REGIONAL TECHNICAL CONFERENCE

1935 - 1985
THE SOUTHEASTERN OHIO SECTION of the SOCIETY of PLASTICS ENGINEERS

ENGINEERING PLASTICS
THE CYCLE OF PROGRESS

THE OHIO UNIVERSITY COLLEGE of ENGINEERING and TECHNOLOGY

Engineering: The Future
50
1935-1985

DATE
WEDNESDAY & THURSDAY
DECEMBER 4 AND 5, 1985

OHIO UNIVERSITY
ATHENS, OHIO

ENGINEERING PLASTICS - THE CYCLE OF PROGRESS

Regional Technical Conference
Sponsored by
Southeastern Ohio Section, Society of Plastics Engineers, Inc.
and
Ohio University College of Engineering and Technology

December 4 and 5, 1985

ABOUT THE CONFERENCE

The opportunities or demands of the marketplace stimulate development of new technology. New or improved materials and processing technology generate new applications and opportunities. The process is accelerated by innovations occuring simultaneously in all fields of technology. Cycle of Progress has been chosen as the theme of this conference to emphasize the innovative process involved in the advancement of engineering plastics technology. The program features recent and new products, applications and technology in rapidly evolving areas of composites, alloys, new polymers, and polymer processing. The sixteen papers presented here are just a sample of the intense activity in these areas.

The Cycle of Progress is the result of human achievement by technically competent people. It is appropriate that this conference is a cooperative effort of Ohio University and the Society of Plastics Engineers and that it be held in the new C. Paul and Beth K. Stocker Engineering and Technology Center at Ohio University.

Ohio University

Ohio University, the first institution of higher education in the former Northwest Territory, traces its roots to enactment of the Northwest Ordinance of 1787, which provided for settlement and government of the territory and stated that "... schools and the means of education shall forever be encouraged." Ohio became a state in 1803 and on February 18, 1804, the Ohio General Assembly passed an act establishing "The Ohio University."

Today, Ohio University takes pride in its traditional residential campus on which a cosmopolitan student body of 15,000 represents every state in the nation and 90 foreign countries. Highly regarded faculty members, including young engineers and scientists working on the cutting edge of knowledge, are bringing increased recognition to the University as, in the words of the Columbus Dispatch, "a new mecca of science and engineering."

A comprehensive center of learning, Ohio University offers more than 120 undergraduate majors through nine colleges. On the graduate level, master's degrees are offered in nearly all major academic areas; doctoral degrees, in selected departments; and a doctor of osteopathy degree, in the College of Osteopathic Medicine.

The College of Engineering and Technology

The College of Engineering and Technology's 1985 observance of its 50th anniversary coincides with its move into its new home, the C. Paul and Beth K. Stocker Engineering and Technnlogy Center.

The Center, which represents the largest capital project in Ohio University history, was made possible, in part, by the $8 million Stocker Endowment in support of engineering, and by the State of Ohio Legislature, which appropriated $11.7 million for construction costs. With more than 3.5 acres under roof, the Center contains all seven of the College's departments, most recently housed in three buildings. In addition, some $4.5 million is currently being raised in the College's Project 85 campaign for equipping instructional laboratories and for accelerating and enhancing academic programs.

Chemical Engineering

Knowledge of science fundamentals and engineering form the basis of study in the Chemical Engineering Department, which prepares students to develop breadth and sound reasoning in a rapidly changing field in which the future is unpredictable.

Among national leaders in research in the areas of coal conversion and polymers for several years, the department is posed to advance work on large, practical scales. The Ohio Coal Research Laboratories Association has praised the department's work in flash carbonization of coal, and and in the development of some coal-oil mixtures that can burn for a limited period without producing ash deposits in boilers. Additionally, the department is currently planning new coal studies using a $1 million pressurized fluidized bed tranferred to the College by NASA. In the area of polymers, the National Science Foundation has encouraged and funded the department's research in polymer melt transformation extrusion.

SPE - SOCIETY OF PLASTICS ENGINEERS, INC.

This international society of over 25,000 individuals involved in polymer science and industry began in the Detroit area during the mid 1940s. In the years since then, members have joined together in sections throughout the Unites States and Canada and now SPE has members in all parts of the world. The stated purpose of SPE is "to promote the scientific and engineering knowledge of plastics."

