March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

# "A Study of Fatigue and Fracture of Foam Cores Used in Sandwich Composites"

**Prof. Mahadev N Harkude[1], Prof. Vijaykumar Chavan[2]**
[1]Department of Mechanical Engineering, VSM Institute of Technology, Nipani, India
[2]Department of Mechanical Engineering, SKSVMACETLakshmeshwar, India

***Article Info***
***Volume 83***
***Page Number: 890 - 899***
***Publication Issue:***
***March - April 2020***

***Abstract:***
This study focused on the fracture and fatigue crack growth behavior in polyvinylchloride (PVC) and polyethersulfone (PES) foams. A new sandwich double cantilever beam (DCB) test specimen was implemented. Elastic foundation and finite element analysis and experimental testing confirmed that the DCB specimen is appropriate for static and cyclic crack propagation testing of soft polymer foams. A comprehensive experimental mechanical analysis was conducted on PVC foams of densities ranging from 45 to 100 kg/m$^3$ and PES foams of densities ranging from 60 to 130 kg/m$^3$. An in-situ scanning electron microscope study on miniature foam fracture specimens showed that crack propagation in the PVC foam was inter-cellular and in the PES foam, failure occurred predominately by extensional failure of vertical cell edges. Sandwich DCB specimens were loaded cyclically as well. For the PVC foams, the crack growth rates were substantially influence by the density. For the PES foams, there was no clear indication about the influence of foam density on the crack growth rate.

***Article History***
***Article Received***: *24 July 2019*
***Revised***: *12 September 2019*
***Accepted***: *15 February 2020*
***Publication***: *12 March 2020*

***Keywords***: *polyvinylchloride (PVC), polyethersulfone (PES) foams, double cantilever beam (DCB), sandwich.*

## 1 INTRODUCTION

A structural sandwich is well-defined as a composite structure consisting of dense surface layers called "facings" bonded to a low density core [9]. Sandwich structures are well established where light weight and high performance are required such as wind turbines, aerospace structures and packaging [6]. The sandwich structure may afford a low cost solution to design for many types of core concepts such as polymer foams, balsa wood or honeycomb. The sandwich structure also holds key features in insulation and buoyancy properties.

### 1.1 Foam materials

As described in Gibson and Ashby [3], a foam material consists of a cellular structure having interconnected small solid struts and or plates forming on open or closed cell foam. The spongy cancellous bone in animals and humans are two of many examples of foam structures occurring in nature. A well-known example of artificial foams is "Styrofoam" which is used for cups for its insulative properties, in packaging and car bumpers for its energy absorbing properties and in surf boards for its buoyancy properties. Substantial efforts are being made to exploit the cellular structure by using materials such as metals, ceramics and glasses. This thesis, however, will focus on polymer foams.

### 1.2 Sandwich construction

A sandwich structure consists of thin face materials bonded to a thick core as shown in Figure 1.1.

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

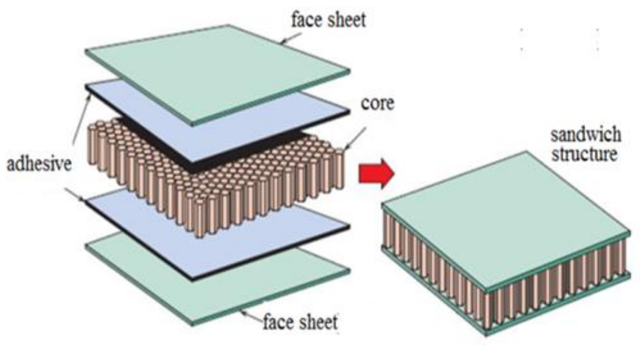



**Figure 1.1: Sandwich structure.**

The concept of sandwich construction dates back to the 1800's but the first known application is the fuselage of the WW2 Mosquito fighter which was a sandwich consisting of wood veneers bonded to balsa wood cores. These materials were selected mainly because of the scarcity of other materials [4,5]. Now sandwich structures are being utilized in many forms such as parts of the supporting structure of wind turbine blades and the rear rudder structure on jetliners. The face sheets are typically much thinner than the core and made from dense materials such as aluminum or glass and carbon fiber composites. The core can be a variety of materials ranging from balsa wood, cellular polymers, metal foams and honeycomb materials. The face-to-core joint is typically a thin layer of adhesive. The main function of the sandwich is to achieve a structure with high bending stiffness at a low weight, similar to an I-beam, where the web that separates the flanges corresponds to the core and the flanges corresponds to the face sheets.

