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NONLINEAR ACOUSTICS AND HONEYCOMB MATERIALS

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ABSTRACT. The scope of research activity that Bruce Thompson embraced was very large. In this talk three different research topics that the author shared with Bruce are reviewed. They represent Bruce's introduction to NDE and include nonlinear acoustics, nondestructive measurements of adhesive bond strengths in honeycomb panels, and studies of flexural wave dispersion in honeycomb materials. In the first of these, four harmonics of a 30 Mhz finite amplitude wave were measured for both fused silica and aluminum single crystals with varying lengths and amounts of cold work using a capacity microphone with heterodyne receiver with a flat frequency response from 30 to 250 Mhz. The results for fused silica with no dislocation structure could be described by a model due to Fubini, originally developed for gases, that depends upon only the second and third order elastic constants and not the fourth and higher order constants. The same was not true for the aluminum with dislocation structures. These results raised some questions about models for harmonic generation in materials with dislocations. In the second topic, experiments were made to determine the adhesive bond strengths of honeycomb panels using the vibrational response of the panels (Chladni figures). The results showed that both the damping characteristics of panel vibrations as a whole and velocity of propagation of elastic waves that travel along the surface and sample the bondline can be correlated with destructively determined bond strengths. Finally, the phase velocity of flexural waves traveling along a 1-inch honeycomb sandwich panel was determined from 170 Hz to 50 Khz, ranging from 2.2×10^4 cm/sec at the low end to 1.18 $\times 10^5$ cm/sec at 40 Khz. The dispersion arises from the finite thickness of the panel and agreed with the results of continuum models for the honeycomb. Above 40 Khz, this was not the case. The paper concludes with a tribute to Bruce for his many wonderful contributions and lessons beyond his technical legacy for all of us.

Keywords: Harmonic Generation, Nonlinear Parameter, Honeycomb, Bond Strength, Dispersion Curves
PACS: 42.65.Ky, 33.15.Fm

INTRODUCTION

Bruce Thompson, or Bruce as he was known to all, was a leader in the evolution of QNDE. He was a Distinguished Professor of Engineering at ISU, Director of the Center for NDE there, a member of the NAE and Editor of JONE, and he served as host and co-organizer of this conference for the past 14 years. He left the technical NDE community with a legacy of over 200 published papers, 24 patents, and a host of friends throughout the world. It is altogether fitting that we honor Bruce's memory with a tribute to him and to the

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wide diversity and excellence of his technical work this morning. He indeed was an intellectual giant.

I first met Bruce when he applied for an open position in my group at the North American Rockwell Science Center (NARSC) in 1969, joining us in 1970 as he finished his graduate work at Stanford. At that time, our company, North American Aviation, then North American Rockwell, was heavily involved in the shuttle program and the B-1 bomber program that placed new demands upon NDE resulting in a request to increase the NDE group size at the Science Center at Thousand Oaks. Bruce was a wonderful addition. It was my privilege to work with him from then until his death in March, 2011. He was my best friend and colleague during this entire time. We shared many research projects and, with the group, developed plans and actions that initiated movement to develop a quantitative NDE technology that would satisfy the needs of the new damage tolerant design practices, initiated the QNDE conference, founded the Center for NDE at ISU, performed several seminal research programs, and initiated the World Federation of NDE Centers.

The work that I will discuss today in tribute to Bruce was ongoing at the time Bruce joined the Science Center and was performed by Bruce, other members of my group, and myself. It represents Bruce's introduction to NDE.

Higher Harmonics of Finite Amplitude Waves in Solids [1]

One of the first projects that Bruce joined at the Science center was ongoing work with Otto Buck and myself in looking at harmonic generation in solids as a way to characterize the dislocation structure of the material. Before we could do that successfully, we all felt that we needed to establish fully the base line of harmonics produced by lattice nonlinearities. Bruce suggested that we utilize Fubini's [2] model that predicts harmonic magnitudes in gases using dislocation free fused silica as a means to establish the baseline. It is a power series expansion for particle displacement that includes only the lowest order nonlinear parameter of several that occur in the nonlinear wave equation expansion for solids. This approach would provide a simpler interpretation of results if it worked.

