrasonic elastic constants of carbon fibers and their composites. J Appl Phys; 43: 2555–2561 with the permission of AIP Publishing.*

inaccurate measurement may actually result from 15° to fibre axis and that at 0° and 90° the velocities may be far more closely related). Further, although C_{44} was calculated at 90° for the theoretical experiments by Smith, Smith also states that C_{44} was calculated using an equation which does not permit C_{44} to be calculated at 90°. To help in this regard, adopting a similar approach to that of [20], i.e. documenting more than one value of C_{44}, or indeed taking a new approach and presenting the determination of C_{44} as a function of propagation angle to fibre axis would have been of considerable merit.

Similar to previous authors Smith obtained the full set of elastic constants for transversely isotropic material. Smith took the previous work further, in that he found that ultrasonic velocity measurements could be used to determine not only the elastic constants outright but also their dependence on (a) the fibre Young's modulus and (b) the fibre matrix bond, while at the same time comparing both graphite fibre and carbon fibre based composite. Further, Smith demonstrated that modelling could be used to theoretically predict the fibre engineering constants such as Poisson ration and fibre modulus. Additionally, the elastic constants were shown that they could be corrected for porosity.

Smith comprises a solid and comprehensive body of work that clearly outlines the applications of simple velocity measurements. It is also the case that improvements could have been made to this paper; quasi-wave analysis was not generally discussed, certain propagation directions for waves (corresponding to C_{44} and C_{13}) were ambiguous and the method of determining C_{44} could have been presented better to provide more clarity on the issue. Lastly, Smith mentions that a higher frequency transducer was used as the receiver to combat any fringe or resonant effects but does not quantify or discuss the implications of these effects in the text.

Moving forward, in 1973, Dean and Lockett, [23], further investigated the applicability of ultrasonic velocity measurements with regards to CFRP. The authors demonstrated that not only could the full set of elastic constants be determined, but also discuss the applicability of using ultrasound to identify and quantify specimen homogeneity, symmetry, degree of fibre misorientation, viscoelastic properties and associated theoretical problems (note defect detection is also discussed but this generally does not concern velocity measurements in this context).

The samples used by the authors were quoted as being transversely isotropic high modulus carbon fibre reinforced epoxy with a front surface of 18 by 11 mm and a variable thickness of 12 mm, 5 mm, 2.6 mm, 2 mm and 1.6 mm. Sample densities were quoted as 1.668 $g\,cm^{-3}$ for 12 mm sample and 1.670 $g\,cm^{-3}$ for the remaining four samples.

The approach taken by Dean and Lockett was the Markham method using in fact, the same type of equipment. That is, at the time of respective publications Dean and Lockett and Markham both worked and conducted experiments at the National Physics Laboratory (NPL) in Middlesex, England; Figs. 5 and 6 outline the measurement apparatus. Additional experimental information not supplied by Markham, [21], but supplied by Dean and Lockett is that the angle of incidence may be varied by ± 0.1° precision and that the initial alignment of the specimen, relative to the turntable, has ± 0.5° and ± 0.1° precision for the 1.25 MHz and 5 MHz transducers respectively. Additionally, the speed of longitudinal waves in the immersion liquid (presumably water, not explicitly stated) was taken from tables and not verified through experiment, density was taken from measurements conducted in both air and in water and the total experimental time per sample was approximately 30 min (with the data analysis performed on a computer).

Similar to Markham, Dean and Lockett documented the variation in velocity changes with respect to angle of propagation in the plane containing fibre direction while also offering further discussion on C_{44}. They state that C_{44} is not able to be measured directly from experiment (90° velocity is different than 0° velocity) and in a similar but not identical way to Zimmer and Cost [20], Dean and Lockett, further provide discussion on extrapolating C_{44} from experimental results.

The authors recorded the elastic constants and a standard deviation; C_{11} and C_{22} recorded as less than ½ %, C_{44} and C_{66} recorded less than 1% with C_{12} being recorded as uncertain. These results provide an improvement on those outlined in Table 2, although [20], did not use CFRP. The omission of an uncertainty value for C_{12}, by Dean and Lockett was based on the premise that a quasi-transverse wave, polarized in the plane of the fibre, has no direction of propagation in which the velocity dependence on C_{12} is significant. Thus, to gauge the accuracy of C_{12} then extremely accurate measurements of the other required constants (noting that quasi-waves are typically dependent on multiple constants) would be required. This is similar to findings that one draws from Markham [21] who also allude to this fact.

Building on the concept of accuracy, it was highlighted by the authors, that while accuracy of result typically relies on the angle of incidence or the measuring equipment, in reality the accuracy is often limited by the quality of the sample, (localized areas of voids, dissimilar fibre alignment and packing sequence all playing a role). It was also reported by the authors, as verified through experiment and similar to [20], that the thickness of sample did not generally play a significant role in velocity measurements; very little changes in C_{11}, C_{22}, C_{33} and C_{44} were observed when reducing the sample thickness – plane body wave behaviour was assumed, i.e. specimen dimensions were kept above two wavelengths.

Further, the authors also found that when propagating waves in the fibre direction that even if the thickness was comparable or perhaps less than pulse wavelength, no significant pulse distortion occurred. Coupling this with the fact that the velocity difference between body waves and waves in proximity to a free surface was found to be around 1%, Dean and Lockett found that data relating to mode changing as the sample thickness was reduced was inconclusive.

Additionally, Dean and Lockett discussed areas only inferred by preceding authors. While Smith [22], presented findings on the relationship between fibre content and elastic constants, but focused more on gauging Young's modulus, Dean and Lockett investigated the variation in elastic constant with fibre volume content – noting that significant scatter (inferring void content) was present in some results.

Further, the authors also reported a method of determining homogeneity by conducting measurements along the same axis but at different points of the sample while also reducing the beam size. The authors state that variations in velocity when propagation is along the fibre axis in unidirectional fibre are indicative of localized variations of fibre content and alignment. Expanding on this, the authors cite earlier work, [24], that sought to determine the elastic moduli of disorientated fibres in composite. The authors also put forward a strategy for gauging the material symmetry through the use of velocity surfaces and crystallographic theory and also conducted a brief analysis of the viscoelastic properties of composites – both areas not touched upon by preceding authors reviewed at this point.

Dean and Lockett, conducted similar tests to those of Markham and presented additional information relating to the test apparatus. The full set of elastic constants were determined with good degree of accuracy, however, unlike previous works, the authors failed to present accuracy statistics for C_{12}. Also, in addition to earlier work the authors documented that C_{44} was only able to be inferred from velocity measurements; based on collective finding between publications it can be said that the correct value of C_{44} is the value associated with waves at 90°. Dean and Lockett also discussed the applicability of using ultrasound to investigate fibre orientation, viscoelastic effects and symmetry, aspects which are only inferred by other authors. There is however, generally no significant investigation or findings presented in this work regarding these concepts (excluding the references cited), but applicability was stated none the less.

At this point, a sidestep back to 1971 to review Dean [24], is appropriate. This work covered both the immersion technique and the development of a model to investigate disorientated fibres. As Dean only presents a general overview of the immersion technique as used by Markham, [21] and not generally any significant findings such as the mathematical framework, the decision was taken to first establish the velocity based elastic constant determination techniques from literature prior to evaluating the disorientation model in this work. Also, while the disorientation model falls outside the scope of this review, determining the elastic constants of a composite rely on correct fibre orientation and so the decision was taken to review this work.

Taking into account that on occasion that fibre direction may be designed to deviate from uniaxial and instead be designed to meet the requirements of a particular load; Dean investigated the applicability of using velocity measurements to determine the degree of fibre orientation for a given CFRP test piece. The fundamental premise presented in this study is to develop a so called orientation function, that is, if the standard method to determine elastic constants is performed on a uniaxial test piece (aligned and misaligned), the constants could then be compared and be related through fibre orientation functions.

To establish the orientation function, Dean documents a simple model of a short chopped transversely isotropic composite fibre in which the composite is broken down into individual elements – noting that each element contained a single fibre surrounded by an irregular prism of matrix. Each element was perfectly bonded together (no voids) and thus a model composite was visualized as comprising individual elements – noting that each element recorded identical elasticity around the fibre axis. On a composite level Dean selected the 3 axis as the axis of preferred direction and on an individual cell basis the 3 axis was also the axis of fibre direction.

Having established the specimen geometry, to define the elastic constants, in terms of the coordinates used to define a particular cell, the constants of a cell were rotated through angle θ. Thus a new constant, which is generally dependent on more than one original constant, was provided and so the elastic constants of a cell were able to be expressed in terms of the elastic constants of the specimen via a directional cosine relationship. It is of merit to note that in this model, disorientation is recorded in only one plane (1–3), hence only one elastic constant rotation was required in this instance. Having shown that a single cell was able to be expressed in terms of the elastic constants of the specimen, the next stage was to present the complete set of elastic constants for the specimen in terms of the total contribution from all cells.

To achieve this, the elastic components of the specimen were taken as an average with an assumption that for a given stress, each unit will experience identical strain. Obtaining the average elastic constant value (mathematically) was done by expressing a single cell in terms of the elastic constants of the specimen and then using the average value for angle of deviation to provide the average value of specimen elastic constant. Dean expresses θ in terms of a normalised probability distribution (noting the probability between 0 and π was equal to 1) and so was able to present the complete equation set required to determine the average elastic constants of the specimen in terms of an individual cells elastic constants and the average value of the directional cosines.

Further, if the elastic constants of an individual cell are equal to those of a continuous homogeneous transversely isotropic fibre sample with no voids, then the equations presented by Dean, relate the elastic constant of disorientated fibre to the elastic constants of uniaxial fibre multiplied by the average directional cosines, noting that these cosines are now referred to as orientation functions. It is also of merit to note that although 5 orientation functions exist, only two are required (the law of cosines allows the remainder to be determined).

Testing the hypothesis, the technique adopted by Dean was the Markham method, noting that both the standard rotation technique and the prism technique were adopted. The chopped fibre specimens were rectangular samples with the long axis being either perpendicular or parallel to preferred fibre direction. The dimensions (length, width, breadth) of the samples were recorded as being approximately 5 by 1 by 0.08 cm or 8 cm by 1.3 by 0.15 cm. Fibre volume fraction for the chopped fibre samples was recorded as approximately 40%, however, a similar continuous composite (required to determine unidirectional elastic constants) was not able to be located and so various samples with degrees of fibre volume fraction were selected and extrapolated to 40% fibre fraction. The results obtained by Dean infer that the samples used in this study were highly orientated (values approaching 1 were recorded for orientation function) principally because C_{33} was recorded as being almost equal to that of continuous fibre, and that the main factors affecting C_{33} are fibre volume and orientation.

Dean, [24], documents an interesting body of work with the average elastic constants for a disorientated transversely isotropic CFRP (disorientation in one plane only) able to be determined. Areas of improvement however, can be found – samples used in this study were of particular dimensions and quality and so when determining the elastic constants of the thinner samples of chopped fibre, it was not possible to successfully propagate a bulk wave in the 1 direction thus C_{11} could not be determined. Also, for certain chopped fibre samples only C_{33} from longitudinal wave propagation was able to be recorded. Continuous fibre samples were also recorded as being poor quality such that, C_{44}, C_{22}, C_{55} and C_{66} were not able to be accurately reported, with C_{44} being determined through a theoretical model. Additionally, C_{66} in some cases was not reported at all and in other cases was determined using the lower accuracy prism technique.

It is also noteworthy to highlight the subtle difference between findings from this text and that from Zimmer and Cost, [20], who reported findings on Young's modulus in terms of fibre orientation. The key difference is that Zimmer and Cost used uniform crystal disorientation as a function of Young's modulus but Dean presented the average elastic constants (elastic constants may be used to determine Young's modulus) as a function of the average disorientation of an individual cell. The system presented by Dean is probably more realistic in that all fibres would likely not be orientated in exactly the same direction, but it is no means the finished article. For instance, disorientation in only one plane is considered, the chopped fibres samples considered were highly orientated and only the average elastic constant (as opposed to a say a standard deviation from true value) of the specimen is presented.

Moving forward to 1974, Wilkinson and Reynolds, [25], sought to further investigate the propagation of shear and longitudinal waves over multiple directions in a unidirectional composite. Although previous work, [20], had shown that dispersion phenomenon effects shear and longitudinal wave propagation to different degrees depending on angle of propagation to fibre direction in glass fibre based composite, Wilkinson and Reynolds sought to better understand this process on CFRP. The authors state that previous work, [26], suggested that internal reflections may interfere with longitudinal wave propagation and alter velocity, thus in this text, shear and compression waves were propagated in various directions with action taken to reduce internal reflections as best possible.

The sample used by Wilkinson and Reynolds was a high modulus unidirectional fibre based composite in the shape of a disk of 140 mm in diameter, 23 mm in thickness, 57% fibre volume and $1.62 \times 10^3\,\mathrm{kg\,m^{-3}}$ density. The transducers used were two cylindrical piezoceramic probes with frequencies of 0.5, 1.25 and 2.5 MHz. Shear waves propagation was achieved through the immersion technique and also a slight variation on the prism technique as demonstrated by [21] (noting that Wilkinson and Reynolds denote this prism techniques as the angled probe approach) and also by adopting the Zimmer and Cost approach. Thus shear waves were able to be propagated at various angles to fibre direction and polarized in the plane of the disk and normal to the plane of the disk. Longitudinal waves were propagated using the angled probe approach; namely, a shoe prism (concave) bound to the disk and transducer using glycerine. Fig. 10 outlines the general composite and typical wave propagation direction to fibre axis arrangement in this work.

As expected, a full set of elastic constants was recorded by the authors. C_{11} and C_{33} were recorded through longitudinal waves while C_{44}, C_{66} and C_{13} were recorded through transverse waves – noting similar to previous work the authors encountered a degree of difficulty in accurately measuring the known problematic elastic constant, C_{13}. Similar to [22], the expected curve outlining the variance in elastic stiffness in relation to the angle of fibre direction to propagation (i.e. 0–90°) was also produced. Similar to what was demonstrated by Smith [22], out with 0° and 90° only the angles of approximately 15–75° were able to be recorded accurately. In this instance, the authors provide no discussion on the potential error in C_{44} with regards to which angle of propagation to fibre direction is selected; going by previous works however, the value of C_{44} used by the Wilkinson and Reynolds was most likely the more accurate value derived from propagating the transverse wave perpendicular to the fibre axis.

Also, the theoretical prediction of the other transverse wave (polarized at a right angle to the plane of the fibre) was also produced in this work. The authors found good agreement with the expected behaviour based on theoretical predictions from Musgrave [18], thus confirming a tacit implication from the work of Smith [22]; the predictions from Musgrave are able to accurately describe the associated elastic stiffness recorded when propagating a transverse wave polarized in the plane of the fibre at an angle between 0 and 90 degrees.

