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## Static versus low frequency dynamic elastic modulus measurement of thin films

*Received 10.10.2006, published 22.12.2006*

A new experimental technique for evaluating Young's (or elastic) modulus of a vibrating thin film from a dynamic measurement is presented. The technique utilizes bending resonance from a remote acoustic excitation to determine Young's modulus. Equations relating the natural frequencies to the mechanical properties are obtained, and Young's modulus is subsequently determined. Young's modulus values from dynamic test are compared with those (static) obtained by a standard tensile test, and consistent results are obtained. The proposed technique is relatively simple and could be used to determine Young's modulus of a wide variety of sheet materials initially having no bending stiffness. It can also be used for determining other mechanical properties, such as compliance methods in connections with fracture mechanical testing, fatigue and damage measurements. This work emphasizes the feasibility of a damage assessment of components in-service by evaluating changes in the material characteristics.

### INTRODUCTION

Thin films are used in a wide variety of applications including packaging materials, heat shrink wrap, consumer plastic bags, and adhesive tapes. The purpose of using them may require high stretching like in food wraps, or low stretching such as for protective coatings. Therefore, elastic modulus, which is the measure of the film's resistance to stretching, appears to be an important property to assess. The films investigated in this study are Low Density PolyEthylene (LDPE) and Paperboard (PPR) of thicknesses 27  $\mu\text{m}$  and 100  $\mu\text{m}$  respectively, shown in figure 1.

The film is considered as a membrane. Membrane structures are thin three-dimensional surfaces providing significant load resistance only in the direction tangential to their surface. In an ideal case, membrane structures are two-dimensional surfaces having no bending stiffness because they have negligible thickness. In the present study, the material is slightly loaded in the longitudinal direction in order to act as a structural material, and thus can be seen as a membrane with small but non-negligible bending stiffness.

Various testing techniques to determine the properties of thin films have been investigated in literature. In a previous work [1], mechanical and fracture properties of typical thin films were studied by the most common technique which is the tensile test. That technique considers a specimen size according to the standard ASTM-D882 [2]. Among other most established techniques, we can cite the Nano-indentation test [3],

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especially of thin films on substrates, which determines closed-form relations of Young's modulus  $E$  in terms of film thickness and properties of the constituent materials. Shu-Lin Bai [4] also used the nano-indentation technique to determine Young's modulus of thin polymer composites. Bulge or membrane test [5] requires the model of the behavior of the test structure and, in the case of a linear material, can provide Young's modulus; by this test, a membrane of a thin film is prepared by etching away a portion of the substrate on which the film is deposited; the membrane is then pressurized and the measured deflection is used to determine the mechanical properties. Micro-tensile test [6] benefits from its direct measurement of force and displacement. Each of these methods does have strengths and weaknesses with respect to test specimen preparation and experimental result analysis.



Figure 1.  
Materials studied

Nevertheless, wave propagation characteristics of elastic materials are used extensively for the determination of material properties. Indeed, various techniques for estimation of Young's modulus of a material using its dynamical response have been proposed in literature. Most of the techniques are applicable to bulk materials and those dealing with the investigation of transverse flexural mode use an impact excitation, and a piezoelectric accelerometer contact transducer [7].

More recent approaches based on non-contact excitation and sensing have been developed for measuring mechanical properties. Among these methods, the cantilever beam loading method, in which the load is applied by various means, has become an effective technique. Comella and Scanlon [8] determined the stiffness and elastic modulus of an array of aluminum cantilever beams that were deflected by Atomic Force Microscopy (AFM). Hogmoen et al. [9], and Kang et al. [10] used the optical method to measure the resonance frequency of a cantilever beam to determine its elastic modulus. Kisoo et al. [11] proposed an elastic modulus evaluation technique of a cantilever beam by vibration analysis based on time-average electronic speckle pattern interferometry (TA-ESPI) and Euler-Bernoulli equation. Knowing that elastic material properties critically affect the vibration behavior of structures, Kisoo applied the reverse of this idea, in which the vibration behavior of a particular material can give the elastic properties of the material. The principle is the foundation of all vibration-based identification methods which use the Euler-Bernoulli beam theory to link Young's modulus with the natural frequency of the specimen. Thus, the elastic

modulus of a test material can be readily estimated from the measured resonance frequency and Euler-Bernoulli equation. Using the same principle, this paper suggests a technique of vibration-based estimation of Young's modulus of thin films of non-structural materials by the use of the theory of membranes. The suggested technique estimates Young's modulus of thin films by only measuring the strain and the resonance frequency of the material, and outlines the applicability of vibration analysis for material characterization.

## 1. MATERIAL PROPERTIES AND METHODOLOGY

Material properties play a major role in the mechanical behavior of structures and the properties have been standardized with previous testing methods such as the tensile test and bending test. However, the material properties of thin film may not be the same as those of bulk materials. Thus, it is important to determine the mechanical properties of thin materials to predict the performances of micro structure devices. Because thin films have a thickness of the order of microns, the measurement methods used for bulk materials become inappropriate.

Various material properties like density, Young's and shear modulus, can be found in literature. However, while density and geometric measures generally portray the real values, this may not automatically apply for the specification of Young's or shear modulus. Since the elastic properties are used for dimensioning tasks, the values that are specified by material manufacturers or claimed in customer material standards often can be regarded as rough estimation quantities. Especially thin films with a nonlinear stress-strain relation generally show a wider spreading of the elastic properties compared to homogenous bulk materials, thus the mechanical properties of thin films may have large difference in them due to variations in processing conditions. Indeed, the temperature, humidity, method of etching (if any), or the order of fabrication procedures may induce a great difference in the parameters governing properties.