We used a newly developed capacity microphone fitted with a heterodyne receiver to detect the harmonic distortions. It was far superior to other methods we had used at that time including direct amplification. The device had a flat frequency response from 10 to over 250 Mhz and could be calibrated in absolute units. A calibration curve is shown in Fig. 1 that covers more than a 60 dB range.

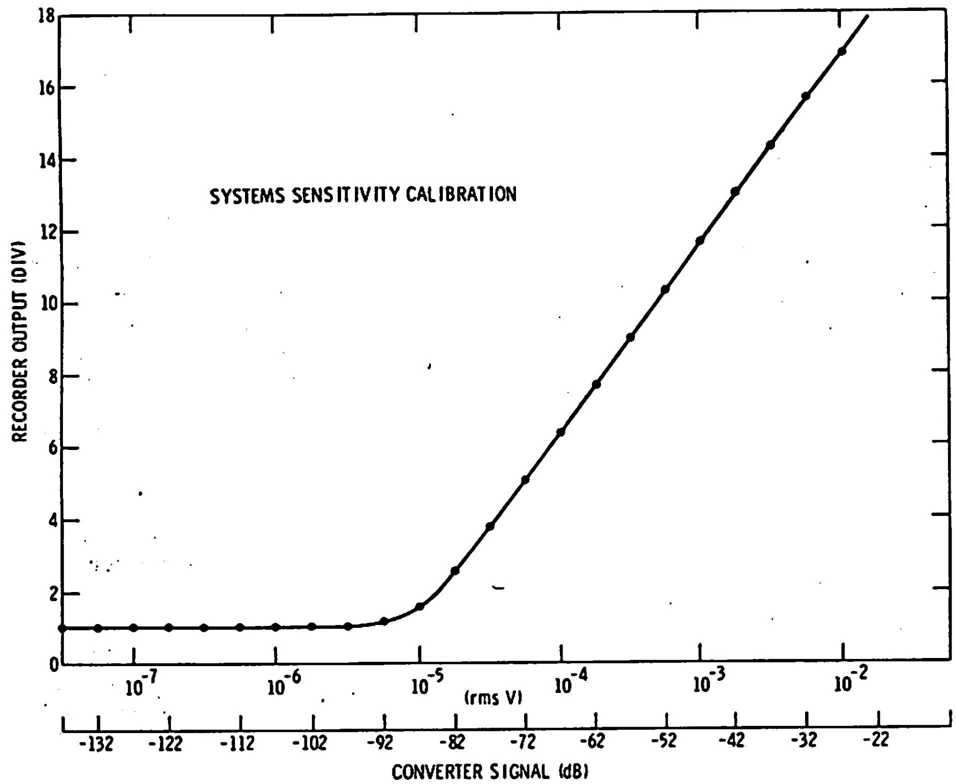


FIGURE 1. Calibration curve for capacitance microphone with heterodyne receiver [1].

Fused silica rods of different lengths with no dislocation component were used to establish the baseline. Figure 2 shows four harmonics in the fused silica both in terms of recorder output and absolute displacement of the stress free end of the sample. Figure 3 shows the result of comparing the results with Fubini's model predictions. In this plot, the vertical axis is the normalized harmonic displacements of the four harmonics plotted against the normalized propagation distance x/Lo from Fubini's model. x is the length of the sample and Lo is a characteristic length and is inversely proportional to the nonlinear parameter. All four harmonics were fitted with only one common value of the parameter Lo and therefore only the first nonlinear expansion parameter was needed. This meant that only third order elastic constants were needed to characterize lattice anharmonicity in dislocation free solids. The establishment of Fubini's model as sufficient to describe lattice contributions in dislocation free material was an important step and established a baseline from which dislocation effects could be measured in ductile materials.

