SANDWICH STRUCTURES: PAST, PRESENT, AND FUTURE

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Abstract The use of sandwich structures continues to increase rapidly for applications ranging from satellites, aircraft, ships, automobiles, rail cars, wind energy systems, and bridge construction to mention only a few. The many advantages of sandwich constructions, the development of new materials, and the need for high performance, low-weight structures insure that sandwich construction will continue to be in demand. The equations describing the behavior of sandwich structures are usually compatible with the equations developed for composite material thin-walled structures, simply by employing the appropriate in-plane, flexural, and transverse shear stiffness quantities. Only if a very flexible core is used, is a higher order theory needed.

Keywords: sandwich structures, sandwich history, sandwich uses, sandwich future.

1. INTRODUCTION

The use of sandwich structures continues to increase rapidly for applications ranging from satellites, aircraft, ships, automobiles, rail cars, wind energy systems, and bridge construction to mention only a few. The many advantages of sandwich constructions, the development of new materials, and the need for high performance, low-weight structures insure that sandwich construction will continue to be in demand. The equations describing the behavior of sandwich structures are usually compatible with the equations developed for composite material thin-walled structures, simply by employing the appropriate in-plane, flexural, and transverse shear stiffness quantities. Only if a very flexible core is used, is a higher order theory needed.

Most often there are two faces, identical in material, fiber orientation and thickness, which primarily resist the in-plane and lateral (bending) loads.

O.T. Thomsen et al. (eds), Sandwich Structures 7: Advancing with Sandwich Structures and Materials, 3–12.

However, in special cases the faces may differ in thickness, materials, or fiber orientation, or any combination of these three. This may be due to the fact that in use one face is an external face while the other is an internal face the former sandwich is regarded as a mid-plane symmetric sandwich, the latter a mid-plane asymmetric sandwich.

A comparison between an isotropic sandwich construction and a monocoque (thin walled) construction is worthwhile If the sandwich construction employs two identical faces of thickness t_f and a core depth of h_c, and the monocoque construction is a flat plate construction of thickness $2t_f$, then the monocoque plate has the same weight as the faces of the sandwich construction using the same materials. If the ratio of face thickness to core depth is 1/20, the flexural stiffness of the sandwich construction has 300 times the flexural stiffness of the monocoque construction. As a result, for a given lateral load the sandwich construction results in a much lower lateral deflection, much higher overall buckling load, and much higher flexural natural vibration frequencies than does the monocoque construction of nearly the same weight. In sandwich constructions subjected to in-plane compressive or shear loads, however, in addition to overall buckling, core shear instability, face wrinkling and monocell buckling (in honeycomb cores) must also be considered.

For a comparison in face stresses, consider the same sandwich and monocoque constructions discussed above subjected to a bending moment per unit width, M. To continue the example used previously, the maximum bending stress in the sandwich face is 1/30 the maximum stress at the surfaces of the monocoque construction subjected to the same bending moment.

Thus for many applications, even if the weight of the core causes the weight of the sandwich to be as much as twice the weight of the monocoque construction the fact that the bending stiffness is 300 times while the maximum stresses are 1/30 that of the monocoque construction makes the sandwich construction very desirable.

In the following, because of page limitations, references will not be given, but the interested reader can easily obtain them by finding the publication list of the authors cited.

2. PAST

Noor, Burton and Bert state that the concept of sandwich construction dates back to Fairbairn in England in 1849. Also in England, sandwich construction was first used in the Mosquito night bomber of World War II which employed plywood sandwich construction. Feichtinger states also that during World War II, the concept of sandwich construction in the United States originated with the faces made of reinforced plastic and a low density core. In 1943, Wright Patterson Air Force Base designed and fabricated the Vultee BT-15 fuselage using fiberglass-reinforced polyester as the face material using both a glass-fabric honeycomb and a balsa core.