The vibration measurement is the approach used in this study for extracting the mechanical properties of the material. Vibration measurements are made for a variety of reasons including the verification of an analytical model of a system, and the determination of the resonance frequencies for a system. Resonance frequencies are extremely important in predicting and understanding the dynamic behavior of a system, but also (during the last decades) in non-destructive estimation of the material mechanical properties.

In many cases, systems are idealized as point masses, rigid bodies, or deformable members without mass, having a finite number of degrees of freedom, inducing a discretization of an analytical model. However, it is also possible to treat systems more rigorously, without discretization of the analytical model. In this study, we analyze a thin film, considered as an elastic body in which the mass and deformation properties are continuously distributed. Because its mass is distributed, an elastic body has an infinite number of natural modes of vibration; as such, its dynamic response may be calculated as the sum of an infinite number of normal-mode contributions. Therefore, the geometry of the specimen will be appropriately chosen (with reduced width for example) in order to involve as few as possible of the normal-modes in the width direction.

The sample under investigation is considered a true membrane, so that the structure satisfies the following conditions:

- The boundaries are free from transverse shear forces and moments in planes tangent to the middle surface.
- The normal displacements and rotations at two parallel edges are unconstrained: that is, these edges can displace freely in the direction of the normal to the middle surface.
- The material has a smoothly varying, continuous surface.
- The components of the surface and edge loads must also be smooth and continuous functions of the coordinates.

These assumptions lead to the two (related) following characterizations of a membrane:

- The material does not have any flexural rigidity, and therefore cannot resist any bending load. As a consequence, although we investigate transverse vibrations, we will not take into account the magnitude of the deflection in the estimation of Young's modulus.
- The material can only sustain tensile loads, which is a key requirement in the derivation of the wave speed from which the resonance frequencies are obtained, leading (in turn) to the estimation of Young's modulus from dynamic measurement.

In this study, we assume that the material is homogeneous and isotropic, and that it follows Hooke's law. Displacements are assumed to be sufficiently small that the response to dynamic excitations is always linearly elastic. The tensile force in the film is assumed to remain constant during small vibrations in the plane of the film.

## 2. THEORY

### 2.1. Governing equation and steady-state vibrations

The equation governing the small-amplitude motion of a thin rectangular specimen is well established in membranes theory. The structure under investigation, with the profile shown in figure 2a, consists of a slightly stretched membrane (having no flexural stiffness) that is free to vibrate transversely.

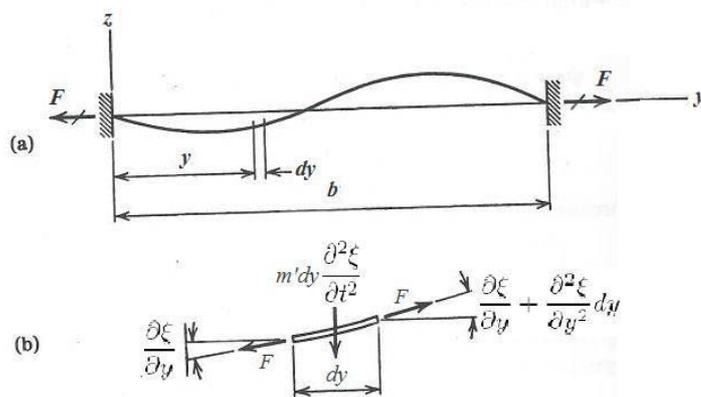


Figure 2.

(a) Stretched membrane in vibration.

(b) Free body diagram.

The tensile force  $F$  is assumed to remain constant during small vibrations in the  $y$ - $z$  plane. In general, vibration of taut membrane which lies in the plane of Cartesian coordinate system and having intrinsic elasticity is governed by the equation [12]:

$$\frac{\partial^2 \xi}{\partial t^2} - c^2 \left( \frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2} \right) + d^2 \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)^2 \xi = \frac{p(x, y, t)}{\rho h}, \quad (1)$$

where  $\xi$  is the displacement of membrane along the  $z$ -axis from its equilibrium position  $z = 0$ ,  $c = \sqrt{T/(\rho h)}$  is the velocity of propagation of bending wave at zero intrinsic elasticity, which is determined by the tensile force  $T$  per unit length of boundary of membrane,  $\rho$  is the density and  $h$  is the thickness of the membrane. The external pressure  $p(x, y, t)$  is a function of time and of spatial coordinates.  $d^2 = Eh^2/12\rho(1-\nu^2)$ , where  $E$  is the elastic modulus and  $\nu$  is the Poisson's ratio.

Figure 2b shows a free-body diagram of a typical segment of length  $dy$ , for which the forces in the deformation direction ( $z$ ) are of primary interest. It appears that during free vibrations, the inertia force is counteracted by the difference between the  $z$  components of the tensile forces at the ends of the segment.

For a free vibration of the membrane, if the relative contribution of the intrinsic elasticity is small in comparison with the tensile elasticity, it was shown [13] that the solution to equation (1) can be written as a sum of the membrane modes:

$$\xi = \sum_{m,n=0}^{\infty} \xi_{mn} = \sum_{m,n=0}^{\infty} A_{mn} \cos\left(m\pi \frac{x}{a}\right) \sin\left(n\pi \frac{y}{b}\right) \sin(\omega_{mn}t + \varphi_{mn}), \quad (2)$$

where the constants  $A_{mn}$ ,  $\varphi_{mn}$  are amplitude and phase,  $\omega_{mn}$  is the natural frequency of mode  $mn$ .