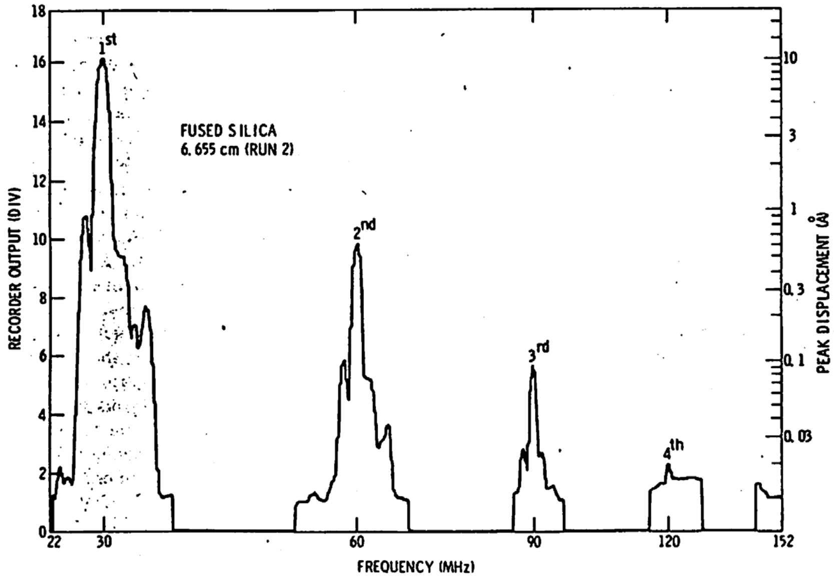


FIGURE 2. Four harmonics detected in fused silica sample. The scale on right is the absolute displacement in Angstroms [1].

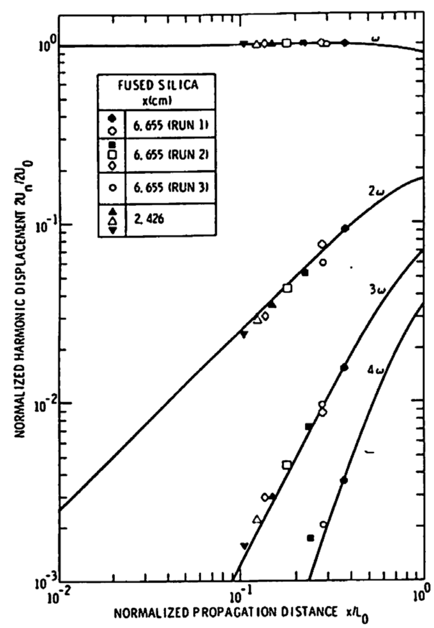


FIGURE 3. Normalized harmonic displacement plotted against the normalized propagation distance. The normalize propagation distance is proportional to the reciprocal of the nonlinear parameter [1].

We also conducted experiments with aluminum single crystals. These experiments showed that the absolute values of the harmonics could not be fitted to the calculated curves shown in Fig. 3 as was the case for the dislocation free fused silica, and furthermore, none of the harmonic amplitudes could be predicted in terms of the fundamental displacement and known third order elastic constants. Figure 4 shows the variation in normalized second and third harmonics for 30 -Mhz fundamental waves with propagation along the [100] axis when the dislocation structure was changed by cold work. Also shown (dotted-dashed straight lines) are the values of harmonics predicted by Fubini's model. It

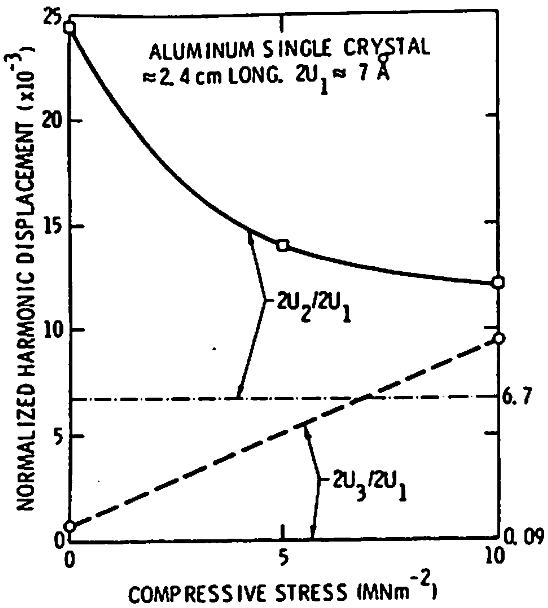


FIGURE 4. The normalized second and third harmonics for an aluminum crystal plotted as a function of compressive stress [1].