SPE activities such as Plastics Engineering magazine, technical publications, conferences, seminars, and educational assistance efforts afford a broad forum for individuals to provide and/or receive plastics knowledge.

SPE is organized to serve its members in several ways, geographically by 85 sections, each ranging in size from 50 to over 1500 members. Seventeen divisions provide emphasis of interest on a finite aspect of plastics involvement ranging from polymer types, processing techniques, market segments and support functions to special product performance.

SPE activities are governed by councilmen elected for three years from each section and division who, in turn, elect an executive board of officers for one-year terms. An executive director is hired by and reports to the executive board. Robert Forger has served in this capacity with dedication and distinction for 25 years and currently manages an international staff of 32 society employees.

Membership in SPE is open to all individuals with training and/or experience in the plastics field.

SEO - SOUTHEASTERN OHIO SECTION

SEO began in the mid 1950s as the thirtieth SPE section under the guidance of our three founders, Jack Knight, George Edwards and Paul Smith, owners of plastics involved businesses in the Cambridge, Ohio area. With the influx of polymer products in the Mid Ohio Valley during the 1950s and 1960s, the membership center gravitated down I-77 to the Marietta-Parkersburg area.

The SEO section conducts technical meetings on the second Tuesday of each month from September through June and publishes a newsletter to keep its membership informed about the plastics activities.

SEO Past President, Dr. Vivian Malpass, our first section newsletter editor and general chairman of our first RETEC in the 1970s, is currently serving on the international executive board as the Society's Secretary. We in the SEO section are proud to have one of our most distinguished past members involved on the governing board of the Society.

THE CYCLE OF PROGRESS

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An SPE Conference is a forum for discussion of contributions to the scientific and engineering knowledge of plastics. Conference preprints aid communication between speakers and audience, encouraging meaningful discussion. They are not a substitute for publication.

Selected conference papers and discussions are added to the literature through publication by the Society in its established periodicals. Others are released for publication elsewhere in accordance with the following policy.

1. All papers submitted to and accepted by the Society for presentation at one of its conferences become the property of the Society of Plastics Engineers, and all publication rights are reserved by the Society.

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TABLE OF CONTENTS

Composite Use in Commercial Aircraft Structures

Paul R. Langston
Du Pont Company

INTRODUCTION

My challenge today is to update you on the growing technical base and composite uses in aircraft. Today I will highlight technical data, sandwich structures, and update uses in filament wound structures, commercial jet aircraft, helicopters, commuter aircraft, jet and turbo props general aviation aircraft, and close with a challenge for the future.

The use of composite structure in aircraft has grown at a 33 percent CPD annual growth rate in the past decade. In 1983, Du Pont shipments of KEVLAR and honeycomb of NOMEX to the aircraft industry were used to produce composite parts worth in excess of one-half billion dollars. By 1988, we forecast that shipments of KEVLAR and NOMEX paper to aerospace applications will grow at a 23 percent CPD annual growth rate and be almost 3 times 1983 sales.

KEVLAR, KEVLAR 29 and KEVLAR 49 have been commercially available since 1972. Cord made with KEVLAR fiber reinforcing tires and mechanical rubber goods is still our major volume market. An important use for KEVLAR 29 in ropes and cables where the low density and unexcelled tensile strength make it possible to construct ropes and cables with free lengths far exceeding what can be achieved with other materials (Free length is the length at which a tensile member breaks under its own weight). The high tensile strength also makes KEVLAR 29 suitable for ballistics protection, coated fabric reinforcement, and tape and webbings. A promising new end use is in friction products where performance can be improved by replacing asbestos with a combination of KEVLAR and a safe, low cost filler.

High modulus KEVLAR 49 fiber is the product that finds its way into advanced composites both in aircraft and aerospace, and it is the other main topic of this paper. KEVLAR has an outstanding combination of high strength and high modulus per unit weight. It is also inherently flame resistant, does not melt and has a high useful temperature range. Since properties per unit weight normally drive the selection of materials for advanced composite constructions, it is appropriate to compare the specific tensile strengths and specific tensile moduli of a number of materials. As can be seen in Figure 1, KEVLAR 29 and 49 have very impressive specific tensile strengths. This provides the basis for the claim that KEVLAR, on a pound-for-pound basis, is five times as strong as steel. KEVLAR 29 and 49 have the same tensile strength, but KEVLAR 49 has roughly twice the modulus of KEVLAR 29. For specific modulus (modulus divided by density) both KEVLAR 29 and 49 fit between fiberglass and graphite. The figure dramatizes the striking contrast between KEVLAR 49 and other organic fibers as well as conventional steel and aluminum materials.