The first research paper concerning sandwich construction was written by Marguerre in Germany in 1944 dealing with sandwich panels subjected to in-plane compressive loads. In 1948, Nicholas J. Hoff derived the differential equations and boundary conditions for the bending and buckling of sandwich plates using the Principle of Virtual Displacements, but pursued only the buckling problem. In the same year, Libove and Batdorf published a small deflection theory for sandwich plates. In 1949, Flugge published on the structural optimization of sandwich panels in which he presented nomograms for the solution of several problems. In all the above the materials were isotropic.

Also in the late 1940s, two young World War II veterans formed Hexcel Corporation, which over the decades has played the most important role of any firm in the growth of sandwich structures. Starting with honeycomb cores, even today they make well over 50% of the world's honeycomb core materials.

In 1951, Bijlaard studied sandwich optimization for the case of a given ratio between core depth and face thickness, as well as for a given thickness.

At about that time, sandwich publications began to emanate from the U.S. Forest Products Laboratory (USFPL), which was attached to the University of Wisconsin. As the name implies they were associated with the use of wood products which are in general especially orthotropic. However, their numerous publications of methods of analysis of wood sandwich structures were applicable to the same structures made of composite materials. Their publications dominated the analysis methods for sandwich structures for well over a decade, and are still valuable. Names such as March, Kuenzi and Ericksen were prolific authors with the USFPL. Also, Military Handbook 23 was published which largely involved the results of the many publication issued by the USFPL. This became the definitive document for use by industry.

In 1956, Gerard discusses sandwich plate optimization in one chapter of his landmark book, "Minimum Weight Analysis of Compression Structures." In 1957, Kaechele published a USFPL Report on the minimum weight design of sandwich panels. In 1960, Heath published a paper on the correlation among and an extension of the existing theories for flat sandwich panels subjected to lengthwise compression, including optimum design.

In 1966, Plantema, in the Netherlands, published the first book on sandwich structures, followed by another book on sandwich structures by

H.G. Allen in England in 1969. These books remained the "bibles" for sandwich structures until the mid 1990s.

Also in the mid 1960s, the U.S. Naval Air Engineering Center sponsored research with Dyna/Structures, Inc. to develop fiberglass composite sandwich constructions to compete in weight with conventional aluminum aircraft construction for aircraft. This effort was directed toward achieving a "stealth" aircraft, although that word had not yet been coined. Much of this research effort was in the development of minimum weight optimization methods. Many of these methods were later published by Vinson.

In the seventies tremendous activity began in Sweden regarding the use of composite sandwich construction for naval ship hulls. This was due largely to the leadership of Karl-Axel Olsson of the Royal Institute of Technology (KTH) in Stockholm. He led the effort among the KTH, the Swedish Royal Navy, the Swedish shipbuilders, and the Swedish banks to change the navy from continuing to use steel hulls, and switch to fiberglass composite sandwich constructions. This effort involved analysis, optimization, small scale tests, full scale tests for both underwater explosions and air explosions, etc. They were able to show that a properly designed composite sandwich hull could be as structurally sound as a steel hull. As a result, from some date in the eighties, all Royal Navy ship hulls were made of sandwich construction-a new world first. Olsson then turned his attentions to the rest of the Scandinavian countries and led them to many of the same results. Today many Scandinavian naval ship hulls are composite sandwich, as well as hundreds of the ferry boats that traverse the waters in and among the Scandinavian countries. There is no single person that has done more to contribute to the use of sandwich structures as Dr. Karl-Axel Olsson

In 1989, Ha published an overview of finite element analysis applied to sandwich construction, that was referenced even in a 2005 paper. In 1991, Bert provided a review of sandwich plate analysis, while in 1996, a review of sandwich structures by Noor, Burton and Bert provided over 800 references, all discussed in the review, and another 559 references as a supplemental bibliography.

In 1995, a monograph by Zenkert supplemented much of the material contained earlier in the Plantema and Allen texts (which by that time were out of print). Zenkert followed this by a sandwich textbook in 1996. In 1999, another sandwich textbook was published by Vinson. Hence today there are only four texts dealing primarily with sandwich Structures: Plantema, Allen, Zenkert and Vinson.