was clear that the dislocation structure contributed greatly to the measured results; it was also clear that the results did not follow the results expected at that time for the dislocation contribution [3]. The third harmonic increased as expected, but the second, measured simultaneously, decreased to a value closer to that expected for lattice contribution only.

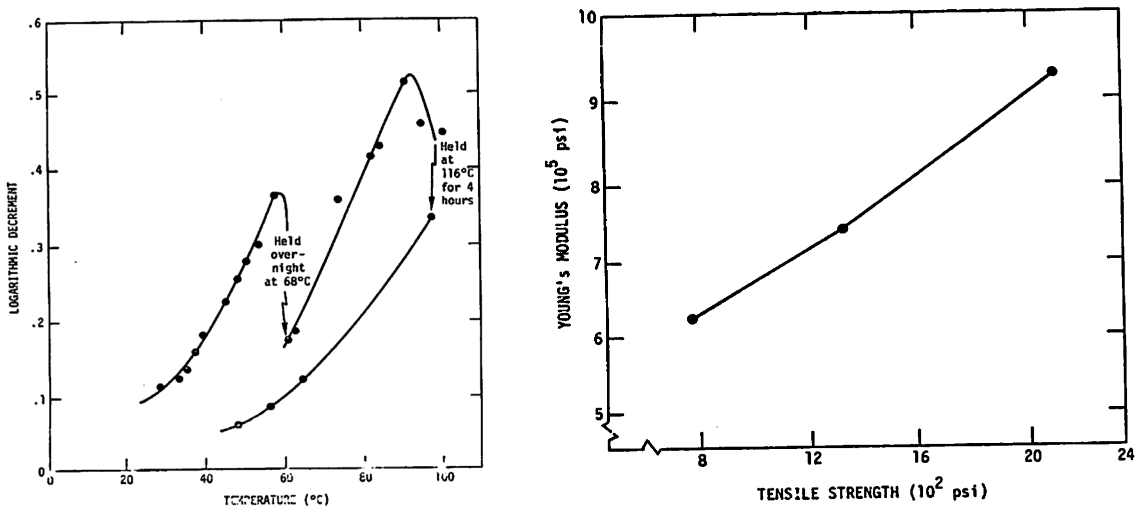
We drew several conclusions from this work. They were:

- Agreement for fused silica with Fubini's model demonstrates that elastic constants of higher than third order do not contribute appreciably to lattice harmonicity in dislocation free material.
- The agreement is striking because it includes only the lowest order non linear parameter that occurs in the wave equation for solids.
- Harmonic results for aluminum crystals do not follow Fubini's model at all and are inconsistent with existing (1976) dislocation models .

Nondestructive Measurement of Adhesive Bond Strength in Honeycomb Panels [3]

Bruce joined another important ongoing project sponsored by the Company as soon as he joined the Science Center. New materials at that time included composites and honeycomb panels and questions of bond and interfacial strengths were paramount in various applications. The Science Center project was coupled with other research activity within the company that was focused upon the investigation of vibrational responses of adhesively bonded honeycomb panels as a possible way to determine bond strength. Then, as now, this was a complicated issue that involved both the adhesive and cohesive strengths of the bond and bond material.