Both KEVLAR and carbon fibers have made significant improvements in their tensile strength with a higher modulus KEVLAR identified.

Figure 2 illustrates tensile stress/strain curves for tensile loading. KEVLAR®, like most other materials, has a classically brittle response with a tensile strength a little greater than 240M psi for a typical unidirectional composite and 525M psi using the impregnated strand test (ASTM D2343). On the other hand, when KEVLAR is tested in compression, the behavior is quite different from the tensile response. At a compressive load about 20 percent of the ultimate tensile load, a deviation from linearity occurs and the composite yields into a plastic region. This is an inherent charactersitc of the KEVLAR 49 fibers representing an internal buckling of the filaments.

This unusual characteristic of KEVLAR 49 fiber has made fail-safe designs possible, because reinforcing fiber continuity is not lost in compressive failure.

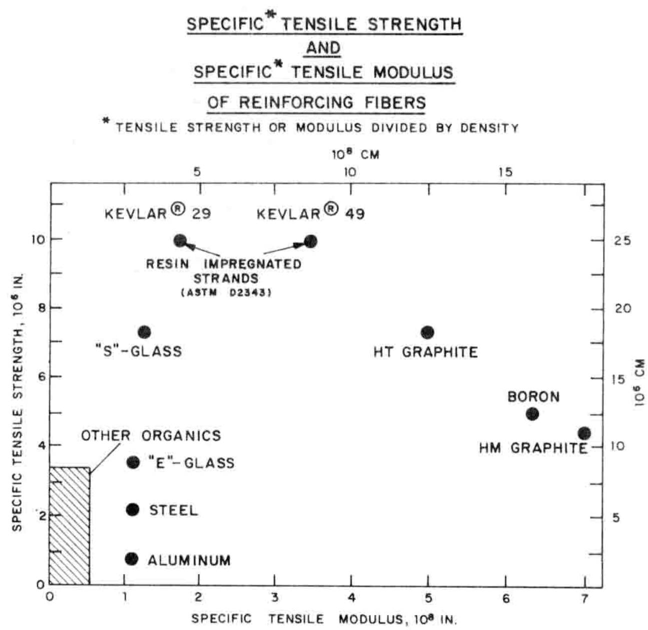


Figure 1

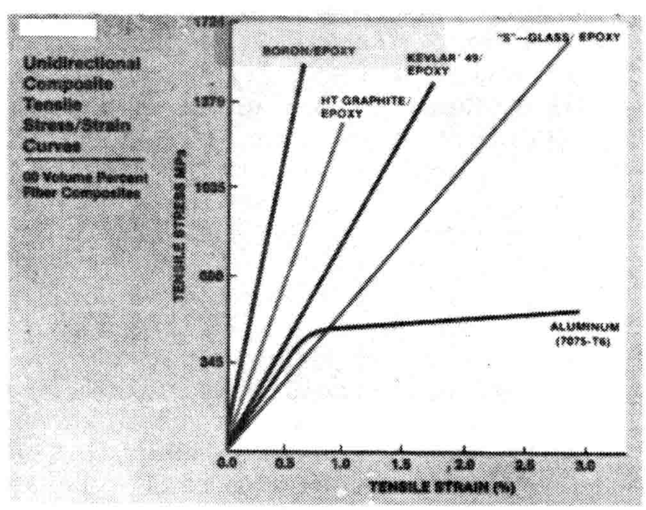
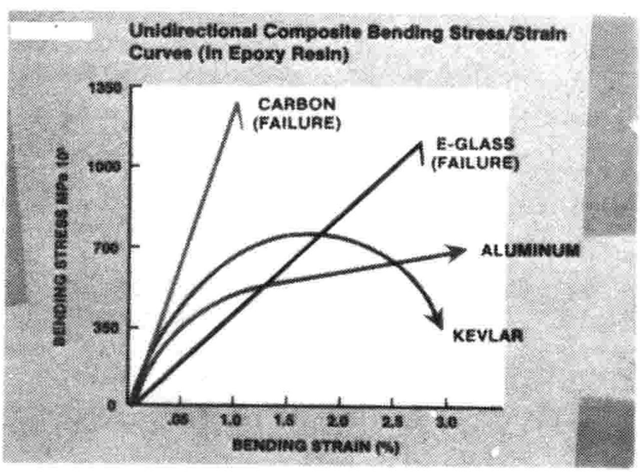
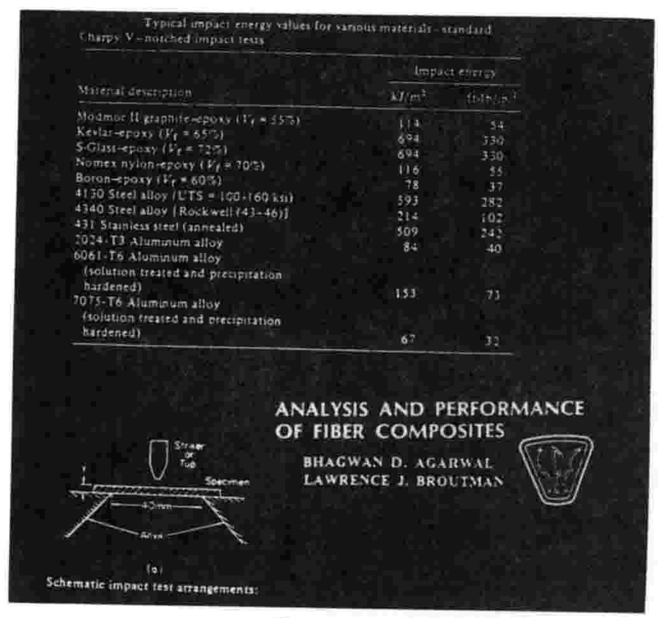


Figure 2

When tensile and compressive loadings are combined in a flexural test, we see a third type of behavior for plastic reinforced with KEVALR aramid fibers. Instead of the brittle failure encountered with glass and graphite reinforcements, we see a bending failure similar to what is observed with metals (Figure 3A). It is important to note that the work to deform the composite containing KEVLAR in this manner is high. This helps to explain the outstanding toughness and impact