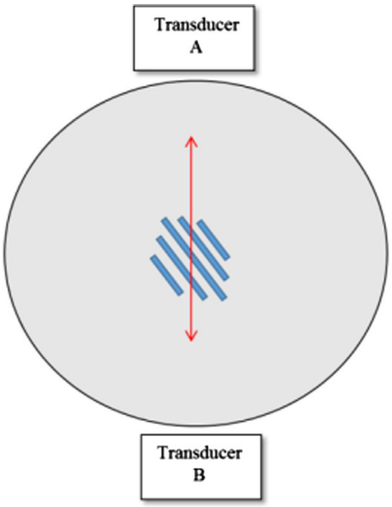

Fig. 10. The sample and fibre direction for a stationary and rotated case is shown. The arrow indicates direction of wave propagation. Smaller non diameter (chord) paths were also used and compared with longer paths to eliminate effects of internal reflection.

Looking now at longitudinal waves, typically used to determine C_{11} (propagated at 0 degrees to fibre direction) and C_{33} (propagated at 90 degrees to fibre direction), Wilkinson and Reynolds documented that the theoretical predictions by Musgrave are insufficient to accurate describe the elastic stiffness associated with longitudinal wave propagation between 0° and 90°. They found, that out with 5° of principal axis (i.e. between 5° and 85°) the associated elastic constants lie between the rotated Young's Modulus (values calculated from using the elastic constants presented in text) and the Musgrave theoretical values for the expected curve (again calculated using the elastic constants presented in text). The authors also documented that the experimental elastic stiffness followed a pattern similar to the rotated Young's modulus and not the curve predicted by Musgrave. Fig. 11 documents the findings from Wilkinson and Reynolds for both the transverse and longitudinal wave propagation to fibre axis.

Regarding the longitudinal wave analysis, the conjecture put forward by Wilkinson and Reynolds was that while Elliot [27] demonstrated via a goniometer technique that the existence of a quasi-longitudinal wave, predicted by Musgrave, is present within

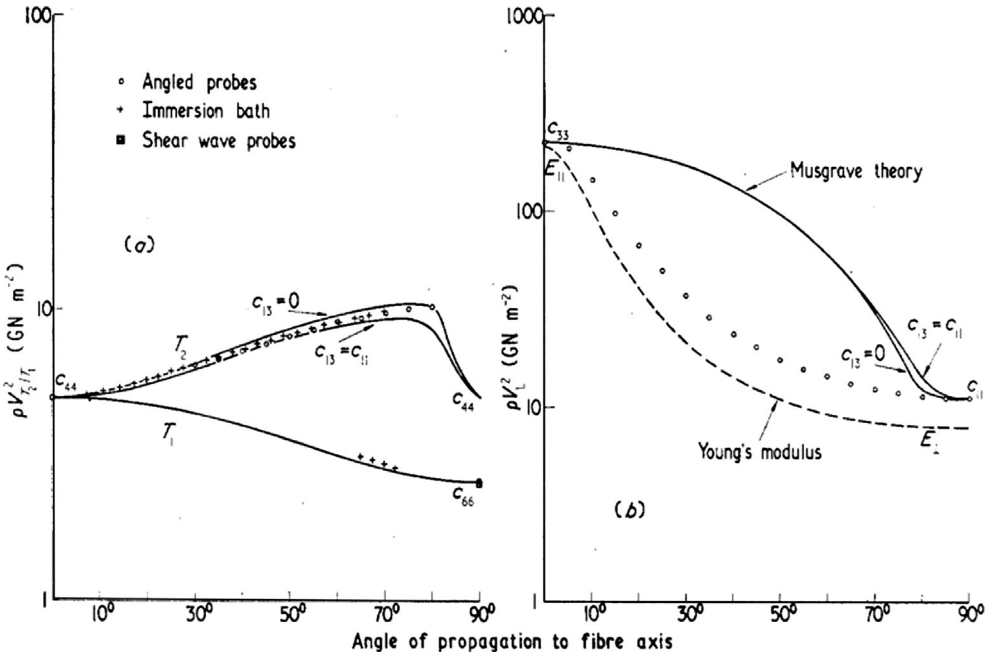

Fig. 11. Figure (a) documents the transverse wave with the solid line being theoretical predictions, figure (b) documents the longitudinal wave, which may be observed to deviate away from Musgrave predictions towards rotated Young's Modulus values. *Wilkinson SJ, Reynolds WN. The propagation of ultrasonic waves in carbon-fibre-reinforced plastics. J Phys D Appl Phys; 7: 50–57,*

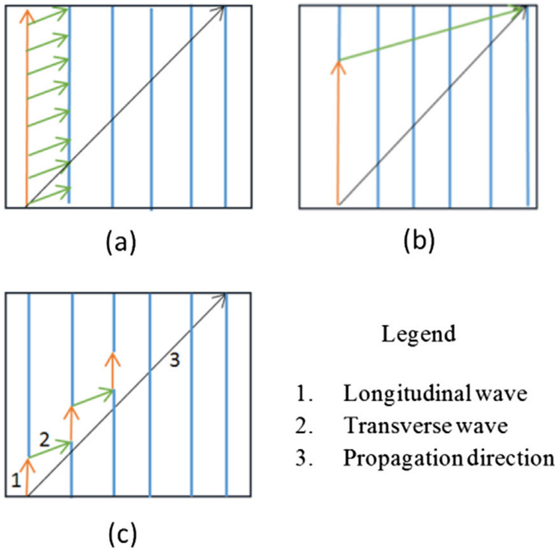

Fig. 12. Figure (a) documents longitudinal waves in fibre direction causing transverse waves at 80° which in turn cause new longitudinal waves in adjacent fibres. Figure (b) documents overall propagation path consisting of both longitudinal and transverse waves. Figure (c) documents wave conversion as given by (a) is a continuous process.

the material, the wave recorded in their experiments was not the same quasi-longitudinal wave. That is, the wave recorded when conducting through transmission experiment is not the Musgrave wave, which quickly attenuates, but instead is another slower wave manufactured within the CFRP sample as a result of the shear bonding of matrix to the fibres; this is denoted by Wilkinson and Reynolds as a pseudo-L wave (noting, that L is previously used by the authors to denote quasi-longitudinal).

The explanation of how this wave originates was put forward as follows. Any disturbance at a fibre end causes waves (longitudinal) to propagate along the fibre direction with little attenuation (assuming no changes in fibres structure) occurring. As a result of the high shear bonding of the fibre to the matrix however, the fibres act in this instance as a source of transverse waves – propagated typically at around 80° (this angle recorded in text as producing the fastest velocity of shear waves). These new transverse wave fronts cause adjacent fibres to experience longitudinal waves by reconversion and so the pattern continues producing a somewhat 'zigzag' propagation pattern. Fig. 12 is given to assist in demonstrating this type of wave.

To demonstrate the pseudo-L wave effect, the authors conducted two experiments; the first experiment incorporated similar samples in the shape of disks with and without a hole excised from the middle and the second experiment involved the transmission of shear waves, converted from longitudinal waves, using CFRP as a mode convertor into a sheet of metal.

The first experiment found, that for angles of propagation to fibre direction of approximately 25–65° the theoretical prediction (presented in text by the authors) is in keeping with experimental measurements. The study also found that for angles outside this range, the experiments deviated more from the theoretical predictions owing to the hole excised from the sample, thus confirming the hypothesis presented. Fig. 13 documents the results.

The second experiment demonstrated that CFRP could be used as a reliable converter of longitudinal to shear waves and thus the shear modulus of the metal could be determined. That is, a longitudinal and shear wave could both be propagated within the metal provided (only in the case of the shear wave) the CFRP acted as a convertor.

Multiple contributions to knowledge were recorded by Wilkinson and Reynolds. In the case of shear wave propagation, the theoretical predictions from [18] were found to be an accurate way to predict the associated stiffness when propagating waves in directions ranging from 0° to 90° within CFRP. In the case of the through transmission based generation of longitudinal waves, the Musgrave prediction was found not to always hold (the quasi-wave attenuates) and the hypothesis of a pseudo-L wave, comprised of both longitudinal and transverse elements, was put forward. This wave was experimentally verified with the authors also noting that CFRP could act as a reliable convertor of longitudinal to shear waves. This work is also the first recorded to state that the known problematic constant of C_{13} is best recorded using the angled probe, noting that rotation system and direct wave analysis were also both used.

However, limitations are also present within this text. For instance, previous works such as [20], are not referenced or discussed, thus no acknowledgement or comparison of the work shown in [20], which demonstrates that in the case of longitudinal propagation in glass fibre composite, experimental results are much more closer aligned to the theoretical predications put forward by [18] or [19]. It is also the case that Wilkinson and Reynolds could have been clearer on problems associated with determining C_{44} (text documented the value at 0° was the same as the value at 90°, which presumably indicates the 0° measurement is fitted or is extremely close to the 90° measurement).

Wilkinson and Reynolds present a good body of work but also missed out an opportunity to seriously build on previous works. It was not at all mentioned by Wilkinson and Reynolds that previous studies all used transverse (and not longitudinal waves) to

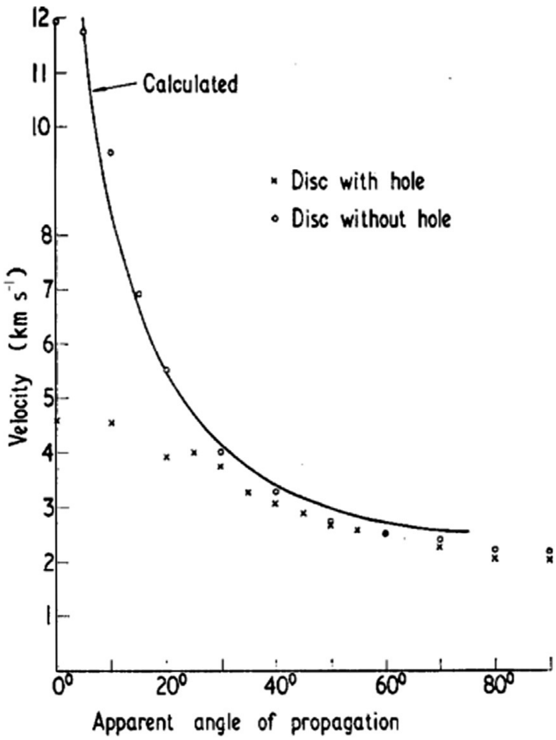

Fig. 13. Variation from theoretical for longitudinal waves in composite disk with hole excised is notable for propagation to fibre direction angles outside of around 25–65°. *Wilkinson SJ, Reynolds WN. The propagation of ultrasonic waves in carbon-fibre-reinforced plastics. J Phys D Appl Phys; 7: 50–57,*

determine off axis constants. However, Wilkinson and Reynolds did present the issues concerned with longitudinal propagation in off axis directions within CFRP, ultimately developing more knowledge on the subject matter.

Moving forward, the hitherto largely ignored (by this review) issue of composite porosity and fibre content is discussed; specifically, an investigation on how to obtain reliable information on the degree of porosity and fibre volume using existing techniques is reviewed. As stated in Table 1, these areas generally fall outside the scope of this review, however it has at this point been documented that elastic constants are directly related to velocity measurements as so relating fibre content and porosity to velocity measurements is thus of interest and therefore is briefly discussed – the particular publication of interest being Reynolds and Wilkinson [28]. Consideration was given to discussing previous works on ultrasonic voids and fibre fraction in CFRP, namely [29–32] however the decision was taken to review [28] only; principally because [28] builds on these previous works and that ultrasonic void content and fibre fraction, while important for the role it plays on elastic constant quantification, is not strictly the object of this review.

Reynolds and Wilkinson highlight that effective ultrasonic attenuation measurements such as C-Scan have been put forward as a means to identify voids within a composite; however, the authors further state that while these methods are able to identify porous regions, they are not really suited for quantifying void effects – for instance the size, shape and distribution of voids can affect the shear strength in various ways. In this work, Reynolds and Wilkinson build on the works of Boucher, [33,34], who presented equations to determine the elastic constants of an isotropic matrix which contains voids – by applying the existing theoretical predictions to analyse CFRP which may contain voids.

The sample under study was quoted as uniaxial orthotropic sections – the idea being that more complicated composites could be created from these sections, should one wish to expand on this work. Transverse isotropy can be considered a special case of orthotropic material in that a plane of symmetry exists which is perpendicular to fibre direction; for orthotropic material this does not exist and so orthotropic material has 9 elastic constants and not 5. Both glass fibres and carbon fibres were used, the results from the glass fibre analysis will be largely overlooked given the scope of this review.

Two varieties of both carbon fibres and epoxy resin were quoted by the authors, thus four different CFRP composites were documented, each having up to 25% of its matrix presenting as randomly distributed spherical voids.

The elastic constants, fibre and matrix density alongside fibre volume fraction of the composite were used by the authors to form theoretical predictions of the velocity. In the fibre direction the predictions indicated that (a) velocity varies noticeably for a change in volume fraction (0–70%), (b) the effect of matrix porosity is not considered to impact the velocity greatly and (c) the velocity has only a small dependence on the type of resin used.