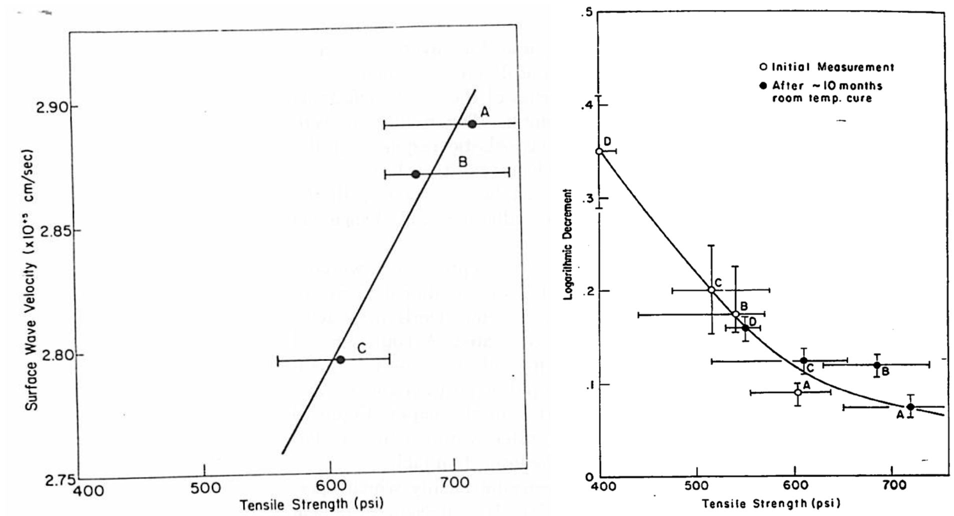
As a first step, we decided to work only with the variation in strength that could be achieved by controlling the adhesive material's cure cycle (the cohesive part) and its effect



FIGURES 5A and 5B. Plot of the logarithmic decrement as a function of curing temperature (Fig. 5A-left) and plot of the Young's modulus as a function of measured tensile strength for the HT-424 adhesive (Fig. 5B-right). [From Materials Evaluation, Vol. XXXII, No. 4. Reprinted with permission of the American Society for Nondestructive Testing, Inc. This reprint contains copyrighted property of the American Society for Nondestructive Testing, Inc. and may not be duplicated or altered in any manner.]

upon the vibrational response of the panel. To understand the properties of the adhesive itself, we made a series of resonant rods from the adhesive only and showed that not only the tensile strength of the rods but also the Young's modulus and damping of the rods were a function of the cure time and temperature. Figure 5A shows the reduction in logarithmic decrement of the adhesive with cure time at temperature, and Fig. 5B shows the variation of Young's modulus with tensile strength at room temperature that was generated by curing at successively higher temperatures.

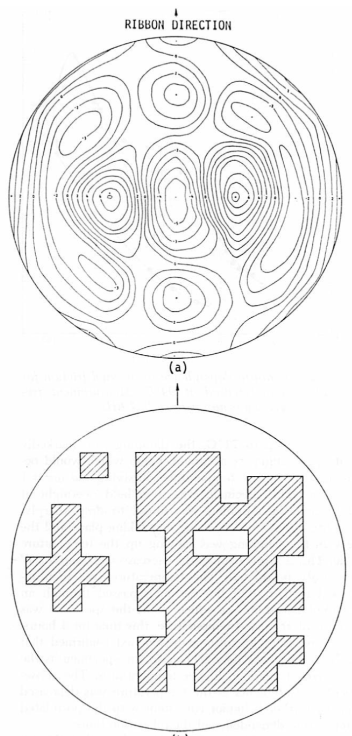
The next step was to transfer this information to a set of fabricated panels and subject them to the same cure cycles and measure their vibratory responses. The panels were 18x18 inches with 1/16 inch aluminum face sheets and 4 ¾ inch phenolic core bonded with a HT-424 adhesive and pre-aged at different times and temperatures. The panels were vibrated by setting them in a test frame, exciting them with a non-contacting electromagnetic driving transducer, and then detecting the vibration with a lightweight phonograph pickup that was scanned over the surface of the panels. Figure 6A shows the surface wave velocity at 300 Khz. and Fig 6B shows the damping of the same panels at 7.2 Khz , both plotted against tensile strength of the panel. Open circles are the results at time of fabrication for different curing conditions and solid circles are the damping values after 10 months at room temperature. Tensile strengths were measured by testing 2 inch squares cut from identical panels.. At 300 Khz. the surface wave energy does not extend through the panel but only penetrates the adhesive layer itself and thus provides a measure of its strength. From these experiments we concluded that vibratory tests provided strength information but that we needed to speed up the test procedure dramatically.