resistance of composites reinforced with KEVLAR. Another important point is that the yielding on the compression side of the composite subjected to a bending overload does not mean loss of reinforcing fiber continuity. Thus, even after flexural or compressive yield, a composite reinforced with KEVLAR can still withstand significant tensile stress.

Dr. Windecker boiled this down to plain language when he states that one of his primary requirements for a general aviation aircraft is toughness, and he sees this toughness requirement being met by KEVLAR, as seen in Charpy Impact Test (Figure 3B). These combinations of properties result in a major




Typical impact energy values for various materials - standard Charpy V-notched impact tests

Material description	Impact energy kJ/m^2	Impact energy ft-lb/in.^{2}
Modmor II graphite-epoxy (V_f = 55%)	114	54
Kevlar-epoxy (V_f = 65%)	694	330
S-Glass-epoxy (V_f = 72%)	694	330
Nomex nylon-epoxy (V_f = 70%)	116	55
Boron-epoxy (V_f = 60%)	78	37
4130 Steel alloy (UTS = 100-160 ksi)	593	282
4340 Steel alloy [Rockwell (43-46)]	214	102
431 Stainless steel (annealed)	509	242
2024-T3 Aluminum alloy	84	40
6061-T6 Aluminum alloy (solution treated and precipitation hardened)	153	73
7075-T6 Aluminum alloy (solution treated and precipitation hardened)	67	32

Figure 3B

asset in the crash failure mode. Another area where KEVLAR is unique is in vibration dampening. Figure 4 shows the decay of free vibrations for KEVLAR 49, fiberglass, graphite, cast iron and steel. The results suggest that KEVLAR 49 should be much less prone to flutter and sonic fatigue problems than other materials.