When studying wave propagation perpendicular to the fibres, the authors recorded a not so straight forward relationship – wave propagation in this direction is generally dependent on both porosity of the matrix and the fibre concentration. Using the matrix shear

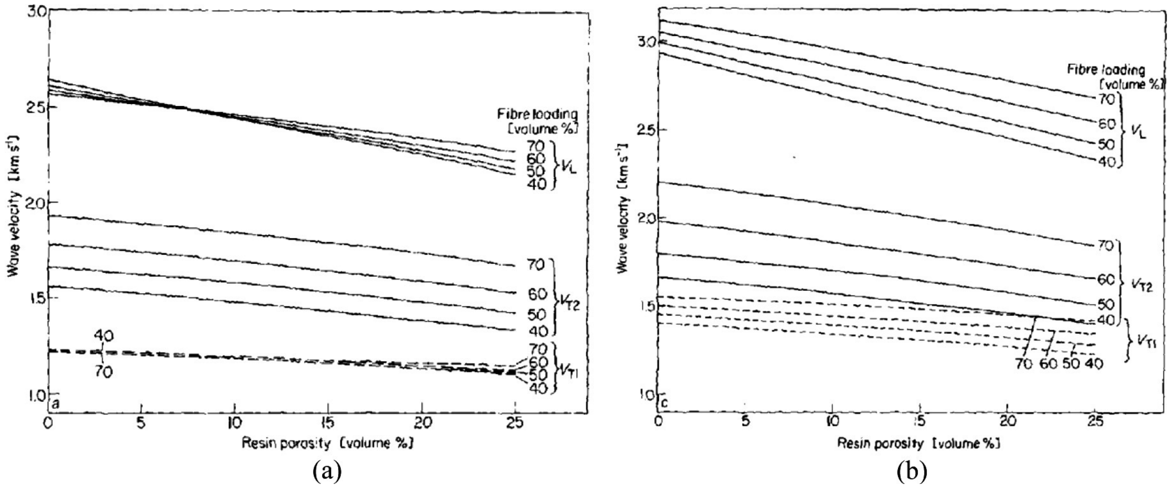

Fig. 14. Figure (a) documents the variance of velocity with regards porosity content and fibre volume fraction for type 1 fibre using ERLA 4617 resin. Figure (b) documents the variance in velocity with regards porosity content and fibre volume fraction for type 2 fibre using ERLA 4671 resin. *Reprinted from Ultrasonics, Vol 16/edition number 4, Reynolds WN, Wilkinson SJ The analysis of fibre-reinforced porous composite materials by the measurement of ultrasonic wave velocities, 159–163., Copyright (1978), with permission from Elsevier.*

and bulk modulus along with the composite density the authors demonstrate that in the case of longitudinal and transverse waves, polarized in the plane of the fibre, the porosity had more effect on the velocity than did the fibre volume. The opposite relationship (not directly polar) was found for transverse waves polarized perpendicular to the plane of fibre in that the fibre volume had more of an effect than did the porosity content. It was also found that the relationship between longitudinal waves and transverse waves (polarized in the plane of the fibre) for type 1 and 2 fibre was not identical, thus, a generalised relationship between two sets of waves was not able to be established, indicating that effects were to some degree fibre specific. Fig. 14(a) and (b) documents these findings from [28].

Reynolds and Wilkinson also conducted similar experiments to those conducted previously on CFRP on GFRP. For transverse waves the results produced a better fit to the theoretical, for longitudinal waves the results provided not such a good fit to the theoretical – some direct contact measurements were recorded far exceeding the boundary limit of C13 = 0. These results are similar to what was recorded in [25] in that the Musgrave wave was attenuated strongly and wave propagation resulted due to both

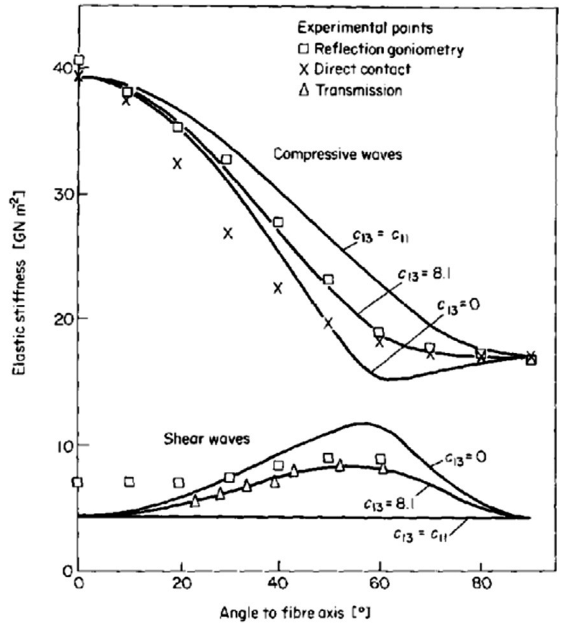

Fig. 15. Variation of stiffness with reference to propagation to fibre direction for both shear waves and longitudinal waves propagating in GFRP. *Reprinted from Ultrasonics, Vol 16/edition number 4, Reynolds WN, Wilkinson SJ The analysis of fibre-reinforced porous composite materials by the measurement of ultrasonic wave velocities, 159–163., Copyright (1978), with permission from Elsevier.*

longitudinal and transverse motion. It should be mentioned that although similar results to that of CFRP were recorded in this study, the variance of the experimental from the theoretical appears to be smaller for glass fibre based composite. These results are given as Fig. 15.

Reynolds and Wilkinson outlined theoretical predictions which allow for the porosity and the fibre volume content to be evaluated when propagating ultrasonic waves in uniaxial composite material. Thus, a key aspect missing from previous reviewed works was addressed i.e. along with elastic constant determination, velocity measurements may also be used to indirectly monitoring the CFRP production process (for example, poor production processes can potentially result in more porous materials).

Draw backs with this study include a lack of experimental work to (a) demonstrate the theoretical predictions are correct (Boucher previously carried out experimental work but not on CFRP) and (b) to provide information on the role porosity plays on the composite elastic constant values (granted, that having shown the velocity this could be worked out if the composite density was known). Additionally, in the case of off axis longitudinal wave propagation there is no quantitative analysis between glass fibre composite and that of CFRP. The inclusion of additional information, would have (a) presented the differences in longitudinal wave propagation effects for the two materials more clearly and (b) built on the work of [20] – who stated that more research should be geared towards dispersion effects associated with off axis propagation of waves.

The next study reviewed, and the last from the 1970s, is Kriz and Stinchcomb [35]. The text is similar to [28], in that calculations relating to fibre volume are used to determine properties of composite with an additional novelty being the exploitation of one of the many seminal theoretical works by Hashin, namely [36].

The authors manipulated the Hashin equations and wrote these in terms of the composite material properties, such as Young's modulus, shear modulus and Poisson's ratio. Using an already existing ultrasonic data set from [29] – those authors calculated the elastic constants of transversely isotropic material – and through curve fitting Kriz and Stinchcomb found that all fibre properties, matching those of [29], were able to be determined – assuming the fibres were transversely isotropic.

The second contribution to knowledge, having shown that the Hashin equations are suitable to allow for extrapolation of fibre properties, is to use them to determine composite properties. Thus Kriz and Stinchcomb perform ultrasonic velocity measurements and compare the results to those as predicted by the standard (non-manipulated) Hashin equations. The nature of the experiment work conducted was closely aligned to that of [20], noting this text is not cited by the authors, in that the sample was bonded to a receiving transducer and a transmitting transducer (through an additional buffer block). This transducer arrangement used by the authors is given as Fig. 16.

The authors created six samples, with each sample having a different angle between the sides of the composite and fibre axis. The transducers quoted for longitudinal and transverse waves were Panametric M110 and V156 respectively with the frequency recorded as being the standard 5 MHz used within academia. By propagating a wave through the arrangement in Fig. 16 and through a buffer block only (sample removed) and comparing the two results, the time taken for the waves to travel through the specimen was determined.

The authors recorded the full set of elastic constants using this technique. Note however, the authors reported that different values of C_{44}, C_{55} and C_{66} were recorded along with documenting accuracy issues for C_{23}, $C_{12,}$ and C_{13}. When presented with different values of C_{44}, C_{55}, and C_{66}, in this case arising from non-identical density and fibre volume fraction, the values which provided the closest theoretical results were used to calculated constants C_{23}, C_{12} and C_{13} – note however Kriz and Stinchcomb do not enter discussion as to why differences were recorded in elastic constants to the same depth as earlier authors such as Zimmer and Cost [20]. Upon using the standard (non-modified) Hashin equations, the authors found that through knowledge of fibre properties, matrix properties and fibre volume fraction, the Hashin equations were in good agreement with the experimentally determined elastic constants.

At this stage, the relationship between phase velocity and group velocity and how this impacts on the potential thickness of a sample has generally not been considered by the works reviewed thus far. Kriz and Stinchcomb provided discussion on this matter. Kriz and Stinchcomb identified that potential exists for transversely isotropic material to cause wave energy to deviate from the wave normal to the extent where the receiving transducer would have to be moved in order to accurately receive the transmitting wave – essentially the group velocity effect. Using an existing equation set from previous work by the author's, Kriz and Stinchcomb calculated the wave energy deviation for wave propagation 45° to the fibre direction. The results are demonstrated in Fig. 17.

Taking group velocity effects in consideration the thickness of the samples was designed to be within limits such that wave energy deviation effects were kept to a minimum – equations provided by the authors allowed for the maximum and minimum thickness to

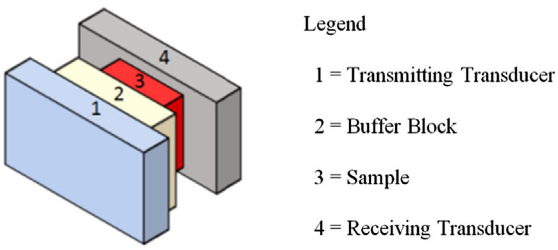

Fig. 16. The transducer and sample arrangement used by Kriz and Stinchcomb is presented. The arrangement is effectively the Zimmer and Cost approach with the inclusion of an additional buffer block (included by the authors to combat any potential pulse transmission reflection cross over issues.)

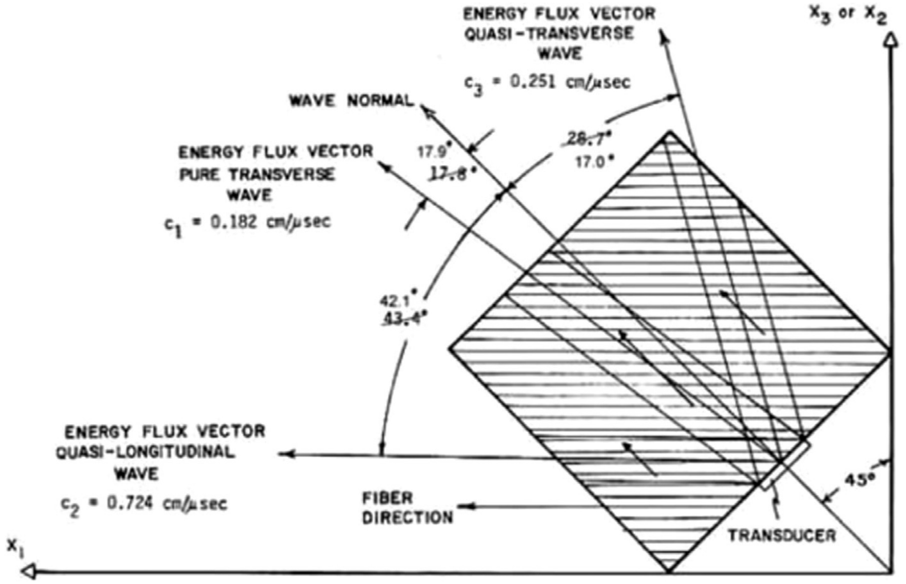

Fig. 17. Group velocity effect for three different types of wave propagating at 45° to fibre axis. Direction of pure transverse records an angle deviation of 17.9° from wave normal. Direction of quasi-transverse wave records angle deviation of 17° from wave normal. Direction of quasi-longitudinal wave records angle deviation of 42.1° from wave normal. *Experimental Mechanics, Elastic moduli of transversely isotropic graphite fibres and their composites, 19, 1979, page 41–49, Kriz RD, Stinchcomb WW, With permission of Springer.*

be calculated. Only 2 out the 6 samples used by the authors showed deviation effects and so 2 samples only were confined in relation to the amount of thickness.

Kriz and Stinchcomb demonstrated that the full set of elastic constants of transversely isotropic graphite fibre could be found from using (potentially in harmony) both ultrasonic velocity measurements and by using both modified and original equations of those by [36]. That is, knowledge of fibre properties, matrix properties and fibre volume fraction has been shown to allow for a good theoretical prediction of composite properties. Kriz and Stinchcomb point out that the known problematic constants, C_{12} or C_{13}, are thus able to theoretical determined – the authors do not validate the accuracy of result however.

Concerning the group velocity effect identified by Kriz and Stinchcomb, it is of interest to note that no preceding author in this review who investigated dispersion effects when propagating waves in non-axial directions has discussed the group velocity effect. This is because (a) none existed, (b) the thickness of sample is coincidentally in the correct region to significantly minimize the effect or (c) effects were counted under the general term of 'dispersion effects'. Note in this instance that Kriz and Stinchcomb did not discover group velocity effects in general; when working on aluminium based composites, [37], identified that the Markham method was using group velocity and not phase velocity. However, Kriz and Stinchcomb recorded these effects on carbon fibre based composites.

Within literature it has thus far been documented that the pulse transmission technique can be conducted via (a) immersing a sample in water, (b) direct contact between the transducer and sample or (c) direct contact between the transducer, a mode changing mechanism (such as a glass prism) and the sample. So established is the pulse transmission technique for conducting ultrasonic velocity measurements that areas such as void content, homogeneity and symmetry, the relationship between fibre and matrix, fibre orientation etc. have all been shown to be approachable areas of study using this technique.

Given the multiple contributions to knowledge outlined thus far, a summary of these findings are presented at the end of this review in Table 9. Having identified the Zimmer and Cost approach and the Markham method, moving forward, Section 4.4 presents literature which develops, documents and utilizes modern experimental analysis of double through transmission and reconstruction algorithms (not present in previous work thus far).

4.4. Group velocity, double through transmission and reconstruction algorithms (1980s–1990s)

Development of the group velocity phenomenon observed by Kriz and Stinchcomb was by Pearson and Murri, [38], when they propagated waves in both principle directions (contains two axis) and in off-axis directions in unidirectional graphite composites.

Pearson and Murri manufactured multiple samples, which observed orthotropic symmetry, with varying fibre axis to sample surface relationships and performed ultrasonic measurements using the Zimmer and Cost approach in the 1–2 plane (1 axis being the fibre direction) – noting only longitudinal waves were propagated. Fig. 18 is provided to illustrate both the samples and the group velocity effect.

The authors found that the time taken for a pulse to propagate through the sample using the group velocity at angle of 0° deviation was the same as the phase velocity. That is, the only difference recorded between the group velocity and phase velocity calculations

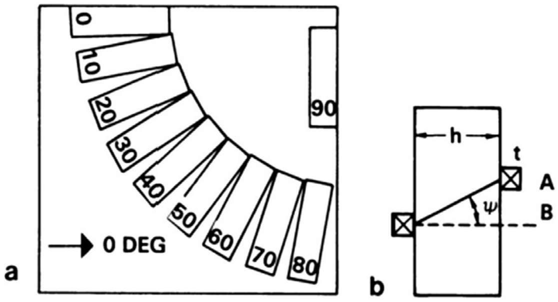

Fig. 18. Figure (a) documents various samples with degrees being reference to the fibre axis, figure (b) documents transducer placement and group velocity effect; transducer must be moved to position A from position B, to compensate for group velocity effect as given by angle Ψ. *Review of Progress in Quantitative Nondestructive Evaluation, Chapter 6, Measurement of ultrasonic wavespeeds in off-axis directions of composite materials, Vol. 6A, 1987, page 1093–1101, Pearson LH, Murri WJ, Copyright* Springer Science + Business Media New York *US, With permission of Springer.*

was that the time taken in the case of group velocity was multiplied by the cosine of the angle of deviation, Ψ. Thus the authors state that if the receiving transducer is positioned to correctly receive the transmitted pulse (in this case point A), the calculated group velocity can be related quite easily to the phase velocity (assuming the refraction angle of phase velocity is 0°, i.e. wave strikes composite at normal incidence) that would be recorded at point B.