FIGURES 6A and 6B. Surface wave velocities at 300Khz as function of panel tensile strength for differently cured panels (Fig. 6A-left) and logarithmic decrement at 7.2 Khz for the same panels (Fig. 6B-right). [From Materials Evaluation, Vol. XXXII, No. 4. Reprinted with permission of the American Society for Nondestructive Testing, Inc. This reprint contains copyrighted property of the American Society for Nondestructive Testing, Inc. and may not be duplicated or altered in any manner.]

We then assembled a computerized test system shown in Fig. 7 that would handle a 4x4 foot panel. Bruce is shown at the computer controls and George Alers is shown setting a panel in place. The panel was driven by a non-contact electromagnetic transducer positioned at the center of the panel and operated at frequencies below 50 Khz; the panel vibrations were detected with a lightweight phonograph pickup. We added some specialized optical equipment to better display traveling acoustic surface waves. The electromagnetic transducer was designed by Bruce and represents his entry into EMAT technology.

FIGURE 7. Photograph of computerized test system with Bruce Thompson seated at the controls and George Alers setting a panel in place. [From Materials Evaluation, Vol. XXXII, No. 4. Reprinted with permission of the American Society for Nondestructive Testing, Inc. This reprint contains copyrighted property of the American Society for Nondestructive Testing, Inc. and may not be duplicated or altered in any manner.]



FIGURES 8A and 8B. Chladni pattern for 24 inch round panel at 4 Khz. (Fig 8A-top) and tensile strength map of same panel (8B-bottom). [From Materials Evaluation, Vol. XXXII, No. 4. Reprinted with permission of the American Society for Nondestructive Testing, Inc. This reprint contains copyrighted property of the American Society for Nondestructive Testing, Inc. and may not be duplicated or altered in any manner.]

Figure 8A shows a Chladni figure at 4Khz that was obtained for a 24 inch round specimen with the automated apparatus. The lines connect the dots of equal vibratory amplitudes. Changes in the panel stiffness influence the nodal spacing and were correlated with flexural wave propagation velocity. Some asymmetry can be noted in the lower right quadrant of the figure. This panel was subsequently cut into 2 inch squares and tensile tested. Figure 8B gives the results of those tests with the shaded areas showing below average tensile strengths and with some correlation with the asymmetric vibration patterns.

We developed several conclusions from this work. They were:

- It's likely that cohesive bond strength could be inferred from various features of the vibrational response of panels. We also expected that variations in the adhesive strength would also affect the vibratory patterns but this possibility was not tested.
- Measurements suggested that data at different frequencies were sensitive to different properties of the bond.
- Results obtained were consistent with the expected viscoelastic response of the adhesive system.

Dispersion of Flexural Elastic Waves in Honeycomb Sandwich Panels

The third and final project that I want to discuss is one initiated by Bruce after our honeycomb studies. As I said earlier, we had learned in that work that important structural characteristics of the honeycomb structure may be selectively sensitive to measurement at