### 1.3 Failure modes

Sandwich structures can fail in several ways which limit the loading capacity of such a structure. Common failure modes of a sandwich structure under bending, compression and shear loads are shown in Figure 1.2 [10].

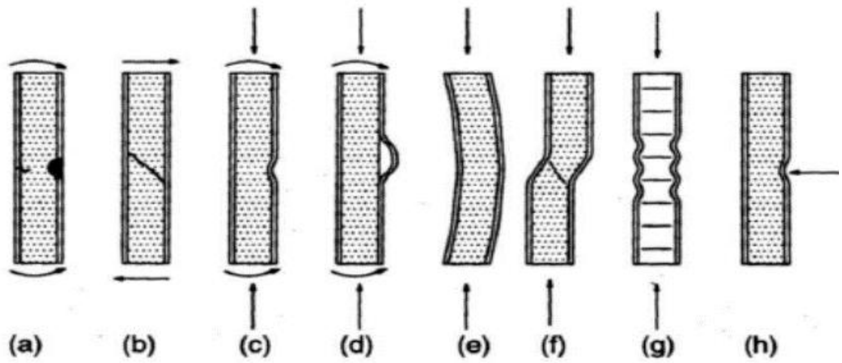



**Figure.1.2 Failure modes in Sandwich beams a) Face yielding/ Fracture b) core shear failure, c & d) face wrinkling, e)global buckling f) shear crimping g) face dimpling h) local indentation**

Failure of sandwich structures can occur due to static or dynamic overloading of the face sheets, core or of the face/core joint. Since the core typically is the weak link of a sandwich structure, core failure is often of main concern. M.Fox, C et al. [6] reported on the crash of American Airlines Flight 587. It was determined that the airplane, an Airbus A300-600, crashed because of an overloaded vertical stabilizer which was made from a sandwich structure having carbon composite face sheets over a honeycomb core. A static analysis of a sandwich structure is the first essential step in the design procedure, but does not guarantee that the structure will remain operational under long-term dynamic service loads. It is widely recognized that defects are likely to be introduced in a sandwich structure due to poor manufacturing procedures and human errors. As shown in the schematic in Figure 1.3, a small defect in the structure may be undetected at delivery, but has the potential to grow during its service life. This defect can eventually grow to some critical size leading to failure of the structure. Studies to understand the crack growth behavior in a sandwich material having such defects are thus important.

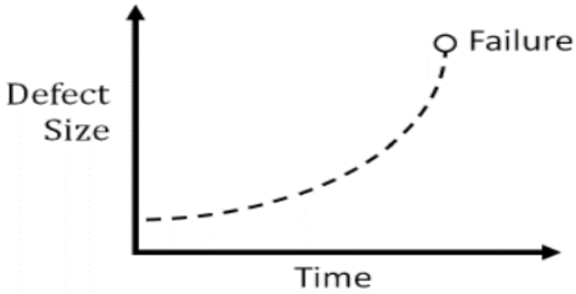



**Figure 1.3: Cyclic loading effects on a defect**

R. Hilgers [7] examined the failure of an Airbus A310 rear rudder consisting of thin aluminum faces bonded to a foam or honeycomb core, see Figure 1.4. He found that a pre-existing defect had propagated to a critical size due to the cyclic pressure changes the aircraft undergoes during its ground-air-ground flight schedule.