Decay of Free Vibrations

	Loss Factor X 10^{-4}
Stainless Steel	6
Ductile Cast Iron	30
Graphite/Epoxy	17
Fiberglass/Epoxy	29
KEVLAR 49/Epoxy	180
Cured Polyester Resin	400

$$\text{Loss Factor} = \frac{A_n}{A_{n-2}}$$

Where A_n = amplitude after $_n$ cycles

KEVLAR and NOMEX® aramid appear to have exceptional resistance to fatigue in cyclic loading. For KEVLAR this property is well documented, and we see that it and boron are in a class by themselves, ahead of glass and aluminum in tension-tension fatigue (Figure 5). The superior performance of aircraft flooring cored with NOMEX suggests similar fatigue attributes.

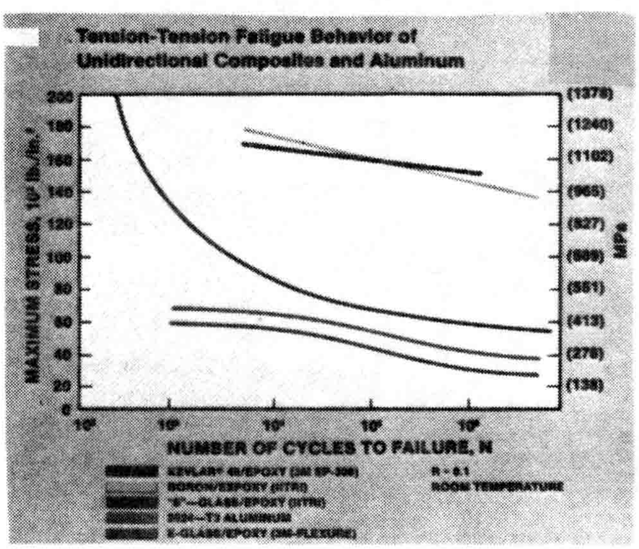


Figure 5

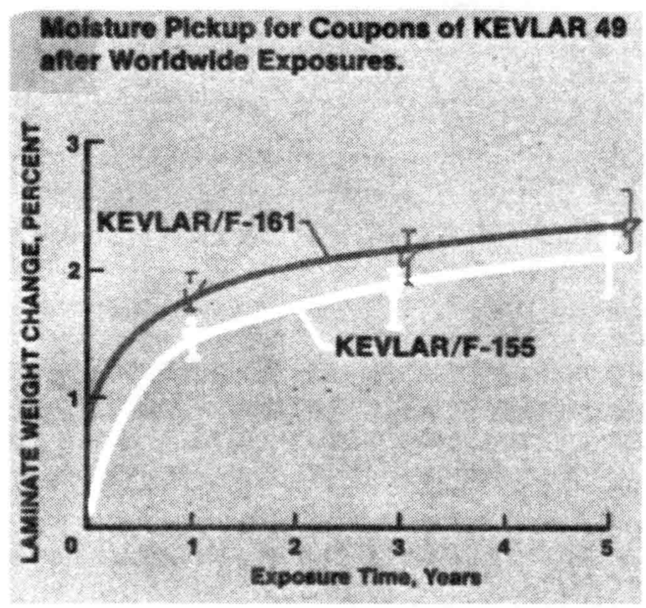


Figure 6

In common with many other organic materials, including epoxy resin and nylon fiber, KEVLAR 49 aramid has an inherent moisture regain. This moisture regain is a function of temperature and relative humidity. At low humidities, such as in a desert, the moisture regain will be well below 1 percent. On the other hand, after very long exposure to extremely humid environments, the regain could theoretically be as high as 7 percent. A question asked by design engineers is what this moisture does to composite properties, and how much moisture is picked up under typical end use conditions.

Figure 6 shows exposure time versus moisture reain of a 100 percent composite of KEVLAR. These data are from a study by Lockheed and NASA in conjunction with the flight service evaluation of KEVLAR 49 on the Lockheed L1011. Two epoxy resin systems with different curing temperatures were studied. The water regain was of the same order of magnitude as for fiberglass and graphite reinforced composites, indicating that the moisture in the composite is tied to the resin properties more than to the fiber properties. Figure 7 shows that flexure, compression, and shear properties were not significantly affected by moisture or time during world-wide outdoor exposure at eight different locations.