Using the phase velocity determined in this plane, the authors conducted a least squares fit procedure to determine all available elastic constants (remembering that transverse waves in various directions are required to determine the full set of constants). The determined constants were found to be in good agreement (accuracy figure not provided) with those obtained via theoretical predictions. It is of merit to note that previous authors did not adopt the least squares fit procedure, but it is also true that Pearson and Murri provide little information on how this was performed. With later works documenting least squares fit in varying degrees of depth, discussion is held off until these future works are discussed. Fig. 19(a) documents the relationship between the experimental and theoretical phase velocity to angle propagation relationship.

Regarding the size of deviation angle arising via the group velocity effect, caused by the anisotropy of the sample, the authors found that theory matched experiment and that in the most extreme cases angles of up to around 55° were recorded. Fig. 19(b) documents the deviation angles recorded by the authors.

Turning attention to quasi-transverse waves, Pearson and Murri documented an interesting set of results. For quasi-waves propagating in the 1–3 plane with propagation angle to fibre axis of 0° to around 65° the angle deviation was recorded as being negative. The negative value of angle deviation infers that the group velocity effects oppose the initial refraction that arises from Snell's laws, thus, bolstering the case that correct transducer placement is key to accurately measuring wave propagation velocity. Further, for propagation to fibre axis angles of angles between 65° and 80° the wave deviation was recorded as being around 55° in some instances. Owing to the inspection technique used, angles of fibre propagation outside 80° were not able to be studied. Fig. 20(a) and (b) documents the findings from Pearson and Murri. Note that the theoretical and experimental did not provide as good a relationship as it did for quasi-longitudinal waves.

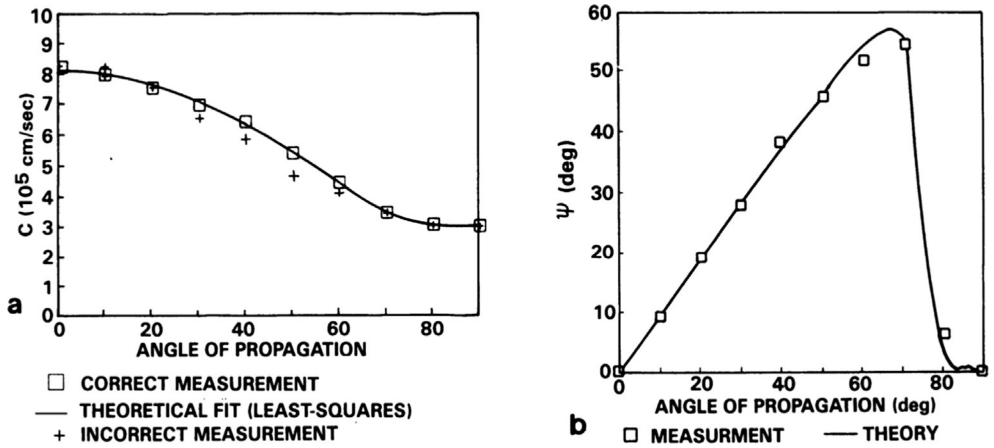

Fig. 19. Figure (a) documents experimental and theoretical agreement for quasi-longitudinal phase velocity, calculated from group velocity, for the samples outlined in Fig. 18(a). Figure (b) documents the group velocity effect causing maximum wave deviation of around 55° for propagation to fibre axis of around 75°. *Review of Progress in Quantitative Nondestructive Evaluation, Chapter 6, Measurement of ultrasonic wavespeeds in off-axis directions of composite materials, Vol. 6A, 1987, page 1093–1101, Pearson LH, Murri WJ, Copyright* Springer Science + Business Media New York*, With permission of Springer.*

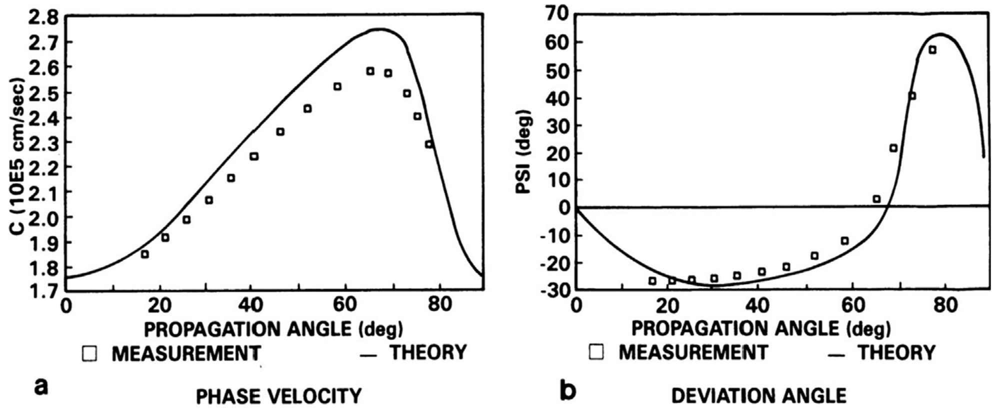

Fig. 20. Figure (a) documents experimental and theoretical agreement for quasi-transverse phase velocity, calculated from group velocity, determined using the Markham method. Figure (b) documents the group velocity effect causing negative angle deviation of around 30° maximum and positive angle deviation of around 55° maximum. *Review of Progress in Quantitative Nondestructive Evaluation, Chapter 6, Measurement of ultrasonic wavespeeds in off-axis directions of composite materials, Vol. 6A, 1987, page 1093–1101, Pearson LH, Murri WJ, Copyright* Springer Science + Business Media New York, *With permission of Springer.*

As mode changing was required by the authors to generate quasi-transverse waves the refraction angle therefore cannot equal 0°. Thus, the authors highlight that the previous relationship (proportionality to cosine of wave deviation angle) is no longer viable. Pearson and Murri provide the solution however and document the relation between group and phase velocity using the Markham method. While not as simplistic as just multiplying the time by the cosine of deviation angle as with the quasi-longitudinal case, the authors do provide an equation set to calculate phase velocity from group velocity for quasi-transverse waves propagating via the Markham method.

The two main contributions to knowledge from Pearson and Murri were (a) when quasi-waves propagate in off-axis directions then particular care should be taken when deciding the correct location of the receiving transducer when employing the through transmission technique and (b) presentations of equations which can be used to relate the phase velocity to group velocity for both longitudinal and transverse waves. Looking closer at point (1) while there is of course no definitive answer to where the transducer should be placed and although the authors put forward the deviation angle as a function of propagation angle, further investigation on the correct placement of transducer would have been of considerable interest. Further, a potential implication of this work is that shear waves may be the most accommodating option for studying wave propagation in off axis directions in unidirectional CFRP; due to refraction and group velocity wave deviation effects being both potentially positive and negative and thus fighting against each other, the transducers may potentially be able to stay directly in line with each other under certain circumstances (this claim is not verified in the work however).

Having documented the group velocity effect, the double through transmission system, an arrangement designed to combat incorrect transducer placement, was developed within literature. First however, given that double through transmission presents as a combination of Markham's method and pulse-echo, a recap of pulse-echo is first given.

Pulse echo is typically used to determine defects or flaws within a particular material but can also be used to determine the elastic constants. In regards to defect detection, pulse echo can be thought of as the following. A wave propagates through a given material and encounters a void which is large compared to the wavelength of wave, the dramatic change in acoustic impedance between the material and void causes a wave to be reflected back to the surface. A time of flight measurement is then taken to gauge the depth of the void.

In regard elastic constant determination, pulse echo can at times be considered the same as through transmission. That is, if the wavelength is large, compared to any potential voids, but small compared to the specimen geometry, then the propagating wave will treat the material as a continuum (ignore the void) and the back wall of the specimen will reflect some of the wave back to the original transducer. A time of flight measurement can be taken and so the wave velocity may be determined. From a physics standpoint this process is really no different to the through transmission approach; owing to aspects such as waves traveling through the specimen twice, it is not classed as through transmission however.

Prior to double through transmission invention, evidence of where the pulse echo technique was used in this era to determine the elastic constants of uni-directional constants can be found in literature, Prosser, 1987 [39]. Prosser demonstrated the applicability of the pulse echo techniques to unidirectional graphite composite when he sought to determine the elastic constants of a composite used in a previous publication Kriz and Stinchcomb, 1979 [35]. Using a pulse overlap system – essentially, the comparison of successive back wall reflections to determine the time difference and subsequently the wave velocity – Prosser demonstrated that the elastic constants of a unidirectional graphite composite (T300/5208) could be determined. As with Zimmer and Cost [20], to obtain the desired velocities, multiple samples were required to allow for propagation at varying angles to fibre axis. Prosser compares the elastic constants determined through pulse echo with those of Kriz and Stinchcomb and found in general good agreement. Note that C_{33} was found to be around only 70% of that calculated in the work by Kriz and Stinchcomb owing to the authors using samples which were not identical to Kriz and Stinchcomb in terms of void content, fibre content and dimensions. Additional reading can be

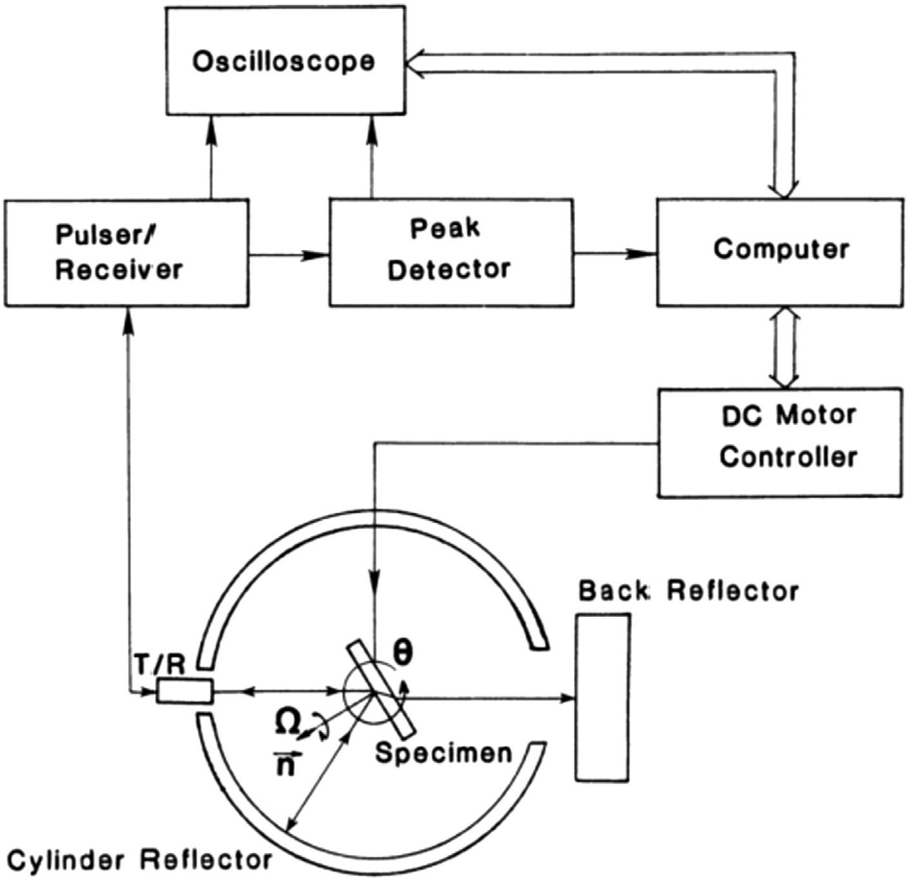

Fig. 21. Experimental apparatus of the double through transmission technique. A single transducer operates as both transmitter and receiver, both surface reflections and through transmission signals are able to be measured with the sample, transducer, cylinder and reflector immersed in water (accurate to temp – 0.1°) *Review of Progress in Quantitative Nondestructive Evaluation, Chapter 8, Ultrasonic evaluation of in-plane and out-of-plane elastic properties of composite materials, Vol. 8, 1989, page 1489–1496, Rokhlin SI, Wang W, Copyright Springer Science + Business Media New York, With permission of Springer.*

found from [40] who present similar analysis when they adopt pulse echo and Fourier analysis to determine attenuation, wave speed, thickness and density simultaneously.

Discussing now the double through transmission technique, in 1989, two publications, Rokhlin and Wang [41,42], documented this technique. The double through transmission technique is essentially the through transmission technique with an arguably slight combination of the pulse echo technique. It is used in many modern publications and is considered a very important technique. Looking first at [41], the experimental apparatus involved in the double through transmission technique is shown in Fig. 21.

The double through transmission technique operates as follows; an ultrasonic wave is transmitted towards the sample, noting that the sample is able to be rotated around a central axis (recorded at 0.01° precision). Upon striking the sample, and depending on the angle of incidence, the wave is both reflected and transmitted through the sample. Looking first at transmission, the wave propagates through the sample in the direction of the group velocity, that is, in the direction of wave energy (not necessarily the refraction angle as dictated by Snell's laws). Upon reaching the reflecting block, the transmitted wave is reflected back towards the transmitting transducer, now acting as a receiving transducer, in exactly the same path taken up to that point. Thus, the problem of wave vector deviation is removed owing to the reflecting path taking exactly the same route as the transmitting path. Rokhlin and Wang elegantly depict this process, given as Fig. 22.

Looking now at surface reflections, the initial incident wave is reflected and heads towards the aluminium cylinder. It is subsequently reflected again and, similar to the through transmission approach, takes exactly the same path back towards the receiving transducer.

