FRACTURE MECHANISM AND ACOUSTIC DAMAGE ANALYSIS OF THIN MATERIALS

Mfoumou, E.M., Kao-Walter, S., Hedberg, C.
School of Engineering, Blekinge Institute of Technology, Sweden

ABSTRACT

The fracture behavior of paper board (100 µm) used in food packaging material is studied. The plane stress fracture toughness is measured based on a centered crack panel. Different crack sizes have been tested. A compromise (crack length) was found, at which Strip Yield Model as well as Linear Elastic Fracture Mechanics allow the validation of experimental results. Meanwhile, accurate results are obtained using the Strip Yield Model with a geometric correction.

Besides, detection of damage in food packaging material is an interesting feature in quality control of the product. Therefore the material is investigated using an acoustic method. The method consists of a vibration-based damage assessment and leads to a first level differentiation between damaged and non-damaged specimens.

1 INTRODUCTION

Most of the liquid food packaging materials use to consist of several different layers of material for the different requirements. Examples are aluminium foil (Al), Low Density Polyethylene (LDPE), and Carton (PPR). It is important to secure that every layer keeps its function during the forming, filling and transportation process. Mechanical properties of these materials have been studied [1-5]. The fracture behaviour of Al-foil (about 6-7 µm) was investigated [6] and the fracture toughness was found to be much lower than what is given in standard materials handbooks. However, a fracture mechanical model of such thin materials was suggested.

The purpose and aim of this work is to extend the results from [6] through investigation of the fracture behaviour of paper board (thickness=100 µm, density=0.684 g/cm^3). The specificity of this continuation study is still the non standard specimen size, particularly the thickness which does not satisfy the ASTM standard No E399 [8]. The study uses experimental method and theoretical analysis to determine a reliable modelling method for approximating the thin material under consideration. Fracture toughness is characterized and measured using the method suggested in [7].

Attempt is also made to apply a nondestructive technique for differentiation between non-damaged and damaged specimens. Since fracture process in laminated packaging material could start on the inner layers, making it difficult to see, investigation is made using an acoustic method and modal parameters of the material. There exists an extensive literature on the subject of damage detection using modal parameters [9,10,11]. Emphasis is put here on the “level 1” vibration-based damage assessment established by Doebling et al. [10].

3 THEORETICAL ANALYSIS

At onset of crack growth a relation between stress and stress intensity factor can be derived by LEFM [12]:

$$\sigma_c = \frac{Kc}{\sqrt{\pi \cdot a} \cdot \varphi(\frac{a}{w})}, \tag{1}$$

with

$$\varphi(\frac{a}{w}) = \sqrt{sec\left(\frac{\pi \cdot a}{2 \cdot w}\right)} \cdot [\,1 - 0.025 \cdot \left(\frac{a}{w}\right)^2 + 0.06 \cdot \left(\frac{a}{w}\right)^4\,] \ , \tag{2}$$

where *a* is half the crack length, *w* is half the width, B is the thickness, σ_c is the peak stress for the given initial crack length, and K_c the fracture toughness obtained experimentally (based on the reasonable crack length for the purpose).

The Strip Yield Model with the appropriate geometry correction factor φ, derived in [6], is expressed as follows

$$\sigma_c = \frac{2 \cdot \sigma_b}{\pi} \cdot asec\left[exp\left(\frac{\pi \cdot K_c^2}{8 \cdot a \cdot \sigma_b^2 \cdot \varphi^2(\frac{a}{w})}\right)\right] \ , \tag{3}$$

where σ_b is the stress at break from tensile test, see [13] for details.

For damage detection through changes in basic modal properties, theory of forced oscillation of membrane (well known in physical acoustics) is used on a specimen configuration shown in figure 1, with the external pressure derived from Newton’s second law of motion, as shown by the system of equations (4)

$$\begin{cases} \dfrac{\partial^2 \xi}{\partial t^2} - c^2 \cdot \dfrac{\partial^2 \xi}{\partial y^2} = \dfrac{p(y,t)}{\rho \cdot h} \\ m \cdot \dfrac{d^2 \xi(\frac{b}{2})}{dt^2} = -p \cdot S = -p \cdot 2w \cdot \Delta \end{cases} \ , \tag{4}$$

with $$c = \sqrt{\frac{T}{\rho h}} \ , \tag{5}$$

where *T* is the load per unit length, ρ the density and h the thickness of the specimen, m is the added mass, *p* the external pressure which acts on the membrane, ρ the density of the material, and ξ the transversal displacement of membrane. The strip with area *S* is roughly assumed to be either a positive mass (addition of mass), or a negative mass (hole or removal of matter).