By substituting (2) into (1), the approximate expressions for natural frequencies are found:

$$\omega_{mn} = c \sqrt{\left(\frac{\pi m}{a}\right)^2 + \left(\frac{\pi n}{b}\right)^2} \left\{ 1 + \frac{d^2}{2c^2} \left[ \left(\frac{\pi m}{a}\right)^2 + \left(\frac{\pi n}{b}\right)^2 \right] \right\}, \quad (3)$$

where  $m, n = 0, 1, 2, 3, \dots$  and  $a, b$  are the dimensions of the membrane. Each mode in the solution (2) satisfies the boundary conditions:

$$\xi_{mn}(x, y=0) = 0, \quad \xi_{mn}(x, y=b) = 0, \quad \frac{d\xi}{dx}(x=0, y) = 0, \quad \frac{d\xi}{dx}(x=a, y) = 0. \quad (4)$$

The conditions (4) correspond to the immovable boundaries at  $y=0, y=b$  and to the free boundaries at  $x=0, x=a$ .

The formula (3) is valid for thin films if the second term in the brackets is smaller than unity, condition which can be rewritten as:

$$\delta = \frac{\pi^2}{24} \frac{Eh^3}{(1-\nu^2)Ta^2} \ll 1. \quad (5)$$

For a standard aluminium foil loaded at  $F = 5\text{ N}$  assuming its Young's modulus to be 70 GPa, the expression (5) leads to the trend given in figure 3. The figure also presents the trend for LDPE with Young's modulus around 150 MPa having a width of  $a = 15\text{ mm}$  and loaded at  $F = 1\text{ N}$ , and for paperboard of same size having Young's modulus of 7 GPa. It appears that the intrinsic elasticity can be neglected up to a thickness of  $100\text{ }\mu\text{m}$  for the polymer and paperboard, and roughly  $50\text{ }\mu\text{m}$  for aluminium foil, justifying the expression used for Young's modulus extraction in the next section.

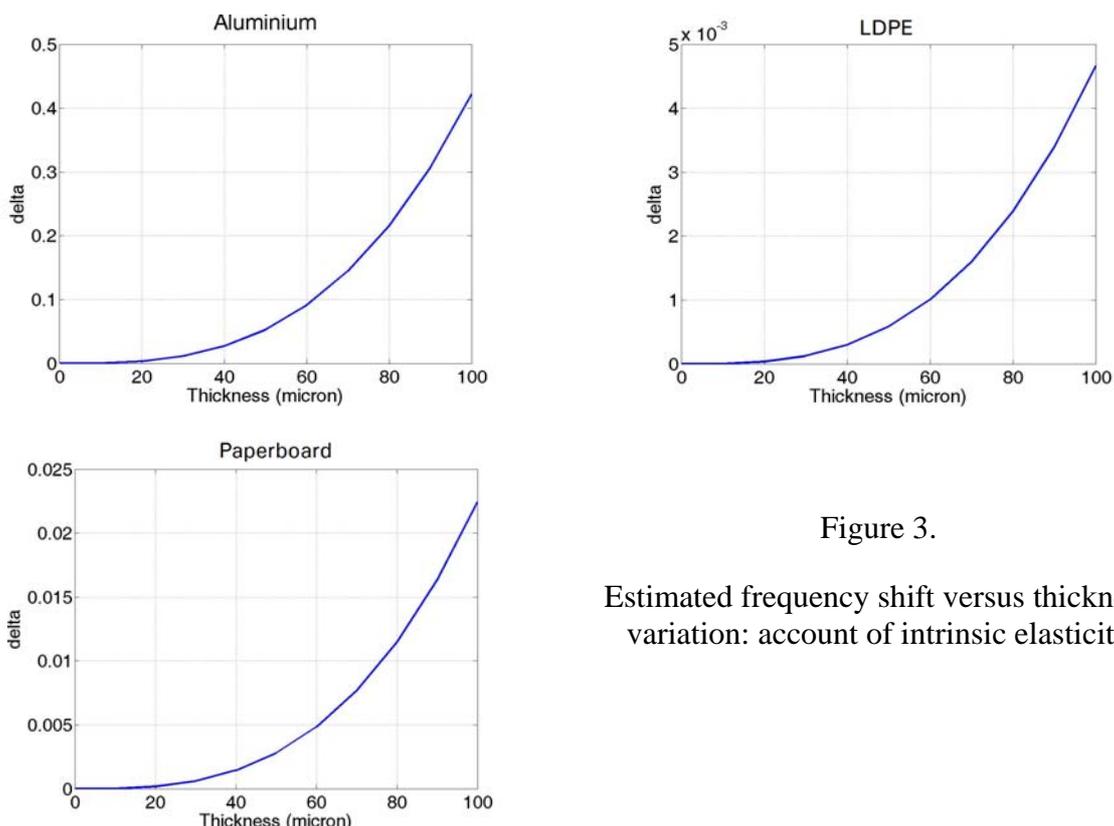


Figure 3.