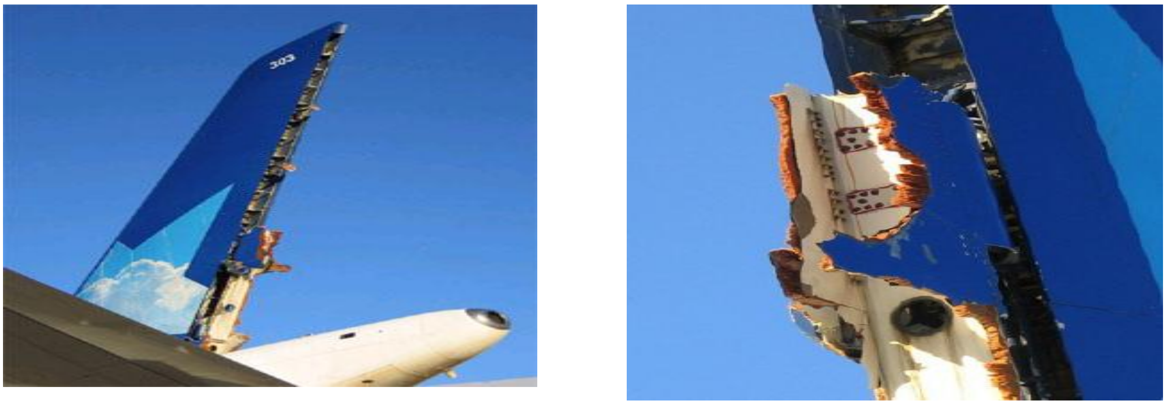


**Figure 1.4 Failure of rear rudder in an Airbus A310**

A sandwich boat hull is another example of a cyclically loaded structure. Defects introduced during manufacturing tend to grow during cyclic loading conditions that ship structures operate under, such as ocean wave slamming. Wind turbines blades also operate under cyclic loading conditions defined by varying and complex wind patterns. A period of high winds could overload a turbine blade and introduce defects, such as a crack, thus reducing the overall life of the structure.

The fracture mechanics approach to cyclic crack growth in metals pioneered by Paris et al. [8] and J.M. Barsom et al. [9], has been extended to foams and sandwich structures by for example D. Zenkert [5], A. Shipsha et al. [10] and N.A.Fleck and Parker [11] characterized the fatigue crack growth rates in single edge notch polyurethane foam beams. Shipsha et al. [12] determined the fatigue crack growth rates in sandwich specimens with a range of PVC foam cores.

**1.4 Objective.**

The main objectives of this work are to develop static and cyclic fracture test methods and experimentally characterize crack growth rates and crack growth mechanisms during static and cyclic

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

loading of polyvinyl chloride (PVC) and polyethersulfone (PES) foams. PVC foams are well-established core materials whereas the PES foams are more recently introduced. The dynamic-mechanical properties, tensile yield strength, ultimate strength, modulus and fracture toughness of solid PVC and PES were first determined. Then the mechanical behavior of the PVC and PES foams was determined in tension, compression and shear. A dynamic-mechanical analysis (DMA) was conducted to determine the glass transition temperature of the foams.

Static fracture testing of PVC and PES foams employed the SENB specimen and a specifically developed foam fracture specimen called the sandwich double cantilever beam (DCB) specimen. Analytical and numerical studies on the sandwich DCB specimen were conducted providing compliance and the stress state. Crack kinking in the foam was analyzed using finite element analysis. The fatigue crack growth behavior of the foams was characterized using the sandwich DCB specimen.

## 2. Background

In this paper, we focus is on polymer foams with the solid constituents being polyvinylchloride (PVC) and polyethersulfone (PES). Polymer foam cores are widely used in naval vessels and wind turbine blades. However, foams made from aluminum are also used as core materials [13]. Polymers tend to display time dependent viscoelastic behavior whereas most metallic materials show a response independent of time. Hence,
polymers tend to be sensitive to temperature changes and creep over extended time periods. Polymer foams have many advantages over other types of core materials, especially in terms of cost. Most polymer foams, however, are weak and brittle and constitute a weak link of sandwich structures.

### 2.1 Solid Polymers

In this paper *two types of polymer foams will be examined herein; viz. PVC and PES foams*. The solid constituent polymers will be discussed briefly. PVC polymer is a widely utilized amorphous thermoplastic produced by polymerization of vinyl chloride monomers.

The PVC polymer contains 40% petroleum; *60% chlorine (Cl)* by weight. The presence of the Cl atom causes an increase in the inter chain attraction and hence increases the hardness and stiffness of the polymer. Moreover, the combustion of PVC produces dangerous fumes when incinerated which can be fatal [14]. Initially, the usage of PVC was limited due to its brittle nature. Additives, such as plasticizers, were introduced to the polymer which made the PVC more flexible and more easily processed [15]. PVC has a softening point at about 78$^{o}$C and is resistant to liquids such as salt water and antifreeze mixtures making it suitable for domestic water piping.