The above system of equations reduces to the following:

$$\frac{\partial^2 \xi}{\partial t^2} - c^2 \frac{\partial^2 \xi}{\partial y^2} = -\frac{m}{\rho h 2 w \Delta} \frac{d^2 \xi(\frac{b}{2})}{dt^2} = \begin{Bmatrix} 1, if\ (\frac{b}{2} - \frac{\Delta}{2}) < y < (\frac{b}{2} + \frac{\Delta}{2}) \\ 0, otherwise \end{Bmatrix}. \tag{5}$$

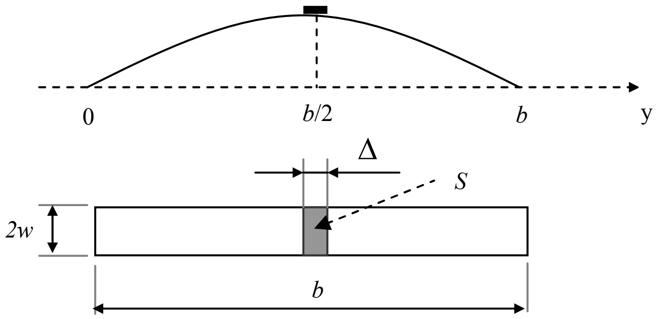

Figure 1: Specimen configuration

For a harmonic excitation and looking for low frequency modes, we write

$$\xi = A \cdot cos(\omega t) \cdot sin(\frac{\pi}{b} y). \tag{6}$$

Introducing (6) into (5), multiplying each side of the equation by $sin(\frac{\pi}{b} y)$, and integrating over 0 and b lead to the following,

$$\frac{\omega}{\omega_0} = \frac{1}{\sqrt{1 + 2\frac{m}{M}}} \approx 1 - \frac{m}{M} \longrightarrow f \approx f_0 \cdot (1 - \frac{m}{M}), \tag{7}$$

where f_0 is the fundamental frequency without adding a mass on the specimen, f the new first mode, and M the mass of the membrane.

4 EXPERIMENTAL METHOD

Center cracked panels as shown in figure 2 are investigated. The MTS Tensile Test Machine is used. The load on the sample is recorded by a piezo-electric load cell mounted between the sample and the crosshead. A 2.5 kN loadcell is used, with a pair of wide clamps see figure 3. The grip separation is set to the specimen length.

Experiment 1 is related to the evaluation of the strength of the material in presence of damage. A “hand-made” notch is performed using a razor blade, with length ranging from $2a$ = 5 mm to $2a$ = 50 mm. The width and gauge length of the specimen are $2w$ = 95 mm and L = 230 mm respectively. The test speed is 9.2 mm/min, and tests are run until the entire cross section breaks.

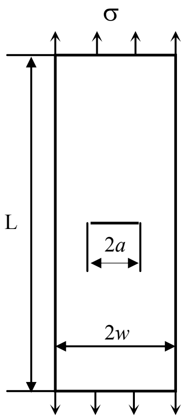

Figure 2: Center cracked panel

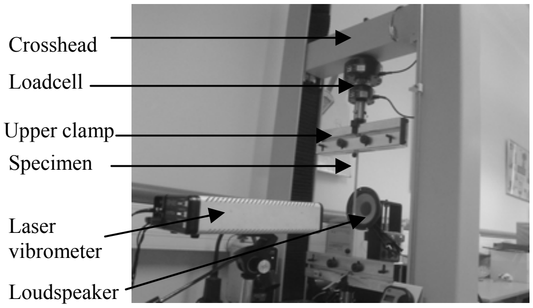

Figure 3: Set up for vibration-based investigation

Experiment 2 is related to vibration-based damage assessment. Specimens without and with damage are considered. For the later, the "hand-made" notch performed has the length $2a$ = 6 mm. The width and gauge length of the specimen are 2w = 12 mm and L = 650 mm respectively. The test speed is 2 mm/min, and the crosshead is stopped when the load reaches 21 N. A low frequency loudspeaker is used to excite bending waves on the clamped specimen, and sensing is performed with a laser beam. The excitation signal is generated by an Agilent 33250 waveform generator, and the response is analyzed in a LeCroy Waverunner LT 364.