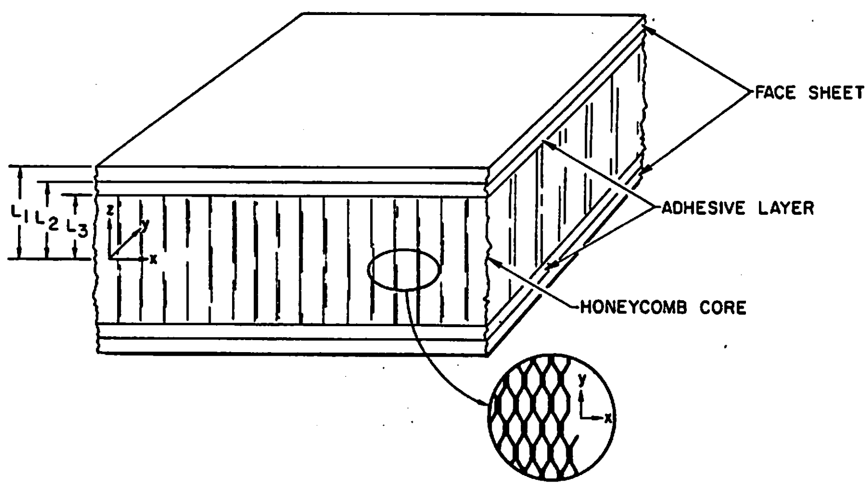


FIGURE 9. The five–layered honeycomb panel considered in this work [4].

different frequencies. Thus, a detailed knowledge of the dynamic elastic response of the honeycomb "plate" from a few hertz to megahertz frequencies was deemed important. The highly anisotropic nature of the structure also made a study of these properties one of high interest in the field of elastic wave propagation. Both of these topics were of especial interest to Bruce. He initiated this difficult project with group support to calculate and measure the dispersion of elastic waves in a honeycomb structure.

The honeycomb panel considered is the same as that used in the previous study and is shown in Fig. 9. It consisted of a symmetric sandwich of three components: a central core bonded between two outer face sheets by thin but finite adhesive layers. Bruce's model thus consisted of a five-layered system in which each layer was assumed to be a continuum described by elastic constants and a density. He considered the face sheets and adhesives to be isotropic with two elastic constants and the core to be an orthorhombic continuum described by nine elastic constants.

Bruce calculated the dispersion of straight-crested guided elastic waves in this medium in two different ways – one based on the theory of plates and the other using elasticity theory. He first assumed using plate theory that cross sections remained perpendicular to the neutral axis during deformation; he later modified this assumption and allowed for shearing in the core and the effects of rotary inertia during dynamic deformation. For the second, more complete elastic case, solutions for the anisotropic equations within each layer were combined to satisfy the boundary conditions to give a family of solutions that describe the freely propagating waves. Figure 10 shows Bruce's results for these two different models. Up to 25 Khz. the elastic theory and the modified plate theory agreed to within 1 %. Above 40 Khz significant differences occurred between the full elastic and plate models. A multivalued phase velocity was predicted by the full-elastic model; this was thought to be due to complications of using a continuum model for the core instead of the real cellular condition.

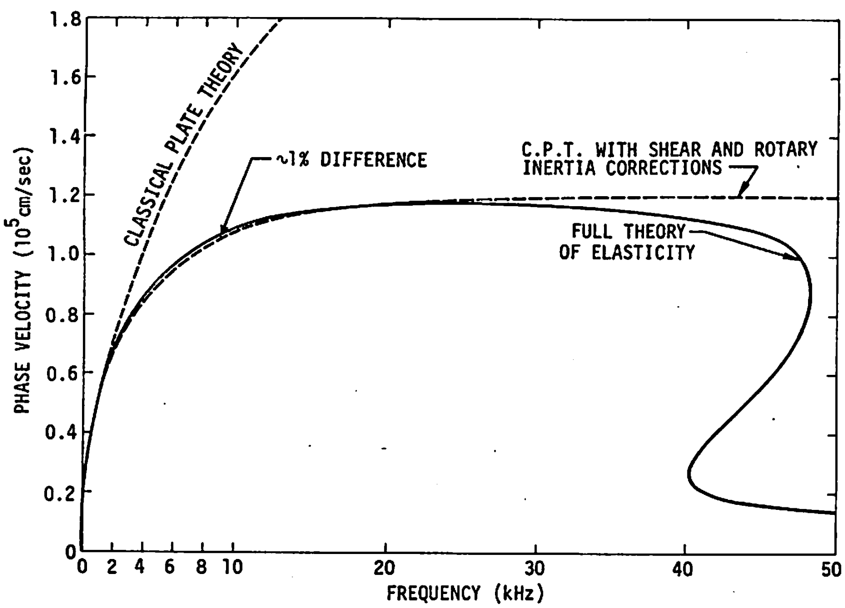


FIGURE 10. Phase velocity predictions from plate theory and full elastic model for honeycomb panel [4].