Polyethersulfone (PES) is a transparent, amorphous engineering thermoplastic similar to polycarbonate. The benzene molecule is a 6 carbon ring having one hydrogen atom attached to each carbon. This ring structure is part of many polymers such as nylon 6-6, polycarbonates and epoxy resins. The molecular chain stiffening from the benzene rings increases the modulus and softening temperature of the bulk material [12].

Bayer and Imperial Chemical Industries (ICI) introduced PES in 1979. Despite its lack of crystallinity, the rigid polymer PES chain structure has a very high softening temperature and is resistant to creep making it a very attractive choice for plastics products subject to extreme temperature environments. Furthermore, attributes such as low water absorption and excellent flame, smoke and toxicity performance make it ideal for several demanding applications. PES, however, exhibits poor resistance to ultraviolet radiation (UV) which may not be a limiting factor for use as a core material. Typical uses of PES include heat resistant plastic parts and thin membranes used for filtering and purification of liquids and gases particularly in the medical industry.

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

The material properties of PVC and PES provided by the manufacturers [3, 19, 21], are listed in Table 2.1.

**Table 2.1: Physical and mechanical properties of solid PVC and PES**

| | ρ ($Mg/m^3$) | Tg ($C^o$) | E (GPa) | $\sigma_{ys}$ (MPa) | $G_{IC}$ ($kJ/m^2$) |
|---|---|---|---|---|---|
| PVC* | 1.43 | 79 | 2.66 | 54.19 | 2.00 |
| PES | 1.40 | 219 | 2.68 | 91.0 | 2.55 |

Note that this particular PVC is a commercial plasticized grade making the toughness comparable to that of the PES. Both polymers have similar density and modulus; however PES can withstand higher temperatures and has much higher yield strength than PVC.

**2.2 Polymer foams**

Polymer foams are classified as cellular structures that could be***open or closed*** Open-cell foams have the simplest structure consisting of beam-like elements defining each cell, providing an open grid-like structure Closed-cell foams have a combination of the beam like structure of open-cell foams, and membranes that close off the open sections of the cell. The fraction of polymer in the beam elements and in the membrane is said to substantially influence the stiffness of the foam. For polymer foams, most of the solid plastic is located in the edges.

Two types of foams were chosen for this paper, viz. *PVC and PES foams*. PVC foams are widely used in sandwich structures varying from pure insulation applications to structural core materials used in marine and aerospace structures, and wind turbine blades. PVC foams dominate the market for polymer foam core material. The low softening point of PVC foams (≈78$^o$C), however, restricts their applications to temperatures below 50$^0$C. To produce the PVC foam, a PVC plastisol consisting of isocyanates, a blowing agent (for initiating the foaming process), and a stabilizer are mixed together at temperatures below 100$^o$C. The mixture is then placed into water which reacts with the isocyanates to initiate the cell nucleation and expansion. The foam is then allowed to cure in a mold to form its final rigid structure. Since the cross-linking and foaming processes occur simultaneously, properties of solid cross-linked PVC are not available.

Solid PES is transformed into foam by immersing PES particles in a hot oil bath near the melting temperature of PES (≈219$^o$C). Carbon dioxide is injected to commence the foaming process. When the specific densities/cell sizes are reached, the foaming process is stopped by quenching the foam in cold water. This process conserves the solid constituent properties of the PES polymer. PES foams are thermoplastics that can be thermoformed, melted and recycled because of the absence of chemical cross-links. PES foams are also more resistant to elevated temperatures than PVC foams. PES foams are used in aerospace, automotive and aviation applications due to their low flammability and low generation of smoke and toxic (FST) gases in any potential fire situations. Table 2.2 summarizes density and material properties as provided by the manufacturer of the PVC and PES foams considered in this thesis, viz. PVC H45, H60, and H100 and PES foams F50, F90 and F130.