Rokhlin and Wang propagated a number of waves (number not specified), with the average amplitudes of reflected signals (both from surface reflections and from through transmission reflection) recorded. Looking first at surface reflection technique the authors quote earlier work, which demonstrated that when the critical angle is reached for both quasi-longitudinal and quasi-transverse waves a maximum reflection coefficient was generally recorded. Thus, with the amplitude of the surface reflection being recorded, the critical angle was also able to be determined. The critical angle is defined in this instance as the point of incidence which causes the refracted energy of the wave to propagate parallel to the plane of incidence – noting that energy (group velocity direction) is used

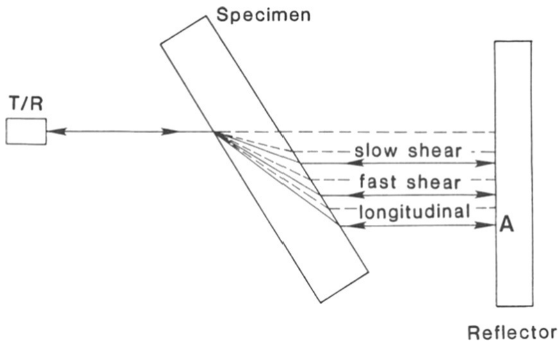

Fig. 22. Showing the transmitted and reflected waves traveling along the same path thus eliminating the need to alter transducer placement in this approach. The dotted lines indicate phase velocity direction; solid lines indicated group velocity direction. *Review of Progress in Quantitative Nondestructive Evaluation, Chapter 8, Ultrasonic evaluation of in-plane and out-of-plane elastic properties of composite materials, Vol. 8, 1989, page 1489–1496, Rokhlin SI, Wang W, Copyright Springer Science + Business Media New York, With permission of Springer.*

instead of phase velocity direction. The critical angle was also shown to change when the fibre axis to propagation direction changed.

Knowing the critical angle and velocity of incident wave, allowed the authors to calculate the refracted wave velocity via Snell's laws. Thus, elastic constants may be realised in this instance. The authors' state however that due to group velocity effects the only available plane in which the above contention is valid, was for propagation in the plane of incidence, or as the authors put it, in-plane phase velocity measurements only.

Looking now at the through transmission arrangement, outside of the contention that this system improves on the Markham technique, which has the potential to provide errors if one is not careful with transducer placement and composite width, there is little to be discussed. The authors effectively conducted exactly the same measurements as conducted by preceding authors, that is, time of flight measurements of different waves at different angles to fibre axis to determine the phase velocity. Note here that the phase velocity is determined through a relationship with the group velocity, which the authors effectively calculate in the same way as was previously outlined by Pearson and Murri [38].

The final area of interest from Rokhlin and Wang is the technique used to determine the elastic constants of the sample. Up to this point, excluding Pearson and Murri, to determine the elastic constants of the composite, literature presented in this review has used the Musgrave equations, [17,18], which effectively force specific waves at specific angles to fibre axis to be measured. This technique was not adopted in this text, the technique adopted was to evaluate a slowness profile and perform a statistical process to find the best values of constant to create such a curve. The process is stated by the authors as being called the 'least squares fit' or 'least squares optimization'. A slowness profile is a particular type of wave surface profile in that what is charted is simply the inverse of the phase velocity against either the angle of wave vector direction or the angle of propagation to fibre axis. Ledbetter and Kriz, [43], can be sighted for additional examples of such surfaces. The least squares method is discussed further in another not yet discussed publication by Rokhlin and Wang, [44].

The authors calculated the phase velocity experimentally using the double through transmission approach and compared these results to the phase velocity derived through the reconstruction of elastic constants from a critical angle measurement and found good agreement, thus verifying both the double through transmission approach, critical angle approach and least squares mechanism. Fig. 23 is given to exemplify the results.

In this work, Rokhlin and Wang demonstrated a novel way to determine the elastic constants of CFRP. The double through transmission technique removes the possible errors that group velocity wave deviation may bring in other techniques such as the Markham method. Also, the experimental arrangement allows for phase velocity to be determined through critical angle measurements. However, this work does not examine the work of [25], who stated that longitudinal wave propagation is a result of a pseudo-L wave. Additionally, this work and equally the work of Pearson and Murri do not examine just how much inaccuracy there is in the existing Markham approach, the authors only state that this method is inaccurate. It was not shown to be the case that wave deviation always introduces significant accuracy concerns for samples of CFRP of certain dimensions.

The other 1989 publication by Rokhlin and Wang [42], discusses using the double through transmission arrangement in the critical angle mode of operation further. As this technique is outside the scope of this literature review, this paper is not reviewed. However, attention can be turned here for additional reading on the critical angle technique.

Three clear strategies are developed within literature at this point, the Zimmer and Cost approach, the Markham method, and the Double through transmission approach. The remainder of this review effectively charts refinement and analysis using these techniques.

Published in 1990, was Castagnede et al., [45]. Similar to Dean, [24], the authors investigated the applicability of using velocity measurements as a means to investigate symmetry within CFRP; more specifically to determine the orientation of principal axis of symmetry. In a not too dissimilar way to Dean, the authors produced an algorithm, based on the standard Musgrave equations, to relate the angular parallax (angular parallax being angle between the geometric axis and crystal axis) along with the elastic constants to standard velocity measurements determined using the standard Markham approach. Not discussed in this text however, are the effects brought on by wave deviation (group velocity effects), which have been shown thus far to have potential to reduce accuracy in

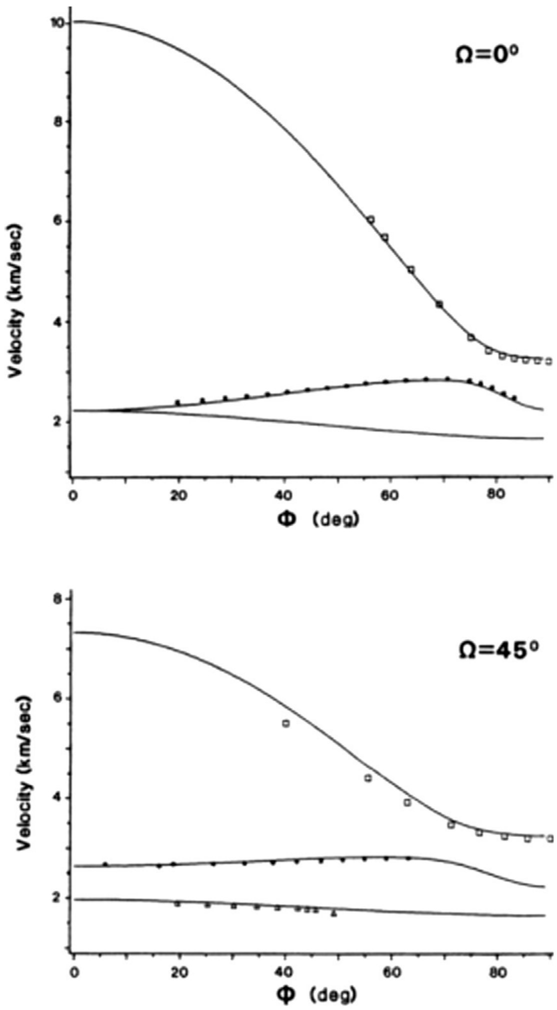

Fig. 23. The solid line is reconstructed phase velocity from elastic constants determined via critical angle technique. The experimental points are phase velocity as recorded via double through transmission technique for two quasi – transverse and one quasi-longitudinal wave for surfaces of 0° and 45° to fibre axis. Φ is equal to 90° – angle of refraction. *Review of Progress in Quantitative Nondestructive Evaluation, Chapter 8, Ultrasonic evaluation of in-plane and out-of-plane elastic properties of composite materials, Vol. 8, 1989, page 1489–1496, Rokhlin SI, Wang W, Copyright Springer Science + Business Media New York, With permission of Springer.*

velocity measurement.

A work which does discuss the fact that hitherto the Musgrave equations were determined using the group velocity and not the phase velocity was by Rokhlin and Wang, 1992, [44]. Building on previous works [38,41], the authors outlined three clear goals, (1) demonstrate – in a different way to [38] – the relationship between phase velocity and group velocity in a unidirectional CFRP sample, (2) discuss the already outlined, [41], double through transmission method and present experimental results and (3) demonstrate the robustness of a non-linear least squares methodology for elastic constant determination – noting that point 3 is the main contribution to knowledge.

Looking at point (1), Rokhlin and Wang demonstrated geometrically that the phase velocity can be related to the group velocity and similar to [41], the authors determined effectively the same equation as previously outlined by [38]. Further, it was also identified that if an incident wave is not refracted, propagates through an isotropic plane, or if the plane generated with an refracted wave vector and the normal to the incident plane coincides with plane of symmetry, then the time taken for the pulse to propagate through the sample at group velocity is equal to the time taken for the pulse to propagate at phase velocity i.e. group velocity will equal phase velocity.

Moving on to discuss point (2), additional information not discussed in [41], was that the water tank was kept at 29.8° accurate to (+/−) 0.05 °C, the transducers used were 15 MHz and the sample was unidirectional graphite epoxy with a thickness of 2.1 mm. The authors propagated both quasi–longitudinal and quasi-transverse waves at angles of 0°, 45°, and 90° between the incident plane and the fibre direction. For all available angles of refraction the phase velocity as a function of 90° minus refraction angle was recorded by the authors. Note also, that to determine the degree of result accuracy, theoretical realisations of the phase velocity, obtained using the aforementioned critical angle technique, were produced and superimposed onto these plots by the authors. Similar to the findings from [41], Fig. 23, the authors found a very accurate relationship between the phase velocity as determined through using the critical angle technique and the double through transmission technique.

Looking now at point (3), a non-linear least squares minimizing technique was used by the authors to evaluate the elastic constants. The system used by the authors is given as Eq. (1).

$$\min\frac{1}{2}\sum_{i}^{m}\,(V^{exp}-V^{calc})^2 \tag{1}$$

where V^{exp} are the experimentally recorded velocities and V^{calc} is theoretical velocities using elastic constants. The authors initially guessed the elastic constants and then using equations presented in text, they calculated and summed, phase velocities over a series of propagation angles. This value was then subtracted from the experimental value of the velocity (over the same propagation angles) with the result being squared – this value was sought to be minimised. The choice of elastic constants was altered and a similar process continued, seeking a lower value of result than from the previous execution. Continually minimizing this difference, by altering the initially guessed elastic constants, will eventually lead to the correct elastic constant values. In this instance, the determined constants were found to be in good agreement with the original value and independent of the initial guess (up to a point of 20% difference) thus, reinforcing the choice of reconstruction technique.

Regarding the determination of elastic constants using the Musgrave equations, the authors state this method of determining the constants (specific waves along specific directions within the material) is somewhat sensitive to error; however, there is no general development of this issue within the text, nor does the text cite any major works which discuss it.

Having established the least squares optimization technique, Rokhlin and Wang investigated the robustness of this algorithm. Phase velocity was calculated using a set of elastic constants which define an orthotropic material; noting here that angles of fibre axis to plane of incidence of 0°, 30°, 45°, 60° and 90° were used. A computer simulation was performed which allowed 0.1%, 1% and 5% noise to be superimposed on the phase velocity results. With each new value of phase velocity, the elastic constants were then determined again. The authors documented that even at 5% noise level the elastic constants determined were adequate. Also, it was recorded that reconstructing the elastic constants using the phase velocities in the plane of symmetry produces slightly better results than doing so using the phase velocities from non-symmetry planes. Given that not all elastic constants are determined from symmetry planes, the authors state for best results a combination of both symmetry and non-symmetry plane velocities should be used when determining elastic constants.

Rokhlin and Wang constitute a good body of work. Building on [41], the authors documented more thoroughly the relationship between the group velocity and phase velocity and also identify that phase velocity is required for elastic constant determination. Further, the authors document a least squares algorithm that allows for the elastic constant to be determined with a good degree of accuracy, even in the face of up to 5% scatter in the phase velocity results.

While the authors touch on the subject of why one should use the least squares algorithm, a comprehensive case was not, in the opinion of the current authors, put forward as to why one should always perform a least squares algorithm. For instance, the authors state that only propagation in non-symmetry planes is required and infer that only one type of wave is needed, while at the same time also stating that the older system using both waves in specific directions is prone to error. However, the text documents no quantitative data which compares these methods of elastic constant determination. Further, for a transversely isotropic material, only five elastic constants are required and only one of these is off axis, thus a comparison would be required in literature to determine if the least squares method (which can potentially require more time spent to perform) is required in every instance.

An upgrade to the double through transmission technique was recorded in a series of publications by Chu Rokhlin, [46–48], via a slight variation of the original technique; with the upgraded technique being known as the self-reference model (SRM). The [47] study, examines a comparison between the double through transmission system and the self-reference model, thus, out of the three this is the paper discussed.

When using the double through transmission, the through transmission or the Zimmer and Cost approach, at some point the time taken for a wave to propagate the reference path (no sample between transducers) is required. With the double through transmission the paper just reviewed, [44], the equations relating group velocity and phase velocity are identified, along with the dependence on the reference path velocity. The self-reference model (SRM), seeks to improve the accuracy of elastic constant determination by investigating the reference velocity measurements. Fig. 24, is given to demonstrate the distinction between self-reference and standard approach when using the double through transmission system; for self-reference the velocity is measured using the sample at normal incidence, whereas the standard arrangement has no sample between transducers.

The improvement the self-reference system has over the double through transmission system is that parallelism of the sample (opposite faces of the sample being flat but not parallel) and surface curvature, both of which have the potential to introduce slight errors into phase velocity calculations, are taken into account.

Gauging the contribution of this novel measurement system, the authors experimentally measured the phase velocity using both the double through transmission system and the self-reference system. In this instance, a unidirectional graphite epoxy composite along with a 5 MHz transducer was used. The incident plane was chosen to be parallel to the fibres (strong angular dependence recorded in this direction) with angular repeatability and resolution (referring to sample rotation parameters) recorded better than 0.01°.

For the double through transmission system the authors found that maximum error due to parallelism was at normal incidence and then reduced as the angle of refraction increased. Via the SRM, a contrasting relationship was found; the most accurate results

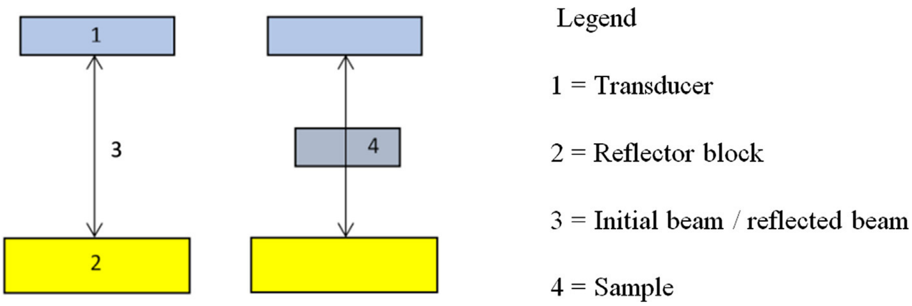

Fig. 24. Documenting the distinction between the standard double through transmission method and the SRM. Fig. a) documents that the acoustic reference signal (water coupling medium not shown) measurement is made without the sample, Fig. b) documents for the SRM that acoustic reference measurement is made with sample at normal incidence.

were obtained at normal incidence with slight increases in error being recorded as the refraction angle increased. Conducting similar tests on isotropic steel with curved sides, the authors recorded up to 7% error in velocity measurements, however for strongly parallel surfaces, these errors significantly reduce. The authors point to these experiments to give basis to the reporting that the self-reference method is more tolerable to surface imperfections than the standard double through transmission approach. Thus it was demonstrated by Chu and Rokhlin that by inserting the sample between the transmitter and reflector to gauge the acoustic reference path then the accuracy of phase velocity result can be improved.