Three different experimental techniques were used to determine the phase velocities using both beam–like samples cut from a honeycomb panel and the panels themselves. They were a resonant frequency method at low frequencies (<1 Khz) where the acoustic wavelength was of the order of the beam length, standing wave patterns for higher frequencies (1-20 Khz) where the beam length was several wavelengths long, and pulsed signals using the full panels for higher frequencies yet (20Khz-50Khz). Figure 11 shows results obtained for the three compared with Bruce's model for the entire range <1 Khz -50 Khz. Only at the high end do the values diverge, probably because the cellular nature of the honeycomb becomes important.

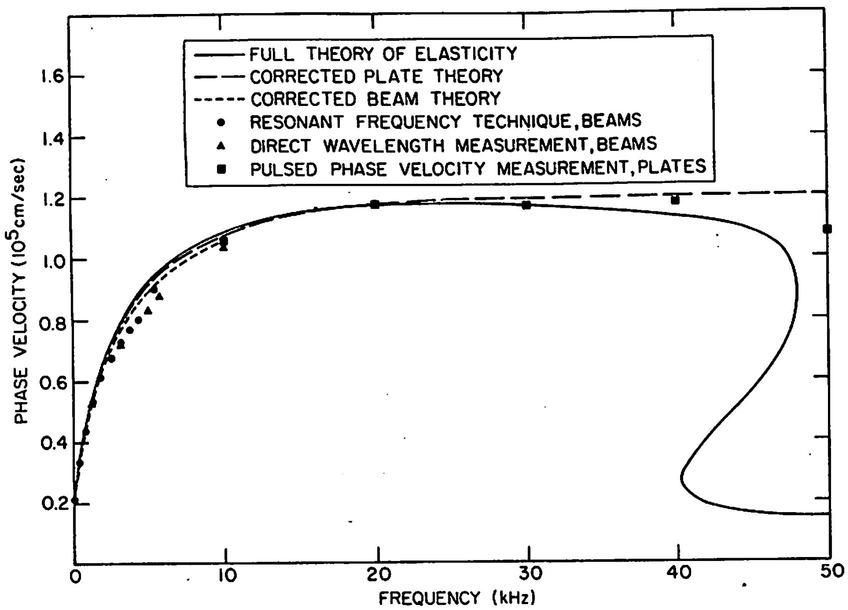


FIGURE 11. Experimental and model results for dispersion of flexural waves in a honeycomb panel [4].

Conclusions that resulted from this work were:

- For frequencies <40 Khz,, phase velocities measured by three different techniques agreed with the models.
- Models diverged widely in their predictions for this honeycomb structure above 50Khz.
- Failure of models above 50 Khz. was due to cutoff effect in periodic structure.

FINAL COMMENTS

I also wish to pay tribute to Bruce for his many gifts to us besides his technical genius**.** He led a life characterized by commitment and passion - his family, his work, outdoor activity, maps, and always new experiences. He was always humble, a genuine person with a heart of gold. As many have said, his boundless wisdom was matched only by his warmth and willingness to share. Some of Bruce's greatest gifts were his interpersonal skills –his ability to communicate with clarity and his sense of fairness for all. He was unequaled in his ability to explain complicated and difficult to understand technical issues. Perhaps his greatest gift was his sense of fairness and its demand for justice for all. He always saw the best in any person's actions and always put the best construction on all that the person did. In doing so, he had a firm faith that "…things will work out." Besides his legacy of technical work and contributions to QNDE, Bruce leaves behind a rich legacy of family and friends, students and colleagues, and a philosophy for life built upon a wise use of bountiful gifts. We all will miss him greatly and are so privileged to have known and shared time with him.

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