**Table 2.2: Mechanical properties H and F Series foams according to the manufacturer.**

| Property | Units | H45 | H60 | H100 | F50 | F90 | F130 |
|---|---|---|---|---|---|---|---|
| Density | $Kg/m^3$ | 48 | 60 | 100 | 50 | 90 | 133 |
| Tensile Modulus | MPa | 54 | 75 | 132 | - | - | - |
| Tensile Strength | MPa | 1.3 | 1.7 | 3.5 | 1.6 | 2.2` | 2.8 |
| Compressive Modulus | MPa | 50 | 70 | 132 | 29.3 | 38.98 | 49 |
| Compressive Strength | MPa | 0.7 | 0.9 | 2.1 | 0.5 | 0.7 | 1.0 |
| Shear | MPa | 15 | 20 | 36 | 7.8 | 9.6 | 11. |

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Modulus | | | | | | | 7 |
| Shear | MPa | 0.5 | 76 | 1.6 | 0.6 | 1.1 | 1.6 |
| Strength | . | 6 | | | | | |

## 3. Fracture mechanics

Fracture mechanics is a methodology to assess the influence of defects and flaws on the overall strength of a material or structure. The concept is highly relevant since crack propagation often leads to extensive property loss and in some cases loss of lives. A study by the National Institute for Science and Technology and Battelle Memorial Institute estimated that the cost for failures due to crack propagation may exceed $100 billion per year. Another case was the WWII Liberty ship failure caused by cracks located in the welds of the hull. Most notably was the fuselage failure of the Comet airplane in the 1950s. Researchers determined that the combination between the cabin pressure cycling and stress concentrations at the corners of its square windows lead to crack initiation, crack growth and the eventual failure of its fuselage.

### 3.1 Fatigue of materials

Fatigue in materials is described as damage to a structure caused by repeated loads, such as automobile traffic on a highway bridge and wind loads on building structures, Problem arises when the stress being applied exceeds the threshold fatigue limit, resulting in crack propagation and possibly failure of the structure sometimes a catastrophic event. A recent example occurred in *August 1, 2007 in* Minnesota with the failure of the I-35W Mississippi River Bridge. An investigation by the National Transportation Safety Board (NTSB) determined that an undersized steel gusset failed due to cyclic crack propagation caused by the road traffic.

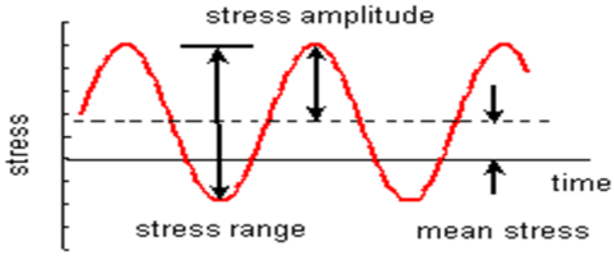



**Figure 1.5 Cyclic stress of fatigue loading plot.**

The simplest form of fatigue loading is the constant amplitude cyclic stress shown in Figure 1.5. This type of loading usually occurs in machine parts such as a rotating driveshaft. The loading can be represented by a constant stress range, $\Delta\sigma$ where the alternating stress is defined by the stress amplitude ($\sigma_{amp} = \Delta\sigma/2$), and a stress ratio R, defined as the ratio between the minimum and maximum stresses.

### 3.2 Micro-models for crack propagation in foams

It is well recognized that low density foams typically are weak and susceptible to fracture, especially under cyclic loading which tends to limit the service lifetime of sandwich structures [10]. Micro-mechanical models for crack propagation in foams have been developed for open cell foams, and honeycomb structures developed a model for fracture of open cell foam in the form of a hexagonal lattice structure (Figure 1.6). It was suggested that the crack propagates an increment of one cell size when a strut near the crack tip fails in bending, "a" in Figure 1.6, or by a combination of tension and bending, "b" in Figure 1.6. Failure of a strut is assumed to occur when the maximum bending stress reaches the tensile strength of the solid polymer. A model based on strut failure in bending led to the following expression for the fracture toughness of the foam, $K_{Ic}$,