In relation to temperature effects, the authors went further than previous authors and investigated quantitatively the effects of temperature variation. Unlike previous authors who state the temperature of the coupling medium should remain at a constant, the authors in this instance recorded that for a temperature change of 1 °C, error of up to 15% can potentially be present. Chu and Rokhlin also outline further techniques that can be used if no temperature regulation equipment is available, while also noting that temperature should be measured to an accuracy of 0.01 °C.

Two additional publications from 1994, Chu and Rokhlin and Chu et al., [49,50], sought to determine the elastic constants of unidirectional CFRP from limited ultrasonic velocity measurements. These works investigate the robustness of determining the elastic constants from measurements in (a) symmetry planes only and (b) non-symmetry planes only. Building on earlier work by [44], who demonstrated that for measurements with up to 5% noise the determination of elastic constants via symmetry planes at various refraction angles was more accurate than through non-symmetry measurements [44]), the authors put forward an analysis of the optimal refraction angles for elastic constant determination along with investigating which elastic constants are determined from symmetry planes and non-symmetry planes only.

Looking initially at the Chu and Rokhlin study, [49], which investigated symmetry planes. The authors expressed the phase velocities in terms of a polarization factor. The polarization factor was identified as a measure of the polarization difference between a pure mode and a quasi-mode – for a pure mode the value is denoted as 0, which increases in value with increasing deviation from pure mode polarization. For a value of polarization factor squared of less than 0.4 the authors denote the material as weakly anisotropic and for larger values the authors denote the material as strongly anisotropic. In this work, the authors recorded that in the case of a weakly anisotropic material, the longitudinal phase velocity in the 1–3 plane (1 direction being the fibre direction) was dependent mostly on the constants C_{11}, C_{33} and the combination ($C_{13} + 2C_{55}$), and in the 2–3 plane was dependent on C_{22}, C_{33} and the combination ($C_{23} + 2C_{44}$). Thus, the authors found agreement with a previous study, [51], and reported that for a weakly anisotropic composite the constants C_{44} and C_{55} cannot be determined directly from longitudinal data in symmetry planes. Therefore, to determine the seven constants available from symmetry plane analysis, transverse wave propagation is also required. The transverse phase velocity in the 1–3 plane was found to depend on C_{55} along with the combination of ($C_{11} + C_{33} + 2C_{13}$) and in the 2–3 plane on C_{44} and the combination of ($C_{22} + C_{33} - 2C_{13}$). Fig. 25 documents the fibre direction to plane relationship.

The authors went further and investigated the sensitivity of phase velocity by performing a partial differentiation of the phase velocity with respect to the specific elastic constants. They found that the phase velocity change was in all cases a function only of refraction angle, thus, the optimal refraction angle for the determination of seven out of a possible nine elastic constants of an orthotropic material were able to be determined. These findings are summarized in Table 5.

Although not stated by the authors, the results outlined in Table 5 are not entirely surprising given that as early as 1970 Zimmer and Cost, and Markham, [20,21] put forward a similar view point (which is a fall out from the Musgrave equations). For instance to determine C_{11}, C_{33}, and C_{44} for example, propagation should be at 0° (longitudinal), 90° (longitudinal) and 90° (transverse). Noting here that refraction angle and propagation direction are in the same direction in terms of wave vector (i.e. propagation in 1–3 plane at 0 degrees to fibre axis is in same direction as a 90° refraction of an incident wave in this plane).

The authors performed a similar sensitivity analysis on strongly anisotropic materials and recorded not so straight forward relationships (in the sense that sensitivity was not strictly dependent on the angle of refraction alone). For longitudinal wave propagation in the 1–3 plane, unlike weakly anisotropic material, the authors found that C_{55} impacted upon the sensitivity, i.e. C_{55} plays a role of noticeably increasing or reducing the phase velocity. Thus, the authors concluded that C_{55} was able to be determined from longitudinal waves in this plane. C_{44} however was still required to be found using a transverse wave. It was also recorded by Chu and Rokhlin that the elastic constants C_{11} and C_{33} played a more prominent role in sensitivity analysis of transverse waves.

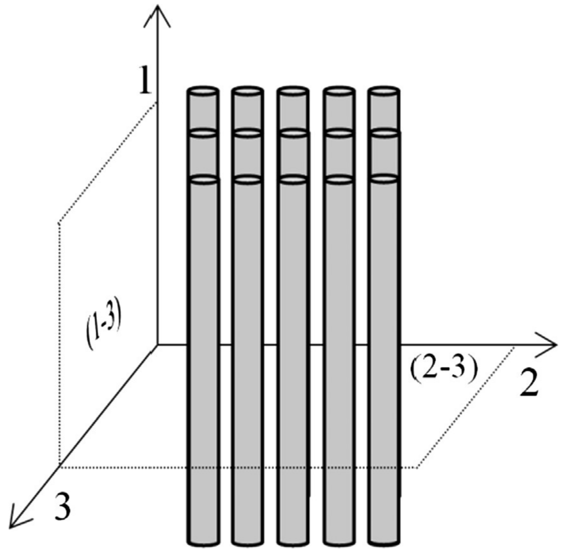

Fig. 25. Documents fibre direction along with the (1–3) plane and the (2–3) plane. The (1–3) allows for propagation in the direction of fibre and through the fibres, the (2–3) plane allows for propagation across the fibres and through the fibres. In this instance, the sample is orthotropic i.e. measurements from both the 1–3 plane and 2–3 plane change with change in propagation direction, for transversely isotropic material, only the 1–3 velocity changes with propagation direction, the (2–3) plane is isotropic and independent of propagation direction.

Table 5
Optimal refraction angles in planes 1–3 and 2–3 for determination of elastic constants from orthotropic unidirectional CFRP composite, as adapted from [49].

Optimal refraction angle for elastic constant determination		
Elastic constant	Refraction angle (quasi-longitudinal velocity) (°)	Refraction angle (quasi-transverse velocity) (°)
C_{11}	90	45
C_{22}	90	45
C_{33}	0	45
C_{13}	45	45
C_{23}	45	45
C_{44}	45	0
C_{55}	45	90

Lastly, Chu and Rokhlin also examined the elastic constant accuracy as determined using the non-linear least squares technique with only limited phase velocity data (i.e. angle range 0–90° not fully covered). Using phase velocity data at scatter level of 2%, the authors found that for satisfactory results of elastic constants (0–3% from nominal value), in the case of longitudinal waves the phase velocity data range should extend from 0° to 45° (or above) and for transverse waves the range 35–75° (or above).

Looking now at propagation in non-symmetry planes, Chu et al., [50]. While the previous authors documented that a non-linear least squares recovery algorithm is robust in terms of 5% scatter and independent of the initial guess of elastic constant in planes of symmetry, Chu et al. recorded a mixed set of results for non-symmetry planes. For an incidence plane rotated 45° around the fibre direction of an orthotropic material, the authors recorded that only C_{33}, C_{44} and C_{55} were independent of both the initial guess (up to 20% difference) and scatter (up to 2%); noting that the remaining elastic constants were influenced by the initial guess and scatter level in varying ways. Using this plane to determine the elastic constants, the authors found that an initial guess of within 2% nominal value with 0.5% scatter produces fairly accurate results (largest deviation from the determined true elastic constant values was shown to be 1.3%), noting that additional scatter or a more inaccurate initial guess drastically causes these results to change.

It was also documented by the authors that if the independent elastic constants C_{12} and C_{66} are calculated using the least mean squares method (note that these constants are not able to be determined from measurements in symmetry planes) and all other constants are known and held constant during the process, then the least squares method is both robust to at least 2% scatter and up to ± 20% inaccuracy of initial guess. Thus, building on [49], Chu et al., put forward the conjecture that when investigating orthotropic materials, one should determine seven out of the nine elastic constants from symmetry planes, using only non-symmetry planes for the remaining constants (which are unable to be determined from symmetry planes).

The optimum method for determination of constants C_{12} and C_{66} was also put forward by the authors. Similar to [49], this was by way of a sensitivity analysis. Using an approximation of the phase velocity for arbitrary angles of refraction, the optimum angles of refraction in non-symmetry plane of 45° to the fibre axis were recorded. Results found by the authors are given in Table 6.

Table 6
Optimal refraction angles for determination of the elastic constants of a orthogonal uni-directional CFRP in a non-symmetry plane of 45° to fibre axis, adapted from [50].

Optimal refraction angle for elastic constant determination			
Elastic constant	Refraction angle (quasi-longitudinal velocity) (°)	Refraction angle (fast quasi-transverse velocity) (°)	Refraction angle (slow quasi-transverse velocity)
C_{12}	90	90	Not dependent on C_{12}
C_{66}	90	45	Not generally dependent on C_{66}

Both [49] and [50] documented phase velocity sensitivity to changes in specific elastic constants along with the optimum set of phase velocity measurements (in terms of propagation angle) for determining the most accurate set of elastic constants via least squares optimization. It is also the case that [38,41,42,44,46–48] demonstrated that group velocity was able to be related to the phase velocity when conducting the Zimmer and cost approach, the Markham method and the double through transmission approach. Thus circa 1994 the methods to determine the elastic constants of unidirectional composite materials were strongly established within literature.

Keeping with the chronological progression of literature, a brief sidestep of the main theme the review (elastic constants determination of uni-directional CFRP via ultrasound through transmission) is undertaken. During the time period outlined thus far, areas of research, while not explicitly concerning the subject of this review, are found which incorporate aspects such as group velocity, reconstruction algorithms, the Markham method and the double through transmission approach. Thus, it is of merit to briefly discuss these areas and identify further literature developed in parallel with the subject matter of this review.

4.5. Viscoelastic properties (1980s to 1990s)

Examination of viscoelastic properties of fibre composite was also an area of ongoing research during this period. Significant contributions to knowledge from a Bordeaux group led by Professor Bernard Hosten documented much work concerning the viscoelastic properties of unidirectional composite materials during this period [52–62].

With aspects such as reflection and transmission coefficient amplitudes and general attenuation measurements routinely used to investigate the viscoelastic properties, the process falls outside the scope of this review. However, given that an understanding of the real part of the stiffness matrix along with the complex part of the stiffness matrix is required when performing viscoelastic investigation, the highlighted papers may be of interest for researchers in this area. The majority of the literature produced by the Bordeaux group [52–62], during this period used the aforementioned Markham method and least squares fit algorithm to determine the real elastic constants required.

4.6. Relating group velocity to phase velocity (1990s)

Through the 1990s relating phase velocity to group velocity measurements within CFRP was a field on-going research, with not all measurement techniques being based on the Zimmer and Cost approach, the Markham method or the double through transmission. As such, indirect relationships between the group velocity and elastic constants were established within literature; indirect meaning that relating group velocity to elastic constants is not direct like phase velocity and relies on aspects such as wave vector deviation and phase velocity refraction angles. Additionally, innovative reconstruction algorithms based on aspects such as ray surfaces and wave normals to these surfaces were developed to help determine the elastic constants from group velocity measurements.

Further reading outlining contributions to knowledge during this period may be found from [51,63–72].

4.7. Modern literature on the determination of elastic constants via double through transmission (1990s to 2014)

Moving back to the immersion based approach, additional improvements (in terms of accuracy) to the Markham method and double through transmission approach are found within literature. These improvements were developed through noticing that on a water/solid interface, a transverse wave records a phase shift when the critical angle for longitudinal waves is exceeded. In 1997 Lavrentyev and Rokhlin, [73], identified that when a longitudinal wave strikes a water/solid (in this case graphite epoxy composite) interface at angles above the critical angle, a longitudinal evanescent wave (exponentially decreasing disturbance created when critical angle is exceeded) is produced which then forces the refracted shear waves to undergo a phase shift.

Thus, to correct for the very slight phase shift the authors put a slight modification (in mathematical terms) to the self-reference double through transmission method. To realise this, the authors initially calculated the elastic constants using the standard procedure and pay no attention to the potential phase shift. Using this data, the phase error shift was calculated, note here that the authors are not very explicit about how this calculation should be performed, however this information is presented in a different publication, [74]. Once the phase shift (degrees) is known, the authors put forward a very slight change to the theory previously outlined in [47], in that for a given incidence angle the phase velocity (a function of refraction angle) now also has a dependence on phase shift. Also, the frequency of operation is required in this relation, the authors advise a narrowband signal should be used when measuring the phase velocity. Iterations of this procedure can be performed to continually increase the accuracy of result.

Using the updated phase velocity relation the authors recorded a difference of 0.2%, 0.3%, 1.2%, and 0.4% in the elastic constants of C_{11}, C_{33}, C_{13} and C_{55} respectively for graphite epoxy composite. Further, the authors recorded differing percentage effects when investigating other materials and further found the area of stress determination to be reliant on accurate phase velocity; both areas are outside the scope of this review.

While this work is of interest (it technically improves the accuracy of elastic constant) the differences recorded in the paper are small in value and so adopting this approach to determine the elastic constants may not be required in every instance, however further work is required to verify this claim. Additionally, the authors present only four elastic constants and do not discuss a typical number of iterations (if any).

Approaching the same issue from a different perspective was Hollman and Fortunko, [74]. This work however does not discuss unidirectional composite. The authors state additional work is required as the findings are not directly translatable to strongly anisotropic material, (noting that unlike [49,50] strongly anisotropic material is not defined), thus work is not reviewed. It of interest however, that the authors used a different method, reliant on Fourier series analysis to measure the phase velocity, and one which has been verified on isotropic steel, improves on the previous method in that broadband transducers are able to be used.

Wang et al., [75], built upon [73] by expanding on the phase correction issue caused by oblique incident angles greater than the critical angle and also investigated possible diffraction effects. Looking first at the phase effects, when investigating the phase shift for unidirectional graphite composite in three different planes, 0°, 90° and 45° to the surface normal, the authors found the most dramatic phase shift was in the 45° plane. At the first critical angle (longitudinal wave) in this plane the authors found phase shift rising to 90° then falling suddenly to 0° as the angle of incidence to fibre axis was increased. Between the first and second critical angle (fast transverse wave) the phase shift increased by less than 2°. Between the second and third critical angle (slow transverse wave) the phase shift fell to around – 90°. Further, the authors present relationships which allow for the realisation of a given materials phase shift, which incorporates such aspects as Young's modulus, density and Poisson's ratio and also identify that phase shift is more stabilized and less severe in the other planes, i.e. planes of 0°, 90°.