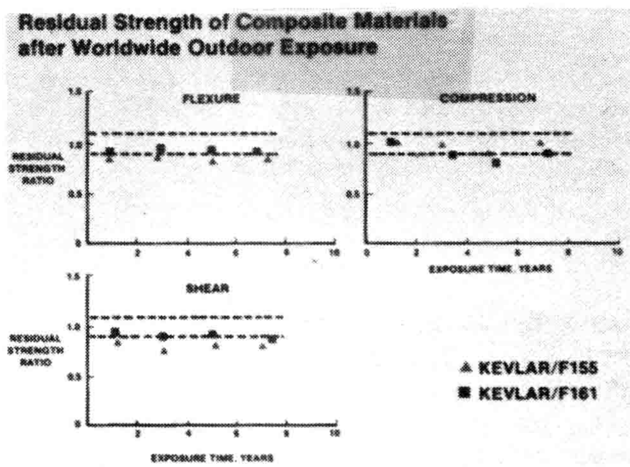
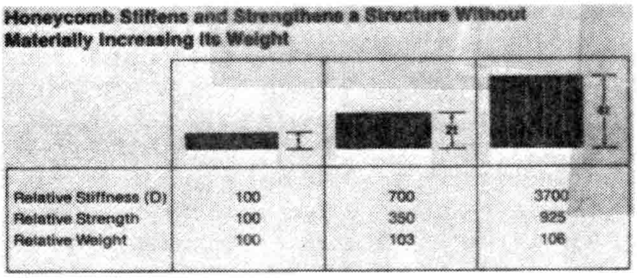


Figure 7

Most uses of KEVLAR consist of sandwich structures with honeycomb core of NOMEX. Therefore, it is important to discuss criteria for selection of materials for sandwich laminate construction. The basic idea behind sandwich construction is illustrated in Figure 8, which shows that a very small increase in a real density or relative weight in the form of a honeycomb core will significantly improve relative strength, or break moment, and apparent stiffness, or relative stiffness.

The reason for this is that, with other things being equal, the apparent stiffness of a panel, is a function of the cube of the thickness. The break moment is a function of the square of the thickness. In real life, things are not quite that simple



Relative Stiffness (D)	100	700	3700
Relative Strength	100	350	925
Relative Weight	100	103	106

Figure 8

because the shear deformation of the core dilutes the advantage of the increase in thickness. However, the benefits of a sandwich laminate construction using a honeycomb core of NOMEX are substancial, as the typical properties shown on Figure 8 indicate.

Figure 9 shows how a honeycomb sandwich laminate is fabricated. The faces are glued to the core material with an adhesive. (When a fiber reinforced prepeg is used for the face, no additional adhesive is needed.) The laminate is structurally

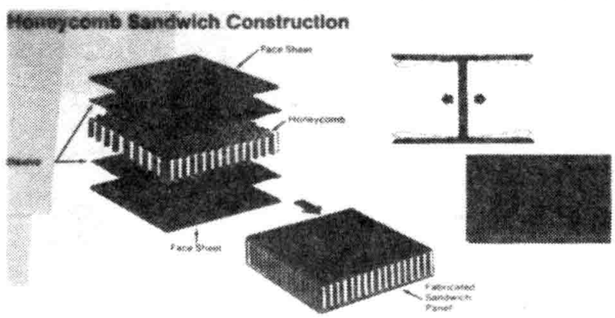


Figure 9

analogous to a 1-beam where the web extends under the entire face. Figure 10 shows how the total deflection of a sandwich beam is the sum of the bending deflection and the shear deflection. When the span is large, more of the work of bending a sandwich beam goes into compressing and extending the faces;

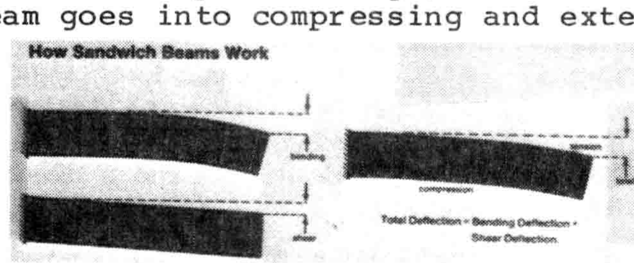


Figure 10

while when we are dealing with a short span, the work of binding the beam goes into deforming the core. Therefore, short spans and localized heavy loads place the greatest demands on the structural integrity of the core material.