Estimated frequency shift versus thickness variation: account of intrinsic elasticity

### 2.2. Estimation of the Dynamic Young's modulus

A variety of dynamic modulus measurement methods exists including ultrasonic wave propagation and the flexural resonance method presented here for which normal modes of vibration are monitored. In an oscillating system, normal modes are special solutions where all the parts of the system are oscillating with the same frequency (called normal frequencies or allowed frequencies). At resonance from equation (3) neglecting the intrinsic elasticity, and knowing that  $c = \sqrt{T/(\rho h)} = \sqrt{E\varepsilon/\rho}$ ,  $\varepsilon$  being the strain, it follows that:

$$\omega_{mn} = 2\pi f_{mn} = \sqrt{\frac{E\varepsilon}{\rho}} \sqrt{\left(\frac{\pi m}{a}\right)^2 + \left(\frac{\pi n}{b}\right)^2}, \quad m, n = 0, 1, 2, 3, \dots \tag{6}$$

For  $m=0$  (bending modes in the length direction), equation (6) can be rewritten as follows:

$$f_{0n}^2 = \frac{E \cdot n^2}{4 \cdot \rho \cdot b^2} \cdot \varepsilon. \quad (7)$$

For a given mode,  $n$  is fixed;  $a$  and  $b$  are constant dimensional properties of the material for a given specimen;  $E$  being in turn a material constant (by definition), it follows from equation (7) that the square of the natural frequency is a linear function of the strain. As a consequence, dynamic Young's modulus  $E$  can readily be extracted from the slope of the curve.

### 3. EXPERIMENT

#### 3.1. Specimens

Rectangular strips of uniform width and thickness such as those defined by ASTM-D882 are used. A wide range of specimen gage lengths is used (100 mm to 300 mm). For each specimen, the width and thickness were measured three times with a micrometer to the nearest thousandth of a millimeter. The values were averaged in order to be taken into account in the calculation as well as in the testing software TestWorks4 of the MTS Universal Testing Machine used. The thickness of the test specimens was then 27  $\mu\text{m}$  while the width was 15mm. The materials were first placed in a conditioned room with 23°C and an atmospheric humidity of 50% during at least three days. All specimens have a width of 15 mm, and five samples are considered with the lengths 100, 150, 200, 250 and 300 mm.

#### 3.2. Experimental setup

Main components in the experimental setup (figure 4) consist of a function generator (Agilent 33220A/20 MHz) **A**, a loudspeaker for remote excitation **B**, a laser Doppler vibrometer (Ometron VS-100) **C**, an oscilloscope (LeCroy LT262/350 MHz) **D**, and a tensile test machine (MTS QTest 100) **E**. The function generator provides an 8 Volts (peak to peak) sine signal to the loudspeaker. The acoustic field excited by the loudspeaker vibrates the sample. Laser detection of the surface vibrational response of the sample is accomplished with the laser vibrometer. The vibrometer used in this study makes high-fidelity and absolute measurements of surface displacement over a bandwidth of DC to 50 kHz. The measured response is monitored by the oscilloscope; this allows the detection of the maximum surface displacement, corresponding to a normal mode, which is related to the mechanical properties of the material.

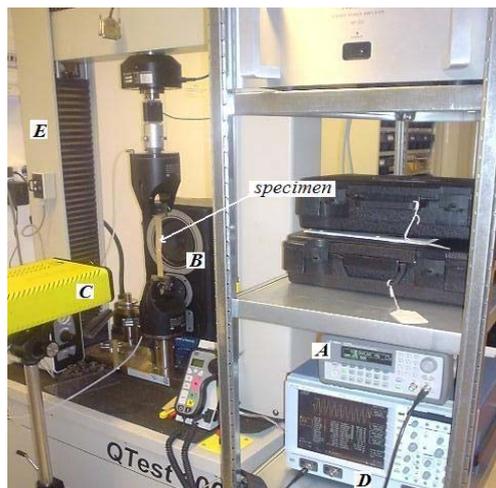


Figure 4.

## Experimental arrangement

The specimen under investigation is rigidly held on the clamps as shown in photo (figure 4). The loudspeaker is placed on the back side of the sample such as to excite transversal vibration of the sample. The laser vibrometer is placed opposite to the loudspeaker, and the laser beam is properly focused on the sample surface. Unlike traditional contact vibration transducers, laser-based vibration transducers, or laser vibrometers, require no physical contact with the test object. Remote, mass-loading-free vibration measurements on contact sensitive specimens such as the ones used in this study are some of the motivations for considering a laser-based vibration transducer as the natural choice. The Doppler effect is utilized here to measure translational vibrations of a single point on the specimen.

### 3.3. Experimental procedure and results

Using the suggested non-contact excitation and measurement setup, a series of acoustic based non-contact experiments were conducted to study dynamic properties, specifically the elastic modulus of the sample sheet material. The ideal medium being assumed to have no stiffness, the specimen is slightly stretched (at most 1 mm) in order to make it a structural element.

An external driving force is remotely and harmonically applied to the membrane by the loudspeaker. In steady state, the membrane then vibrates at the frequency of the driving force. When the driving force is at a normal mode frequency, the energy transmission is efficient, so that the material has the maximum surface displacement and vibrates at its resonance frequency. Since the specimen geometry is a rectangular membrane of small width (to avoid huge interference with propagating waves in the width direction) resulting to normal modes of vibration, the resonant frequencies are sufficiently far apart to permit the use of the peak-amplitude method to determine the resonant frequencies. This transverse vibration response of the material is monitored at a single point of measurement. For each specimen, four sets of measurements are taken corresponding to the four first normal mode of vibration.

For each mode and for each load case (step), the corresponding normal mode as well as the strain was recorded and dynamic Young's modulus was determined by graphical analysis. For each plot obtained from equation (7), a straight line is fitted and Young's modulus determined from the slope of the curve. The initial regions of the plots were ignored because they were

non-sensible experimental artifacts. Young's modulus values for all load steps and for each mode were averaged to determine specific dynamic Young's modulus value for each specimen length.