Additionally, the authors put forward a means to estimate the error introduced into the experiment. The authors state that while phase shift is significant around the critical angle regions, phase error for a small number of angles is not sufficient to account for a drastic change in elastic constants when using the least squares algorithm over a large data set (multiple angles of incidence). Taking this into consideration, it is clear that the authors expanded on the initial observations from [73].

Looking now at diffraction effects caused by finite sized transducers; note that an ultrasonic beam spreads out as it propagates and so it is possible that owing to a fixed sized transducer facing (not covering the whole beam), that waves are picked up at the rear and sides of the transducer thus causing possible interference with the transmitted signal on the front face of the transducer. Presenting a theoretical model (noting that diffraction transducer analysis can be cited as far back as 1940), for a recorded beam width of 5 mm and a distance between the transducer and the reflecting block of 80 mm, the authors demonstrated that diffraction effects, when the transducer is in the far field, accounted for less than 0.2% difference in phase velocity. That is, the phase shift was virtually non-existent, thus diffraction effects are such that the recorded time difference is extremely small. Thus, the authors put forward the conjecture that in general, diffraction effects can be ignored. Judging by earlier works which do not consider diffraction effects while still recording fairly accurate results – in 1970 [22] recorded elastic constants accurate to 3%, in the 1990s, [50] recorded constants accurate to $\leq 1.3\%$ – this argument has solid basis.

Note a caveat, similar to phase effects, the authors recorded that for measurements at the critical angles, the diffraction effects caused the plane wave approximation to be recoded as invalid and so could not be ignored. The authors further document that diffraction effects in a general sense cause a reduction in amplitude of the signal. While not strictly a concern when conducting elastic moduli evaluation this finding is of course important when determining aspects relating to sample attenuation.

Hitherto 2005, as a means of determining the elastic constants of transversely isotropic unidirectional composite, the double through transmission system had not generally been thoroughly compared with the standard Markham method. Reddy, [76], investigated this gap in knowledge.

When determining the elastic constants, of isotropic glass epoxy composite, graphite epoxy composite and isotropic aluminium, Reddy et al. took the average of 100 signals (required to offset noise) wave velocities from both the double through transmission system and the Markham method. The double trough transmission system used by the authors is given as Fig. 26.

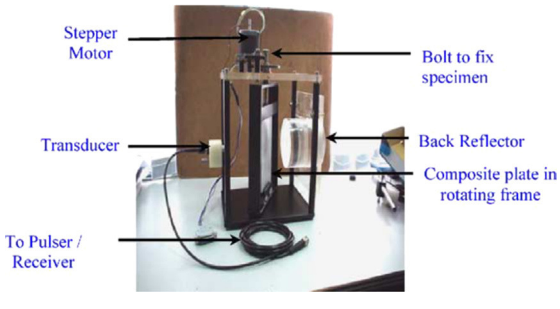

Fig. 26. Experimental arrangement of the double through transmission system as used by [71] *Reprinted from Composites structures, Vol 67/Edition number 1, Reddy, S. Siva Shashidhara, Reddy; Balasubramaniam, Krishnan; Krishnamurthy, C. V; Shankar, M; Ultrasonic goniometry immersion techniques for the measurement of elastic moduli, Pages 3–17., Copyright (2005), with permission from Elsevier.*

Table 7
Elastic constants as determined using the double trough transmission technique and Zimmer and Cost approach for glass epoxy 10.88 mm thick. *Reprinted from Composites structures, Vol 67/Edition number 1, Reddy, S. Siva Shashidhara, Reddy; Balasubramaniam, Krishnan; Krishnamurthy, C. V; Shankar, M; Ultrasonic goniometry immersion techniques for the measurement of elastic moduli, Pages 3–17., Copyright (2005), with permission from Elsevier.*

Elastic constants (in GPa)	Immersion testing	Contact testing
C_{11}	15.42 ± 0.78	15.30 ± 0.33
C_{13}	12.10 ± 1.04	Not measurable
C_{33}	50.15 ± 1.14	Not measurable
C_{44}	3.8 ± 0.42	Not measurable
C_{66}	4.76 ± 0.03	4.77 ± 0.17

The authors recorded that the double through transmission system was more accurate in relation to the elastic constants and more precise (repeatability) than the through transmission technique – noting that reference elastic constant values were taken from contact testing (Zimmer and Cost approach) and from the manufacturing data. Also, as the thickness of the sample grew the more the through transmission method differed from the contact based analysis; Tables 7 and 8 outline the elastic constants of two glass epoxy samples measured using the double through transmission technique and Zimmer and Cost approach.

Comparing the elastic constants as recorded via double through transmission and Markham method, with regards to glass epoxy composite and aluminium, the authors put forward the conjecture that the double through transmission system was the best option for determining elastic constants.

There is however problems associated with this publication and also areas in which, in the opinion of the current authors, warrant more rigorous investigation. In terms of the subject of this review the elastic constants from the graphite epoxy were only determined using the double through transmission technique, i.e. the authors did not record figures using the Markham technique and contact testing (Zimmer and Cost approach). Thus, while the authors quote graphite epoxy precision and accuracy figures for the double through transmission system, they do not exist for the through transmission technique. We must take the author on good faith that the precision and accuracy is lower; note the authors cite an earlier master's thesis to establish this claim.

Further, the authors state the receiving transducer is held fixed during the through transmission technique. As group velocity effects have been well documented up to this point in literature, it is clear that holding the receiving transducer in a fixed position has the potential (depending on sample width) to decreases the accuracy of the determined elastic constants. Thus, it may be premature to point blankly state the double through transmission method produces more accurate results if no measures have been taken to ensure optimal receiving transducer placement.

Lastly, the accuracy of the through transmission and double through transmission methods are measured against the elastic constants, and so these results can be said to be dependent on the aspects such as equipment and technique.

Returning to the issue of possible experimental error caused by diffraction, a series of publications by Adamowski et al., [77–80], expanded on [75]. Unlike [75] who conducted only a simulation of the diffraction effects, the aforementioned authors conducted physical experiments.

Employing video scan 19 mm (diameter) transducers of 1, 2.5, 5 and 10 MHz and focused 10 mm transducers of 5 MHz, diffraction effects via the through transmission approach were investigated by [77]. The authors found for the 19 mm transducers with frequencies lower than 2 MHz and for 10 mm transducers with frequencies as high as 5 MHz, that diffraction effects caused around 1% error in velocity measurements (note that in both cases diffraction effects were found to reduce as the frequency increased). To counter these effects, the authors replaced the receiving transducer with an 80 mm diameter polyvinylidene fluoride (PVDF) receiver. The authors recorded that the diffraction effects caused a negligible effect on phase velocity measurements, thus the effects were eliminated. Using a 10 mm 5 MHz transducer along with the PVDF receiver, the full set of transversely isotropic CFRP constants were determined. Additionally, the authors noted that as the operational frequency increased so did dispersion effects.

A similar analysis was presented by [78,79], who developed the dispersion aspect slightly further. Using a 19 mm transducer and

Table 8
Elastic constants as determined using the double trough transmission technique and Zimmer and Cost approach for glass epoxy 4 mm thick. *Reprinted from Composites structures, Vol 67/Edition number 1, Reddy, S. Siva Shashidhara, Reddy; Balasubramaniam, Krishnan; Krishnamurthy, C. V; Shankar, M; Ultrasonic goniometry immersion techniques for the measurement of elastic moduli, Pages 3–17., Copyright (2005), with permission from Elsevier.*

Elastic constants (in GPa)	Immersion testing	Contact testing
C_{11}	14.54 ± 0.11	13.65 ± 0.68
C_{13}	11.40 ± 0.42	Not measurable
C_{33}	47.5 ± 0.15	Not measurable
C_{44}	2.9 ± 0.38	Not measurable
C_{66}	4.58 ± 0.36	4.15 ± 0.16

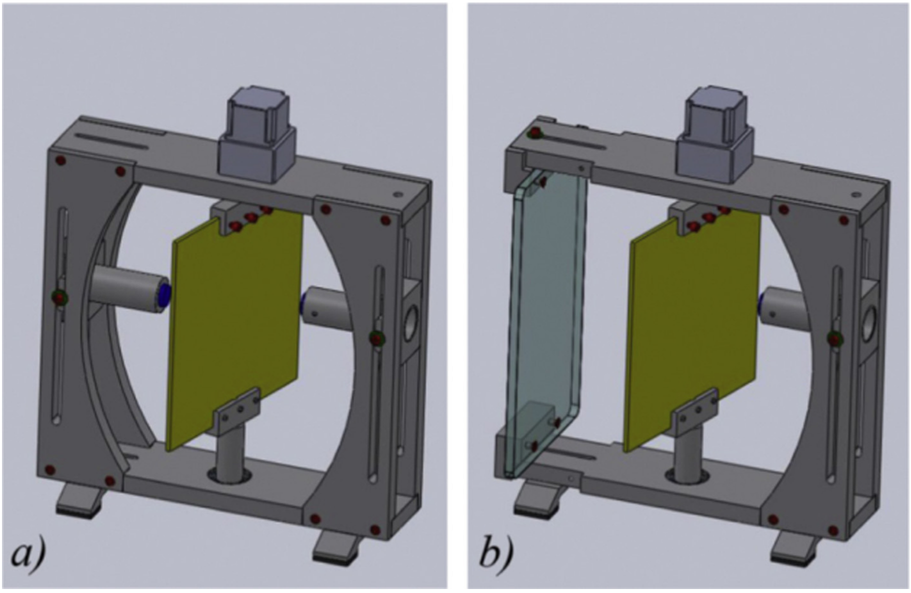

Fig. 27. Equipment used by [83] that allows for both the Markham method Fig. (a) and the double through transmission method Fig. (b) to be used. *Reprinted from Composites part B: Engineering, Vol 66, Castellano, A; Foti, P; Fraddosio, A; Marzano, Salvatore; Piccioni, Mario Daniele; Mechanical characterization of CFRP composites by ultrasonic immersion tests: Experimental and numerical approaches, Pages 299–310, Copyright (2014), with permission from Elsevier.*

PVDF receiver, it was documented that between 1 MHz and 10 MHz, the velocity increased by approximately 1% owing to dispersion effects. Similar reconstruction of elastic constants was also recorded with a 5 MHz and 2.25 MHz transducer being used in the respective publications. Thus, the authors allude to (this aspect is not explicitly investigated) the idea that using a PVDF receiver is a better option when seeking to obtain the phase velocity effects with a high deal of accuracy. Additionally, it can also be stated that although [77–79] demonstrate the elimination of diffraction effects, in terms of unidirectional composite the diffraction effects were not recorded – aluminium was used to record these. Thus these text's cannot be exactly compared with the findings of [75].

An additional publication, extending the diffraction effect further is [80]. Closely paralleling the previous works (note however, this paper also includes density measurements of liquids outside the scope of this review), using the through transmission technique the authors determined the elastic constants via a PVDF based receiver. As before, the changes in velocity caused by diffraction effects in aluminium were found and the authors also report that the distance between transducers was 100 mm. As such, the changes in velocity owing to diffraction effects were again recorded at 1% and changes to velocity owing to dispersion effects within CFRP were found to be 1%. Filling, somewhat, a gap of the previous works, the authors found that if the elastic constants were reconstructed using velocity data that was 1% inaccurate, the resultant constants were within 4% of their correct value.

Concluding this review is [81]. At this point some 45 years of literature documenting bulk ultrasonic wave through transmission of unidirectional fibre composite has provided much information. Thus, [81] document not a new experimental approach designed to increase the accuracy of measurement but instead document a bespoke computer programme to handle an existing measurement technique.

Using the double through transmission approach as pioneered by [41,42] the authors determined the full set of transversely isotropic CFRP elastic constants. The authors used bespoke apparatus which allowed for both the Markham method and the double through transmission approach to be used. Fig. 27 documents the system used.

The main novelty herein was the use of bespoke LabVIEW software. The software, deployed on a commercial PC, was used to control the oscilloscope, the rotation of stepper motor and the acquisition and reprocessing of experimental data to allow for a fully automated experimental process.

Fig. 28 documents the graphic interface developed by the authors.

Such is the precision of the bespoke experimental arrangement, via Snell's laws the three waves which propagate in both the isotropic and anisotropic plane were picked out with good deal of accuracy. Fig. 29, is given to demonstrate the results obtainable.

5. Information tables

This review has identified multiple contributions to knowledge concerning the determination of elastic constants of uni-directional CFRP. These findings are now recorded in two unique information tables. Notable findings documented within literature within the period 1970–1980 are documented in Table 9 and notable findings for the period 1980–present day are documented in Table 10.