The overall requirement for a sandwich structure (Figure 11) is that the structure needs to have enough flexural and shear rigidity to prevent excessive deflections under design loads. To achieve this, the facings need to be thick enough to withstand the tensile, compressive and shear stresses induced by the design loads (Figure 12). The core needs to have sufficient strength to withstand the shear compressive stresses induced by the design loads (Figure 13). The core must be thick enough and have enough shear modulus to prevent overall buckling of the sandwich under lateral loads and to prevent crimping (Figure 14).

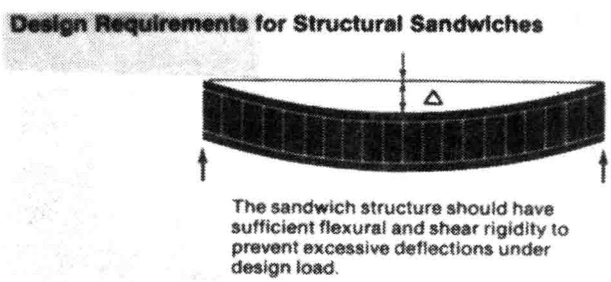


Figure 11

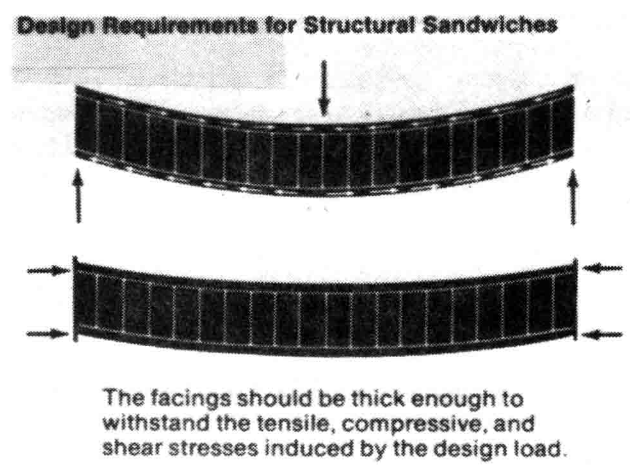


Figure 12

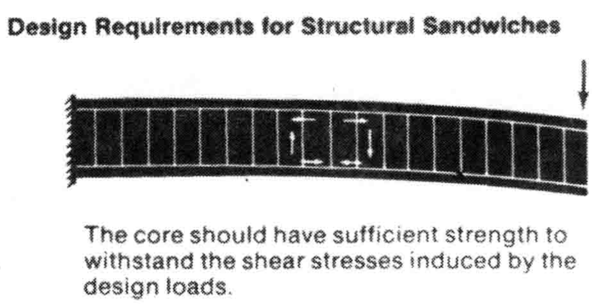


Figure 13

Figure 14

The need to prevent buckling under lateral loads often far overrides other considerations in actual design of sandwich structures. It is not only enough to prevent buckling of the whole part, it is also necessary to prevent wrinkling of a face in the sandwich laminate (Figure 15). This is achieved by having an adequate compressive modulus of the facing and the core. The core cells also need to be small enough to prevent intracell dimpling of the faces under design load. Basically, the thicker and stiffer the skin, the larger a cell size one can accomodate (Figure 16).

Last but not least, the core needs to have a sufficient compressive strength to resist crushing by design loads acting normal to the panel facings as well as compressive stresses induced through flexure (Figure 17). For applications where the finished part is subject to localized loads and localized impact, it is desirable to have a core material with a high but not excessive compressive modulus and high compressive strength. When this is the case, the skin of the laminate that is exposed to the load can deflect inward in the area of impact without damaging the core underneath.