In parallel, the tensile behavior of the films was monitored as the films were loaded at a constant strain rate of 5% per minute. At least four specimens were tested for each sample. The strain was calculated as the extension divided by the initial length, while the applied force was divided by the cross-section to obtain stress. The stress was then divided by the strain to yield the elastic modulus, within elastic region as given by equation (8):

$$E = \frac{d\sigma}{d\varepsilon}, \quad (8)$$

where  $d\sigma$  is the incremental stress, and  $d\varepsilon$  is the incremental strain.

The elastic modulus was investigated in MD (Machine Direction) for all specimens. The characteristic tensile curves are shown in figures 5 and 6, and the basic statistics about the central tendency and variability of data from tensile test are summarized in tables 1 and 2 with:

- min: smallest value in the data set;
- max: largest value in the data set;
- mean: average of all the values in the data set;
- std: a value characterizing the amount of variation among the values in the data set;
- range: interval between the lowest and the highest value in the data set.

Table 1. Young's modulus obtained from tensile testing: LDPE

length [mm]	min [MPa]	max [MPa]	mean [MPa]	std [MPa]	range
100	130.2	182.9	151.5	9.75	52.74
150	168.4	210.5	183.4	8.86	42.16
200	96.09	163.3	132.1	12.7	67.11
250	137.7	183.1	161.1	11.69	45.43
300	144.1	244.9	196.4	17.29	100.8

Table 2. Young's modulus obtained from tensile testing: Paperboard

length [mm]	min [MPa]	max [MPa]	mean [MPa]	std [MPa]	range
100	5.870	6.966	6.447	0.455	1.096
150	6.378	7.544	7.017	0.449	1.166
200	6.737	8.187	7.169	0.583	1.450
250	6.296	7.100	6.769	0.353	0.804
300	7.016	7.386	7.208	0.353	0.370

Dynamic Young's modulus is extracted from the frequency measurement according to equation (7). Dynamic and static Young's modulus are then plotted together for comparison for each mode as a function of the specimen length, and presented in figures 7 and 8.

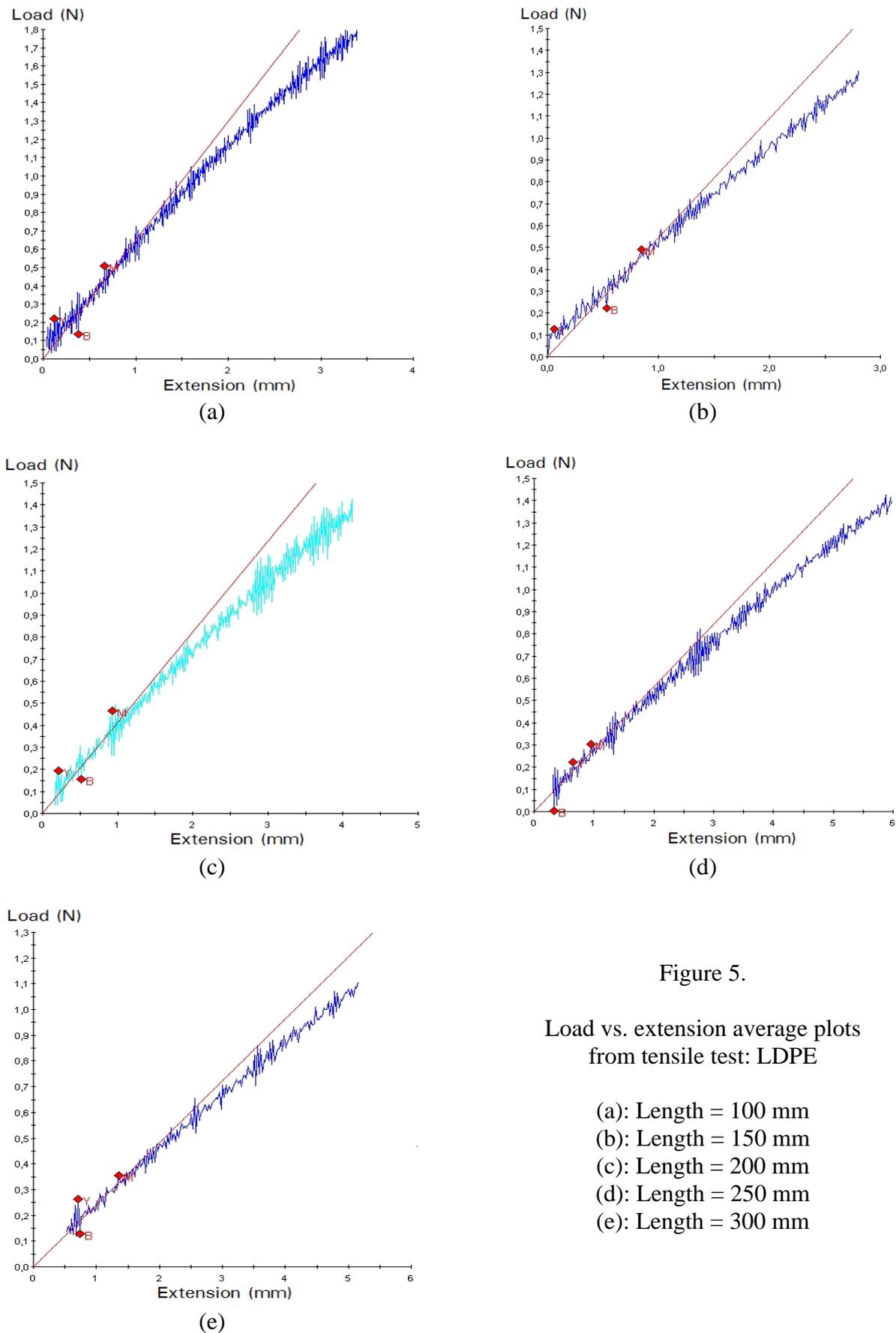


Figure 5.