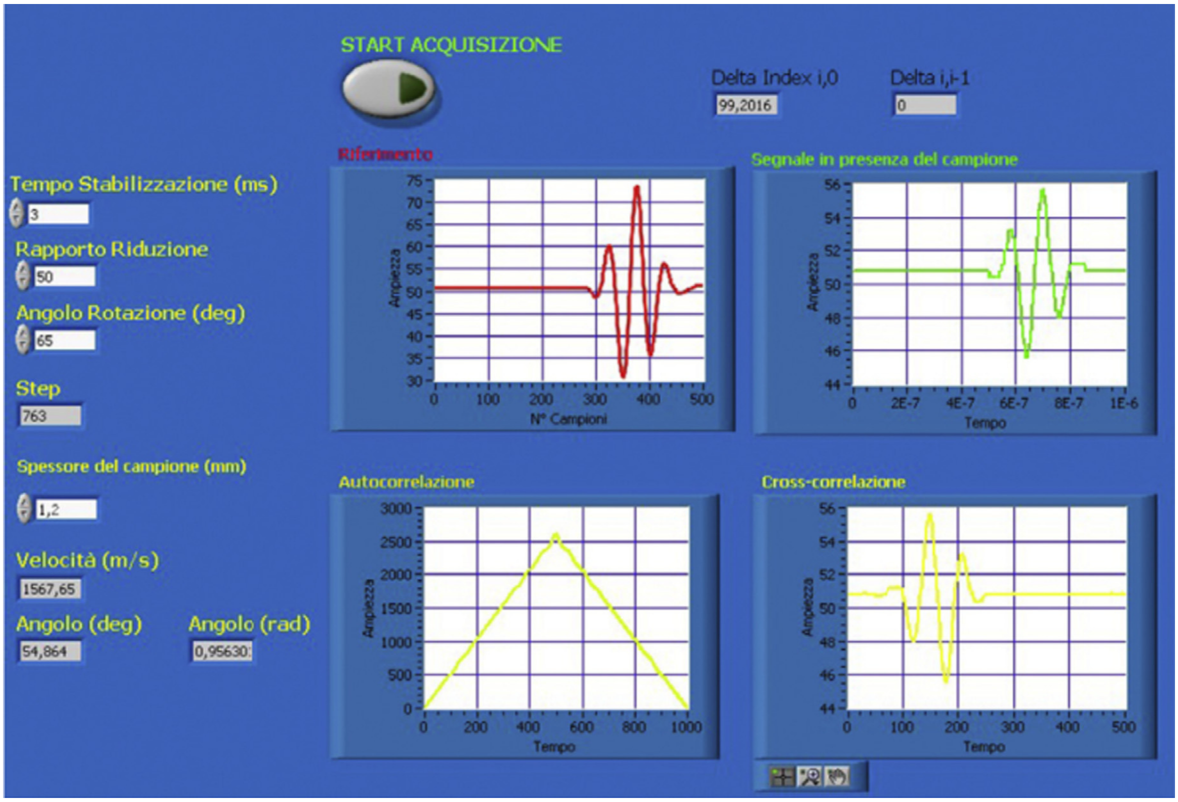

Fig. 28. LabVIEW GUI used by the authors to execute double through transmission experiments. *Reprinted from Composites part B: Engineering, Vol 66, Castellano, A; Foti, P; Fraddosio, A; Marzano, Salvatore; Piccioni, Mario Daniele; Mechanical characterization of CFRP composites by ultrasonic immersion tests: Experimental and numerical approaches, Pages 299–310, Copyright (2014), with permission from Elsevier.*

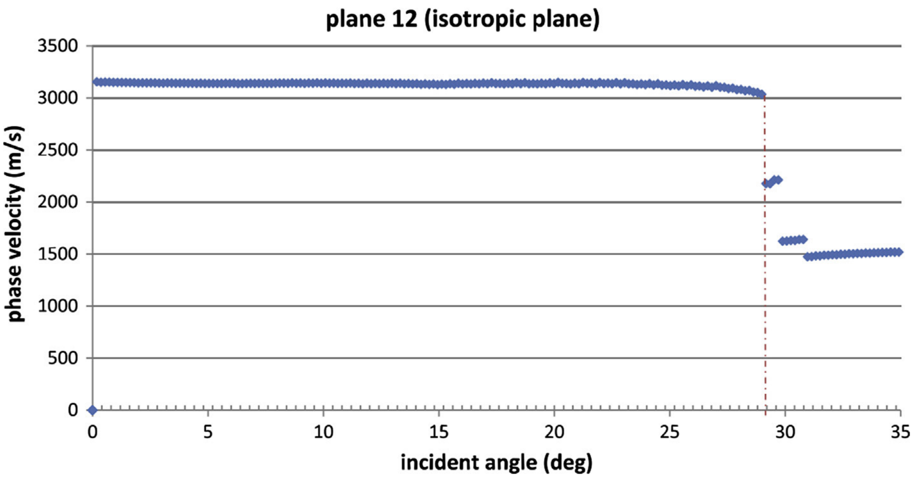

Fig. 29. The longitudinal, fast transverse and slow transverse wave velocity recorded in the isotropic plane. Data between the longitudinal wave and the fast transverse wave is thought to be experimental error. *Reprinted from Composites part B: Engineering, Vol 66, Castellano, A; Foti, P; Fraddosio, A; Marzano, Salvatore; Piccioni, Mario Daniele; Mechanical characterization of CFRP composites by ultrasonic immersion tests: Experimental and numerical approaches, Pages 299–310, Copyright (2014), with permission from Elsevier.*

6. Further reading

6.1. Air coupled ultrasound (developed in parallel with immersion methods)

An area not discussed in this review is the determination of elastic constants via air coupled ultrasound, i.e. only wave

Table 9
Key findings from the reviewed text. Findings demonstrate the ultrasonic velocity measurements are a legitimate and able practice to determine the elastic constants of transversely isotropic CFRP and what the constants are dependent upon. Findings also indicate the applicability of ultrasonic velocity measurements to gauge the porosity, fibre concentration and degree of disorientation of transversely isotropic CFRP.

Key findings: 1970–1980	Authors
Standard transmitting frequency used in measurements is 5 MHz but some authors also reported lower frequency at around 1 MHz	All
Sample specimen is limited to ensure body wave behaviour (in general thickness kept above two wavelengths and wavelength kept above fibre diameter)	All
When propagating in fibre direction, if pulse width equal to sample width, data on mode changing in inconclusive	[23]
Unidirectional composite causes the wave energy direction to skew at angle, θ, from the phase wave front normal when waves strike surface obliquely	[35]
Velocity able to be measured using direct contact through transmission technique	[20,25,28,35]
Velocity able to be measured via immersing transducers in water and rotating sample and using through transmission technique	[21–25,28]
Velocity able to be measured using prism technique	[21,23–25,28]
All elastic constants determined	[20–23,25,28,35]
Composite Young's Modulus (at varying angles to fibre axis) can be determined from velocity measurements	[20,23,24]
C_{44} changes value depending whether the fibre axis is perpendicular or parallel to wave direction	[20–24,35]
Theoretical predictions for stiffness are in general in close agreement with experiment when propagating shear waves polarized in plane of the fibre from 0° to 90° in CFRP (using C_{44} measured perpendicular to fibre axis)	[22,25,28]
When propagating longitudinal waves for angles greater than 0° and less than 90° to the fibre direction in CFRP (in the plane of the fibre), the experimental values for stiffness do not follow the expect theoretical curve, thus, through attenuation, refraction and reflection (a pseudo-L wave is actually being propagated throughout the sample)	[25,28]
Theoretical predictions for stiffness are in general closer to experimental values when angle of propagation direction to fibre axis is > 65° when propagating shear waves polarized perpendicular to plane of the fibre from 0° to 90° in glass composite or CFRP	[20,25]
Theoretical predictions for stiffness are not in as good agreement with experiment to those of shear waves when propagating longitudinal waves from 0° to 90° in glass composite	[20],
The elastic constants determined through ultrasound velocity technique may be used with theoretical predictions to calculate individual fibre properties	[22,28,35]
Composite elastic constants $C_{11,}$ C_{33} and C_{66} are dependent on the fibre Young's modulus, while C_{13} and C_{44} are independent of fibre modulus but vary with fibre type (graphite fibres) and have a slightly unclear relationship in carbon fibres. Also, elastic constants do not greatly depend on shear strength of composite	[22]
Average elastic constants of disorientated CFRP (in one plane only) can be calculated	[24]
Velocity in fibre direction is not greatly impacted by void content and only a small dependency on type of resin used	[24,28]
Velocity perpendicular to fibres dependent on both void content and type of fibre concentration	[24,28]
Elastic constant determination through velocity measurements may be used to determine degree of porosity and fibre content	[28]

propagation via a gel, or fluid has been considered. Given that techniques such as double through transmission are documented in this area, [82], it is of merit to briefly discuss the benefits and drawbacks of air coupled ultrasound and to identify further literature.

A difficulty associated with air coupled ultrasound, not generally present in immersion based ultrasound, is the efficient propagation of ultrasonic waves. This arises from a typically large impedance mismatch between the transducer and the naturally compliant air (noting that opposite relationship is found in solids and fluids). Further, the much slower wave speed recorded in air when compared to solids and fluids can cause extreme refraction angles for incident waves, Further still, coupling work best when the densities and wave speeds of mediums are approximately the same; this is not the case with solids and air and so air coupled ultrasound leads to problematic and high attenuation [12].

Air coupled ultrasound does have its advantages however; advantages include the ability to conduct experiments in both a laboratory and field setting, the ubiquitous nature and free cost of air, the lack of additional equipment needed to create an immersion medium and the fact that air does not contaminate any advanced materials which may otherwise be susceptible to contamination by a particular coupling agent.

As this review has focused on literature which used very efficient coupling mediums, and the fact that the laws of physics governing the elastic constant relationship to phase velocity do not change with respect to the coupling medium, the decision was made not to include air coupled ultrasound in this review. Given the advantages outlined however, even with the drawbacks air coupled ultrasound is an area of interest in NDT/E. A recent literature review by Professor Chimenti of Iowa State University, [83], identifies both pertinent literature and also gives particular focus to the many seminal works conducted by a Bordeaux research group led by Professor Hosten at Bordeaux University.

6.2. Composite incorporating reclaimed fibres – processing structure property relationships

This review has examined the adoption of ultrasound through transmission to determine the elastic constants of transversely isotropic virgin CFRP. In this measurement system the structure and properties of the material are directly related to phase velocity; phase velocity is dependent on material density and stiffness.

Currently, the material structure and properties of virgin CFRP are such that the various ultrasonic experimental arrangements identified in this review are capable means to determining phase velocity and elastic constants; in some instances highly accurate results can be obtained (region of 1% of expected value).

Conversely, with increasing mechanical and fibre reclamation based composite recycling operations, [84], the processing

Table 10
Key findings from the reviewed text. Findings demonstrate the double through transmission is used extensively along with elastic constant reconstruction algorithms. These findings also indicate the optimum way to determine constants from orthotropic material along with methods to increase accuracy of results.

Key findings from 1980 to 2014	Authors
Establishment of group velocity relationship to phase velocity using time of flight data	All
Identification of possible error arising from incorrect placement of receiving transducers in Markham Method	[38,41,44]
Group velocity effects cause different degrees of deviation for different wave types	[38,41,44,81]
A least squares minimization technique used (wholly or in part) to determine the set of elastic constants	[38,41,44,49,50,73,75–81]
Investigated robustness of least squares algorithm in relation to the choice of initial guess of elastic constant and noise inserted onto phase velocity measurements	[44,49,50]
Identification that when using least squares algorithm for limited velocity data on orthotropic unidirectional graphite composite that ideally longitudinal waves should cover the region 0–45° (or above) and transverse waves should cover the region 35–75° (or above) to the fibre axis	[49]
Double through transmission method used to determine phase velocity/elastic constants	[41,44,76,81]
Orientation of the principal axis of symmetry determined using the Markham method	[45]
15 MHz transducer used in double through transmission arrangement	[44]
Self-reference method used to determine phase velocity/elastic constants	[47,49,50,73,75]
Double through transmission system encounters maximum error due to parallelism effects at normal incidence and decreases as angle of refraction increases with the self-reference method having a contrasting relationship for phase velocity measurements in unidirectional graphite fibre composite	[47]
Identification of the optimum wave refraction angles, within a plane of symmetry, for determination of seven out of nine elastic constants in a weakly anisotropic composite (orthotropic unidirectional graphite composite)	[49]
Identification that for a strongly anisotropic composite (orthotropic unidirectional graphite composite) the sensitivity of elastic constants is not dependently only the refraction angle (i.e. phase velocity is not dependent on angle of refraction only)	[49]
Identification that for orthotropic materials that determination of seven, out of nine, elastic constants from symmetry planes and the remaining two, out of nine, from non-symmetry planes will result in more accurate values than would determination of all constants from non-symmetry planes	[50]
Identification of optimum refraction angles for determination of two elastic constants in non-symmetry planes of unidirectional orthotropic graphite composite	[50]
Identification, including subsequent compensation measures, that at certain angles of incidence a resultant phase shift can cause erroneous phase velocity measurements	[73,75]
Diffraction effects cause a reduction in amplitude while having little effect on phase velocity measurements for refraction angles out with critical angle regions on unidirectional graphite fibre composite	[75]
Double through transmission verified as producing more precise and repeatable results than Markham method with more inaccuracy being recorded as the thickness of samples grew (transducers fixed)	[76]
Demonstrated that as frequency increased diffraction effects decreased and dispersion effects increased for an aluminium plate and employed a PVDF receiver to reduce possible diffraction effects and measured elastic constants of unidirectional graphite fibre composite	[77–80]
Demonstrated that bespoke PC software, created on LabVIEW, was able to facilitate automated double through transmission based experiments	[81]

structure property relationships of modern materials manufactured using fibres obtained via recycling may be such that through transmission needs to be re-evaluated as a means to determine elastic constants.

Developing this, consider [85,86], who identify processing structure property relationships ultimately responsible for the final properties of virgin carbon fibre and CFRP; areas such as fibre type, fibre arrangement, longitudinal and transverse properties, manufacturing process, fibre volume fraction, external environment, fibre coating, fibre fracture toughness, and compressive strength etc. are discussed. A similar literature review by [6] on glass and carbon fibre recycling and subsequent reuse in new composite identifies multiple areas of where the recycling processes can affect the property structure relationships, with areas such as fibre length, fibre degradation, sizing removal, alignment, fibre type, type of recycling process, pitting, manufacturing process all discussed.

Given that the composite recycling process at present does not produce ideal fibres in an identical pre-impregnated state, and the proliferation of mechanical recycling in this area and lack of ultrasonic NDE literature, this review has outlined multiple areas of ultrasonic based investigation for researchers involved in composite reuse. Further reading on the composite recycling and reuse is found, including the structure of the resulting fibres is available via [5,7,8,87–90].

7. Conclusion

This review has documented the progression of how the elastic constants of unidirectional composite were experimentally determined using ultrasonic bulk wave velocity measurements as outlined in publications spanning 1970–2014. Additionally, it outlines which experimental techniques are used by which authors and documents the most accurate technique of modern times, the double through transmission technique.

This review differs from previous review works in that the scope was limited in order to enable a deeper analysis (in terms of experimental findings) of the individual publications. Performing such an analysis allowed for (a) the contribution to knowledge from a particular publication to be presented in its own right, with significant findings being presented in Tables 9 and 10 (documenting some 40 different contributions to knowledge), (b) any issues with a publication were identified and (c) seminal works during this period were able to be collated and organized in one document, resulting in a review which is chronological in structure and has arguably more depth than current existing reviews.

It was also recorded that there is a paucity of literature concerning ultrasonic through transmission based determination of elastic constants of CFRP manufactured using reclaimed fibres obtained via recycling. With over 45 years of recorded knowledge and experimentation conducted on uni-directional v-CFRP, this review has given insight into the type of research that has yet to be conducted on these relatively new materials. Given that composite recycling may result in materials with wide ranging properties, areas outlined in this review such as elastic constant determination, critical angle measurements, phase shifts, group velocity effects, robustness of reconstruction algorithms in terms of scatter and plane of determination, etc. are all potential areas for future investigation.

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Author contributions

David Paterson prepared an initial draft of this manuscript. Winifred Ijomah, James Windmill and David Paterson reviewed and revised the submitted manuscript. All authors approved the final article.

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