5 RESULTS AND DISCUSSION

Critical stresses for different crack length (up to 50 mm) were measured by experiment. Normalized critical stress versus crack length curves for experiment, LEFM equation (1) and SYM equation (3) are plotted in figure 4. Good agreement is found between the measured results and the analytical results both with LEFM and SYM for crack lengths larger than $2a$ = 20 mm. Meanwhile, for crack lengths less than 20 mm, SYM shows a better correlation with the measured values, whereas LEFM fails to describe the experimental result for such short crack lengths. A compromise is found at $2a$ = 45 mm, and leads to Kc = 3.12 MPa·m$^{1/2}$.

Figure 5a shows a difference between damaged and undamaged specimens in experiment 2. Only odd harmonics are generated because of the position of laser beam. A new spectral line appears above the first mode, indicating presence of damage; this leads to a mode shift to the right of the fundamental.

Figure 5b shows the influence of adding mass on the first mode; this leads to mode shift to the left. The current results confirm the Doeblin et al. [9] speculation on damage detection by changes in the dynamic properties or response of systems in a qualitative manner, using acoustic techniques. However, the basic idea remains that commonly measured modal parameters (specifically frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Consequently, changes in the physical properties, such as reductions in stiffness resulting from the onset of cracks or loosening of a connection, will cause detectable changes in these modal properties.

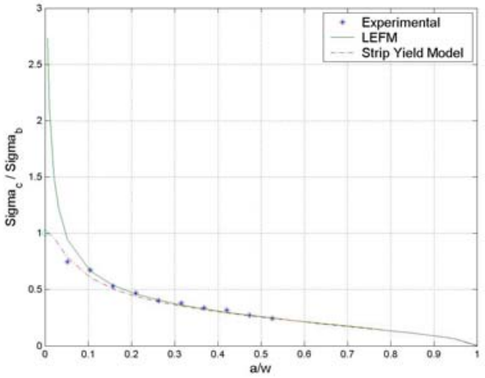

Figure 4: Normalized stress vs. Crack length

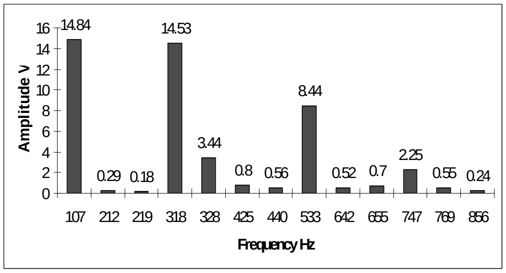

Figure 5a: Dynamic response (undamaged specimen)

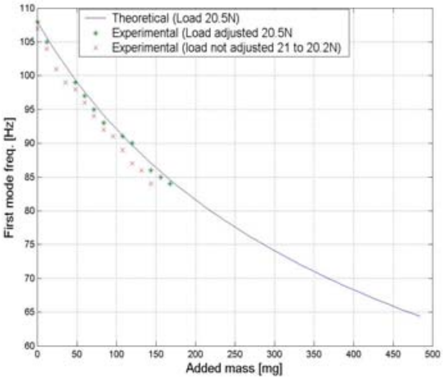

Figure 6: Mode (first) shift to higher range frequencies with positive mass.

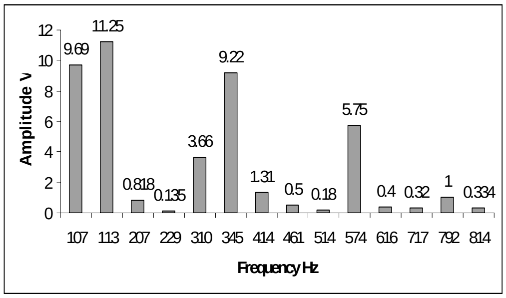

Figure 5b: Dynamic response (damaged specimen)

6 CONCLUSION

An experimental investigation was performed for the determination of plane stress fracture toughness for non standard materials. A single layer (paper board) from a laminated liquid food packaging material was tested. The result can be concluded as follows:

- The modified strip yield model developed in [6] was found to suit the material under investigation.
- As found in [6] for aluminium foil, a compromise was found at crack length 2*a* = 45 mm, at which the fracture tough ness is estimated.
- The fracture toughness was found to be $Kc = 3.12$ MPa.m$^{1/2}$.
- The "Level 1" damage identification was a success using acoustic method and without any structural model.

- Positive mass (addition of mass) leads to mode (first) shift to lower range, while negative mass (crack) leads to mode shift to higher range.
- The last observation shows a very important enhancement of vibration-based analysis applied to fracture mechanism, as well as nondestructive evaluation of thin material strength in presence of damage. Current results are expected to improvement in a quantitative manner.

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