Load vs. extension average plots from tensile test: LDPE

- (a): Length = 100 mm
- (b): Length = 150 mm
- (c): Length = 200 mm
- (d): Length = 250 mm
- (e): Length = 300 mm

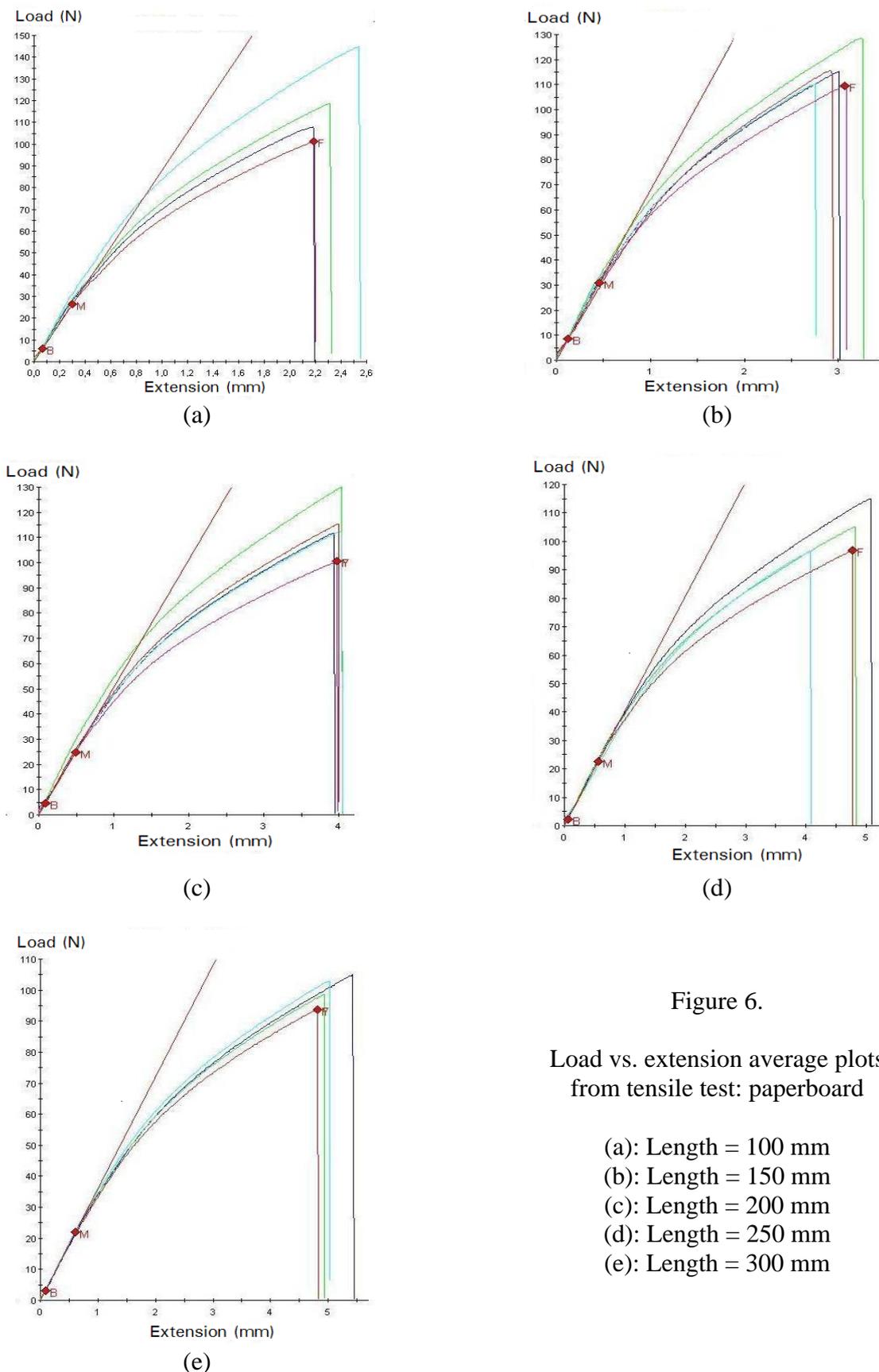


Figure 6.

Load vs. extension average plots from tensile test: paperboard

- (a): Length = 100 mm
- (b): Length = 150 mm
- (c): Length = 200 mm
- (d): Length = 250 mm
- (e): Length = 300 mm