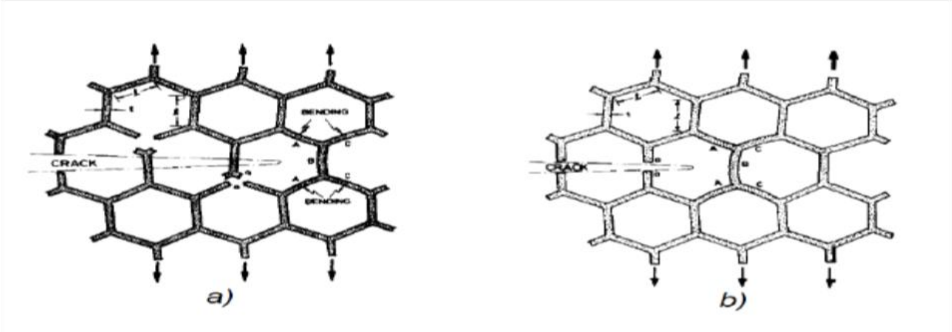



**Figure 1.6: Crack propagation in open cell foam. a) bending failure of the non-vertical cell elements b) tensile failure of the vertical cell elements.**

## 4. ANALYSIS OF SANDWICH DCB SPECIMEN

To analyze the fracture response of the polymer foams, an adhesive double cantilever beam test, as proposed by Ripling et al, was modified to include a relatively thick layer of foam bonded adhesively between two aluminum adherents, see Figure 1.7.

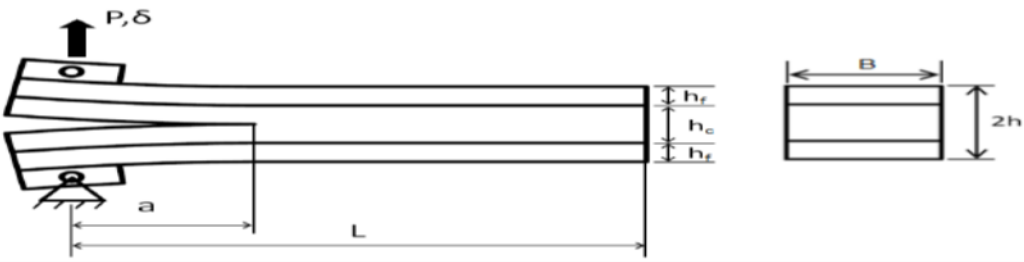


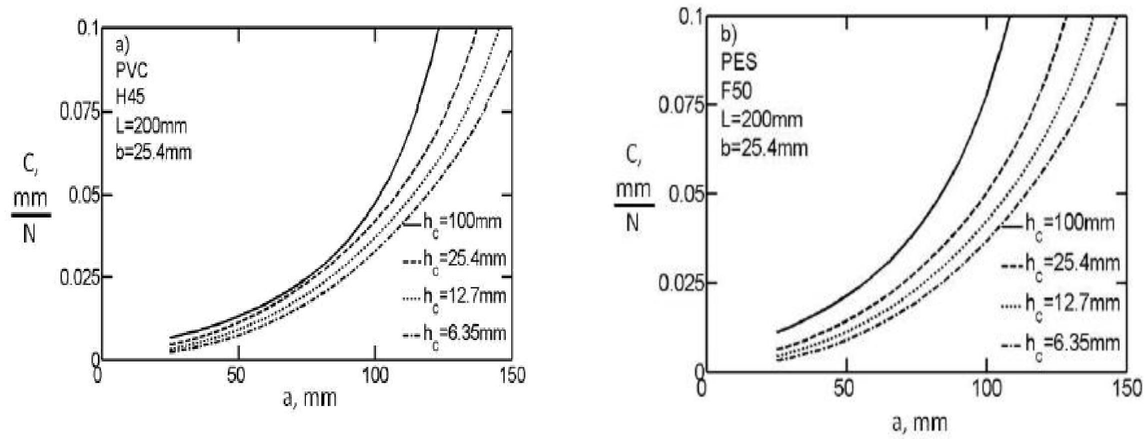

**Figure 1.7: Sandwich DCB specimen.**

### 4.1 Parametric study

The compliance of the sandwich DCB specimen will be examined for specimens with PVC (H45, H60, H100) and PES (F50, F90, F130) foam materials listed in Table 2.2 bonded to 6.35mm thick aluminum adherents. However, for the parametric study only H45 and F50 cores will be considered. The core thickness was varied from 6.35 to 100mm to examine its influence on the compliance of the DCB specimen.