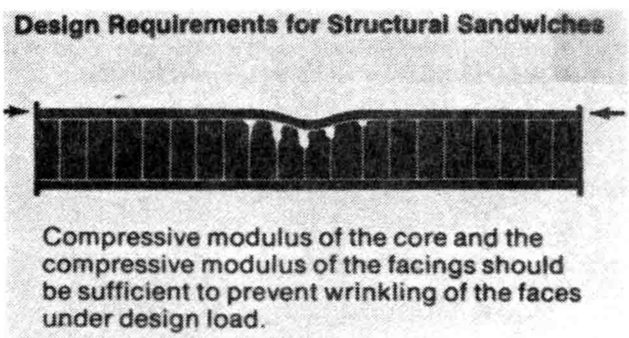


Figure 15

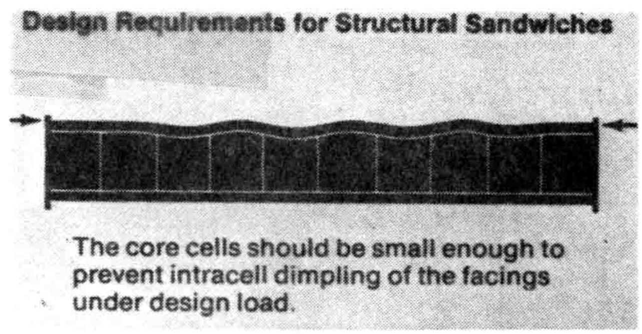


Figure 16

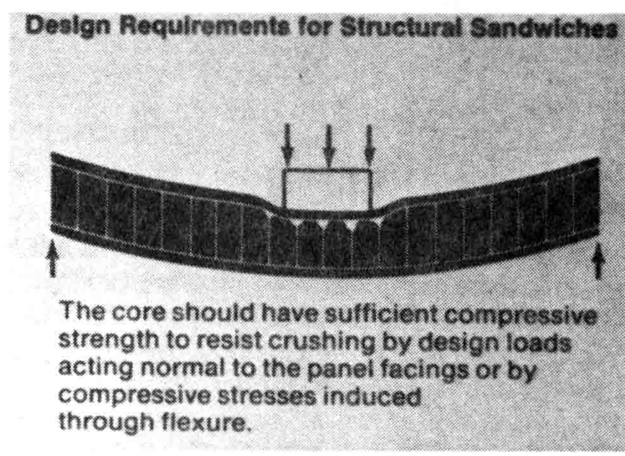


Figure 17

The skin itself will go into tension around the site of the load. If the skin has adequate tensile strength and the core has adequate compressive strength, the final laminate will be extremely resistant to localized ipacts and over laods. These considerations can be very important in aircraft flooring and other panels. They explain the excellent performance of flooring made from skins of KEVLAR® aramid and a core of NOMEX® aramid in the DeHavilland Dash-7. NOMEX and KEVLAR are ideal materials for cores and faces of sandwich laminates because of their physical properties. A good core material does more than save weight directly. With a high performance core material like honeycomb NOMEX, face weight can also be reduced because the faces do not need to be "beefed up" to protect the core.

Many of these benefits of NOMEX are also applicable to KEVLAR aramid. Both products have a high thermal tolerance and can be readily cured using resin systems with 350 degrees Fahrenheit cure cycles (Figure 18). Generally (with a few exceptions), if the resin can take it, so can the KEVLAR and NOMEX aramid. Both materials have high specific properties and low denisities.

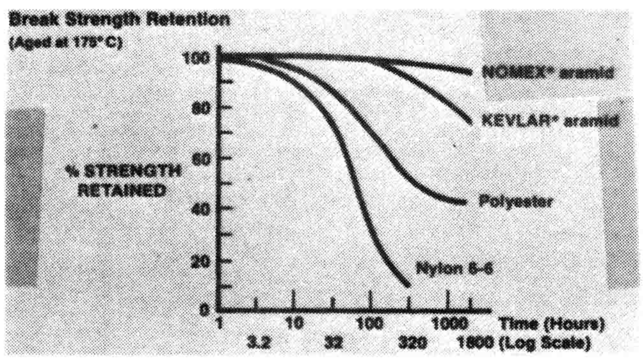


Figure 18

NOMEX is available fabricated into honeycomb with denisties ranging from 1.5 to 9 lbs/ft^3 (24-144 kb/m^3), and KEVLAR with a density of 0.052 lbs/in^3 (1.44 g/cm^3) is less dense than other face reinforcements.

Compared with other core materials, NOMEX has a high specific shear strength. This, combined with a shear modulus falling between other honeycombs such as glass and aluminum and the rigid organic foams, results in greater toughness than other core materials at equal density. Both NOMEX and KEVLAR are self-extinguishing, and panels cored with NOMEX meet stringent shipboard smoke, toxicity, and flammability standards. The excellent creep and fatigue performance of KEVLAR compared with metals and other composite materials was discussed above, and airline experience and a McDonnell Douglas study show that aircraft flooring cored with NOMEX has superior durability both in actual use and in performance-oriented testing.