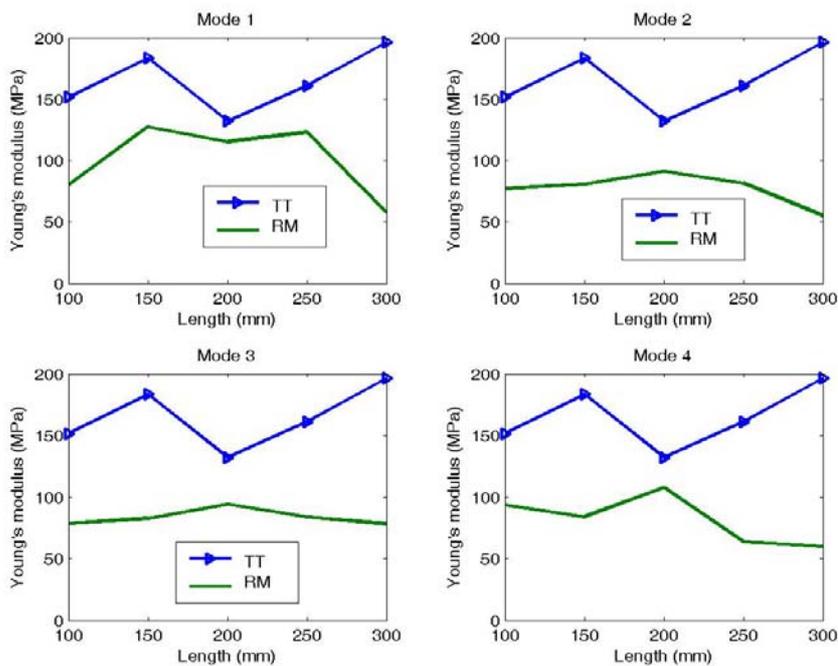


Figure 7. Young's modulus from Static and dynamic methods for LDPE.  
 TT — Tensile Test, RM — Resonance Method

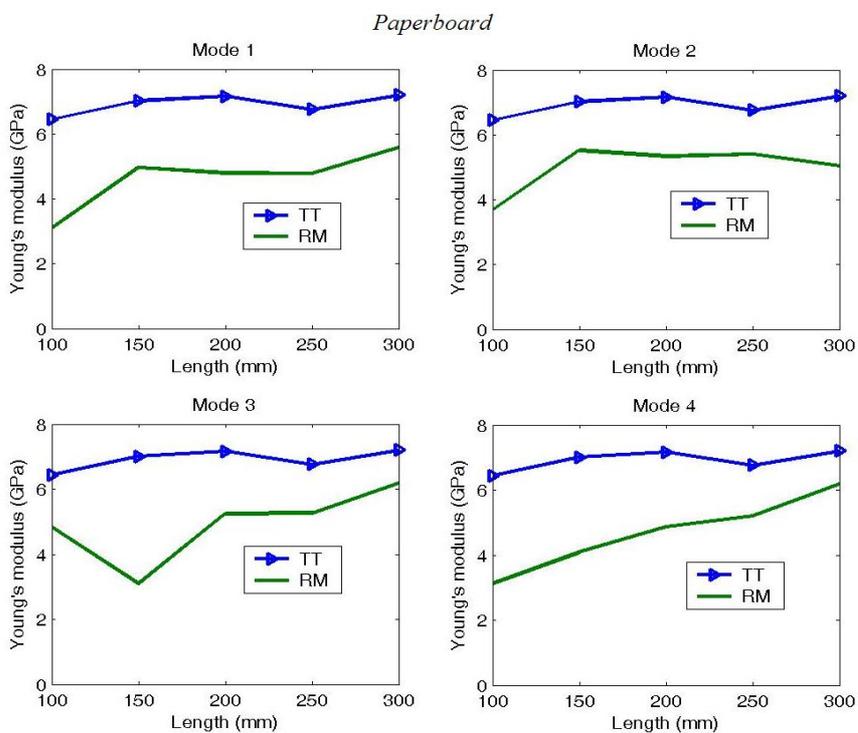


Figure 8. Young's modulus from static and dynamic methods for paperboard.  
 TT — Tensile Test, RM — Resonance Method

#### 4. DISCUSSION

The discrepancies between the dynamic and static results may be due to the following reason: in the dynamic measurements, Young's modulus is obtained from the dynamic behavior of the specimen and therefore, reflects the frequency dependence of the material. Moreover, the difference of deformation mechanisms may also explain different moduli: the specimen is extended in tensile test, while it is submitted to bending in vibration analysis. Such a difference was explained in a previous work [14] applied to steel, by the fact that certain internal mechanical motions, which lead to a portion of the observed strain, take a fine time to occur. Hence, if there is not enough time during the application of the dynamic (oscillating) force for the strain to occur, the overall strain appears smaller in that case and hence the modulus from the dynamic method becomes higher than the static one. Meanwhile, the Young's modulus of the materials studied in this paper cannot actually be compared with those mentioned in the literature. In fact, Young's modulus values obtained for thin films usually depend on the constitution and manufacturing process of the material. However, the values of Young's modulus in the present study are in the acceptable range of the values generally obtained, while being lower than those obtained by standard (static) methods. This difference between static and dynamic Young's modulus can be seen on figures 7 and 8 and tables 3 and 4. The extracted values of Young's modulus are found to be between 4.7–6.2 GPa for PPR and between 80–127 MPa for LDPE, for suitable specimen lengths between 200–300 mm and 150–250 mm respectively, within which the results are not appreciably affected.

Table 3. Comparison of static and dynamic Young's modulus: LDPE

Length [mm]	100	150	200	250	300
TT [MPa]	151.5	183.4	132.1	161.1	196.4
Mode 1	80	127.3	115.42	123	57.7
Diff [%]	47.19	30.58	12.62	23.64	70.62
Mode 2	77.17	80.6	91.52	81.7	55.2
Diff [%]	49.06	56.05	30.71	49.28	71.89
Mode 3	78.44	82.8	93.88	83.6	78.2
Diff [%]	48.22	54.85	28.93	48.10	60.18
Mode 4	93.27	84.1	107.45	63.8	59.7
Diff [%]	33.43	54.14	18.66	60.39	69.60

The literature reports the estimation of dynamic Young's modulus, but only for bulk materials, showing that it is higher than static Young's modulus [14–17]. The current work is the first investigation of the estimation of Young's modulus using a dynamic method with a remote acoustic excitation, applied to thin films, showing, in opposition to bulk materials, that the result from the dynamic method is slightly lower than the one from static method. Young's moduli from dynamic method found for each sample length are normalized by the

corresponding static values and it follows from figure 9 that the normalized dynamic Young's moduli of both paperboard and LDPE are 70 to 85% of the tensile test values, for specimen lengths between 150 and 250 mm. Their difference could not be measured accurately because of the dispersion observed on the data, which is caused by the extreme sensitivity of the frequency measurement to any inhomogeneity within the material. These residual strain and stress may appear in structures in service because of fatigue loading, or from a combination of mismatched thermal expansion coefficients and intermolecular forces.