A specimen length (L) of 200mm, width (B) of 25.4mm and crack lengths from 25.4 to 150mm were considered. Figure 1.8 shows the resulting compliance vs. crack length for the DCB specimens with H45 and F50 cores.

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899




**a- H45 core** **b-F50 core**

**Figure 1.8: Compliance versus crack length of sandwich DCB specimen. a) H45 core b) F50 core**

The results show that the compliance increases as the core thickness increases. This occurs since the foundation modulus, kc, decreases when the core thickness increases. The influence of core modulus may be examined by comparing Figure 1.8 a & b where the core modulus, Ec, is 33.2 and 17.5 MPa for H45 and F50 foams respectively. The compliance values for specimens with F50 foam are much higher than those for the H45 foam. Note that the H45 modulus is almost twice that of the F50 foam. Parametric studies on the effect of the length of the supported region, were conducted on sandwich DCB specimens at constant crack length, a=50mm, for 12.7mm thick H45, H60, H100, F50, F90 and F130 cores. The unsupported length was varied from, c=25 to 150mm. The specimen width (B) was 25.4mm.

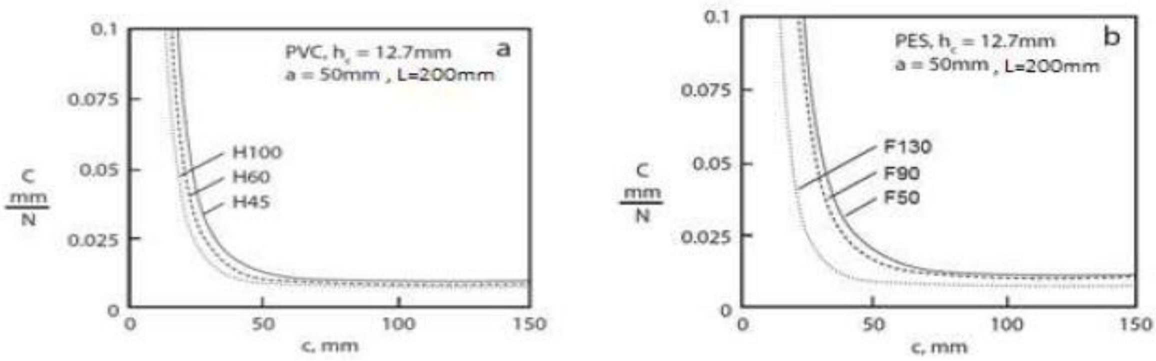



**Figure 1.9: Compliance vs. uncracked length, (c), for 12.7mm thick DCB sandwich specimens at a crack length, a=50mm**

Figure 1.9 shows compliance plotted vs. the supported length. It is observed that the compliance of the DCB specimen attains very high values for short unsupported lengths. At long supported lengths, however, the compliance becomes independent of the length, c. This occurs since the compliance given by the elastic foundation model includes hyperbolic functions, which asymptotes when, c>>a.

### 4.2 Fatigue testing of DCB specimen

The sandwich DCB specimen, shown in Figure 2, was also used for the fatigue test program to determine cyclic crack growth behavior. It is a

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

difficult task to physically monitor the crack growth in the sandwich DCB test specimen since the exact crack location is obstructed by the irregular coarse cellular foam structure. Specialized equipment to monitor crack growth like. For this study, two methods were used to monitor crack extension and the length of the crack. The first method used a traveling microscope where the crack tip could be monitored with a microscope having a crosshair in the microscope [21], see Figure 2.

**Figure 2: Traveling microscope to measure crack growth in the sandwich DCB specimen.**

## CONCLUSION

This study has focused on the fracture and fatigue crack growth behavior in polyvinylchloride (PVC) and polyethersulfone (PES) foams. PVC foams of densities ranging from 45 to 100 kg/m$^3$ and PES foams of densities ranging from 60 to 130 kg/m$^3$ were examined. The study first introduced the sandwich double cantilever beam (DCB) specimen. The sandwich DCB is a specimen that was developed to determine the mode I fracture toughness and crack propagation rates during cyclic loading of the polymer foam materials considered. The specimen consists of a rectangular strip of foam with a mid-plane edge crack bonded to two aluminum adherents loaded in a DCB configuration. The results were overall in close agreement over a range of crack lengths for the foams examined. A positive T-stress was observed ahead of the crack tip in thicker specimens, whereas the T-stress in specimens with a thinner core ($h_c$=12.7mm) was negative. This result agrees with experimental observations of crack paths. This indicates that thinner foam cores should be used for fracture testing.