Table 4. Comparison of static and dynamic Young's modulus: Paperboard

Length [mm]	100	150	200	250	300
TT [GPa]	6.447	7.017	7.169	6.769	7.208
Mode 1	3.0909	4.9649	4.7949	4.7884	5.590
Diff [%]	52.05	29.24	33.11	29.25	22.44
Mode 2	3.6808	5.5167	5.3336	5.4020	5.0362
Diff [%]	42.90	21.38	25.60	20.19	30.13
Mode 3	4.8277	3.0891	5.2392	5.2668	6.1915
Diff [%]	25.11	55.97	26.91	22.19	14.10
Mode 4	3.1297	4.0844	4.8651	5.2092	6.1938
Diff [%]	51.45	41.79	32.13	23.04	14.07

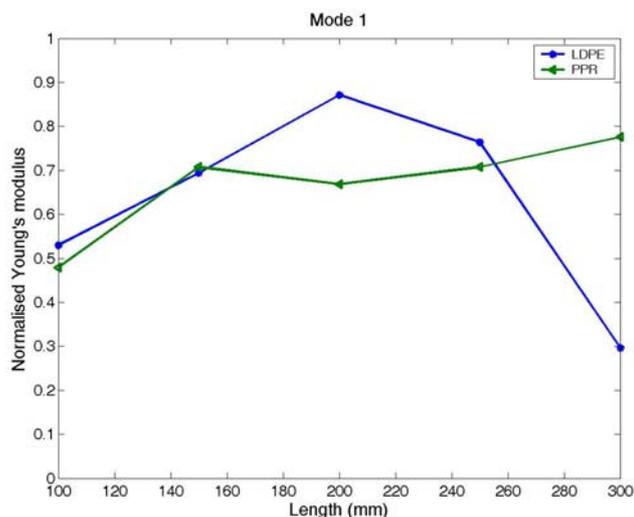


Figure 9.

Normalized Young's modulus

The acoustic method presented in this study has several good features. It is non-destructive, easy to perform, and allows repeated measurements to be made on one specimen. It can be used to characterize a wide range of flat materials. More importantly, it gives a reliable result that can be assured during testing as it has been repeated until the same values, or those within 5% of each other, were obtained at least three times consecutively. Meanwhile, the accuracy of the measurement is strongly dependent on the suitability of the specimen shape and size required. Therefore, flat rectangular specimens must be considered.

In addition, specimens must be clamped in a way to display a preload of 0.1 to 0.2 N, as the toe compensation may have a significant influence on the results. The toe region is an artifact caused by a take-off of slack, and alignment or seating of the specimen; it does not represent a property of the material. Therefore, because the  $E$  value is directly related to the strain as shown in equation (6), an erroneous estimation of the strain has a direct influence on the slope of the curve and in turn, on the  $E$  value.

A deviation is observed from one specimen length to another on the dynamic measurement of Young's modulus. This might come from the fact that the modes are not pure bending along the length of the specimen, which has not been accounted in the derivation of the equations used. Although this limitation, the current results allow to consider the suggested method as an alternative for the purpose of structural health monitoring of materials of specific sizes. The stiffness of the material changes with introduction of a defect, which can be monitored at a certain interval of time. Therefore, Young's modulus being estimated from natural frequencies, the method confirms the use of the latter for defect detection as already mentioned in a previous work [18].

## CONCLUSIONS

Young's modulus is an extremely important parameter to the fracturing process, and also for having a direct relationship to any kind of variation in the structural integrity of the inspected material. Although this material property can easily be measured in the laboratory, it is recommended to be able to assess its changes for use in structures in-situ for the purpose of condition monitoring.

A new non-destructive method for estimation of Young's modulus of thin films from dynamic measurements is therefore presented. This method, based on membrane resonance, uses a non-contacting laser vibrometer system. The non-contacting response measurements, single point measurement, low and high frequency capabilities, and large area coverage are among the advantages of this method.

It is shown that the resonance frequency measurement of thin films in flexural mode is very sensitive to the estimation of the stiffness of the material for a displacement (stretching) as small as 1 mm; this makes the presented method extremely challenging because such sensitivity cannot be expected from standard tensile testing on specimens of the size investigated in this study.

Proper selection of the testing vibrational mode appears important in the suggested method in order to avoid dispersive results (observed on longer and shorter specimen lengths). The dynamic method has the advantage of being simple to set up, however the issue regarding the relevance of dynamic versus static measurements has not been fully addressed. Meanwhile, this work provides the basics for the possibility of remotely predicting damage evolution of structures in service, caused by a residual strain (as small as 0.3%) or stress, a crack, or a local or global weakness of the material. The method can also be applied for evaluation of the effect of water absorption of paper-based sheet materials. Consequently, one can expect the sensitivity of this method to be acceptable for nondestructive testing of sheet materials.

## ACKNOWLEDGEMENTS

This work was supported by the School of Engineering at Blekinge Institute of Technology. The authors gratefully acknowledge valuable discussions with PhD student Kristian Haller from the same institution, and Professor Shu-Lin Bai, Director of the Centre for Advanced Composite Materials of Peking University, China.

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