## REFERENCES

1. Merriam-Webster, The Merriam-Webster Dictionary. Merriam-Webster, 2005.
2. DIAB Group, “DIAB H Series Data, DIAB F Series Data,” DIAB Products - Divinycell. [Online]. Available: http://www.diabgroup.com/americas/u_products/u_prods_2.html. [Accessed: 10- Mar-2008].
3. L. J. Gibson and M. F. Ashby, Cellular Solids Structure and Properties, First ed. Cambridge: Pergamon Press, 1988.
4. J. Batchelor and M. V. Lowe, Plane Essentials. Publishing Solutions, 2008.
5. D. Zenkert, Handbook of Sandwich Construction. London: Engineering Materials Advisory Services Ltd., 1997.
6. M. Fox, C. Schultheisz, and J. Reeder, “Fractographic Examination of the Vertical Stabilzer and Rudder from American Airlines Flight 587,” American Institute of Aeronautics and Astronautics, Washington, D.C., NTSB Accident Report, 2004.
7. R. Hilgers, “Substantiation of Damage Growth within Sandwich Structures,” Tokyo, 2009.
8. P. Paris, M. Gomez, and W. Anderson, “A Rational Analytic Theory of Fatigue,” Foundations of Linear Elastic Fracture Mechanics, vol. 13, pp. 9–14, 1961. 177
9. J. M. Barsom and S. T. Rolfe, Fracture and fatigue control in structures: applications of fracture mechanics. West Conshohocken: ASTM International, 1999.
10. A. Shipsha, M. Burman, and D. Zenkert, “On Mode I Fatigue Crack Growth in Foam Core Materials for Sandwich Structures,” Journal of Sandwich Structures and Materials, vol. 2,

March- April 2020
ISSN: 0193-4120 Page No. 890 - 899

no. 2, pp. 103–116, 2000.
11. N. A. Fleck and P. Parker, “Part II project report fatigue of foams,” Cambridge University Engineering Department, no. 1, 1988.
12. Shipsha, Burman, and Zenkert, “Interfacial fatigue crack growth in foam core sandwich structures,” Fat FracEng Mat Struct, vol. 22, no. 2, pp. 123–131, Feb. 1999.
13. Y. Sugimura, J. Meyer, M. Y. He, H. Bart-Smith, J. Grenstedt, and A. G. Evans, “On the mechanical performance of closed cell Al alloy foams,” ActaMaterialia, vol. 45, no. 12, pp. 5245–5259, Dec. 1997.
14. A. B. Strong, Plastics: Materials and Processing, 2nd ed. Columbus: Prentice Hall, 1999.
15. J. A. Brydson, Plastics materials. Woburn, MA: Butterworth-Heinemann, 1999.
16. J. B. Rose, “Sulphonatedpolyarylethersulphone copolymers,” U.S. Patent 27390316-Jun-1981.
17. Solvay Advanced Polymers, “Radel Design Guide,” Sulfone Polymers.
18. H. Sun, G. S. Sur, and J. E. Mark, “Microcellular foams from polyethersulfone and polyphenylsulfone: Preparation and mechanical properties,” European Polymer Journal, vol. 38, no. 12, pp. 2373–2381, Dec. 2002
19. W. V. Titow, PVC technology. New York, New York: Springer, 1985.
20. Cole-Parmer, “Chemical Compatibility Chart.” [Online]. Available: http://www.coleparmer.com/Chemical-Resistance. [Accessed: 28-Jan-2012].
21. M. T. Shaw and W. J. Mac Knight, Introduction to polymer viscoelasticity. Hoboken: John Wiley and Sons, 2005.
22. ASTM E647-11e1, “Test Method for Measurement of Fatigue Crack Growth Rates, ASTM International, Testing Standard ASTM E647-11e1, 2001.
23. P. Poapongsakorn and C. Kanchanomai, “Time-dependent deformation of closed cell
24. PVC foam,” Journal of Cellular Plastics, vol. 47, no. 4, pp. 323 –336, 2011.