To date there have been seven International Conferences on Sandwich Constructions. They are as follows: the first in Stockholm, hosted by Karl-Axel Olsson in 1989; the second in Gainesville in 1992; the third in Southampton, hosted by H.G.Allen in 1995; the fourth in Stockholm in

1998, again hosted by Olsson; the fifth in Zurich, hosted by Hans-Reinhard Meyer-Piening in 2000; the sixth in Ft. Lauderdale, hosted by Jack R. Vinson in 2003; and now the seventh Conference is being held in Aalborg, Denmark in 2005, hosted by Ole T. Thomsen.

In 1999, the Journal of Sandwich Structures and Materials was initiated and it is the only Journal fully devoted to sandwich structures and Materials. Over 180 research papers have been published in the journal to date.

3. SANDWICH STRUCTURES TODAY

In 1992 Bitzer of Hexcel gave an excellent overview of honeycomb core materials and their applications. Bitzer states that every two (or more) engine aircraft in the western world utilizes some honeycomb core sandwich, and that while only 8% of the wetted surface of the Boeing 707 is sandwich, 46% of the wetted surface of the newer Boeing 757/767 is honeycomb sandwich. In the Boeing 747, the fuselage cylindrical shell is primarily Nomex honeycomb sandwich, and the floors, side-panels, overhead bins and ceiling are also of sandwich construction.

The Beech Starship uses Nomex honeycomb with graphite and Kevlar faces for the entire structure-the first all sandwich aircraft. Also. a major portion of the space shuttle is a composite-faced honeycomb-core sandwich. Almost all satellite structures employ sandwich construction.

The U. S. Navy uses honeycomb sandwich construction for bulkheads, deck houses, and helicopter hangars to reduce weight above the waterline. Also recently, they have incorporated a complete hexagonally shaped mast on the USS Radford that is ninety three feet tall and weighs 90 tons. Not only is this a foam core sandwich but the use of exterior materials for stealth purposes make this an asymmetric sandwich. Pleasure boat hulls today are made primarily of fiberglass sandwich.

As stated earlier, the Royal Swedish navy has been using fiberglass and graphite composite sandwich construction for more than twenty years. The newest ship, the YP2000 Visby, is a stealth-optimized graphite/epoxy composite vessel using sandwich construction primarily. Similarly, the Royal Australian Navy uses high performance foam composite sandwich for its inshore mine hunters.

Since 1980, composite front cabs of locomotives have been built for the XPT locomotives in Australia, the ETR 500 locomotives in Italy, the French TGV and the Swiss locomotive 2000. Interestingly, the major design criteria are the pressure waves occurring during the crossing of two high speed trains in a tunnel. In Japan, the new Nozomi 500 bullet trains use honeycomb sandwich for the primary structure.

Also in 1995, Starlinger and Reif reported that sandwich construction is now being used in double-decker buses.

In the U.S., approximately 40% of bridges are structurally deficient or not capable of handling present demands. There are not enough tax dollars to replace all of the bridges in the conventional way. The American Society of Civil Engineers 2005 Report Card gives a "D" for the crumbling infrastructure and states that billions are needed over the next five year period. Half of the cost of bridge replacement is in rerouting traffic during construction. Using composite sandwich construction, pre-made sandwich deck panels can be put in place in days, rather than weeks by conventional construction. Add to this the advantage of no corrosion, and the light weight afforded by the composite sandwich construction. The state of Ohio instituted a plan to replace one bridge in each county with a composite sandwich bridge deck.

In Europe, COBRAE was founded (Composite Bridge Alliance Europe) which is leading the way in promoting composite bridges throughout the European Union.

Another major use for sandwich composite structures during the last decade is wind energy systems. GE Energy states they have 6900 installations worldwide, and that ther growth rate is 20% per annum. The Global Wing Energy Council ranks the leaders in wind energy installations as: Germany, Spain, U.S., and Denmark.

The core of a sandwich structure can be of almost any material or architecture, but in general, cores fall into four types:

a) Foam or solid core
b) Honeycomb core
c) Truss core
d) Web core

The two most common honeycomb types are the hexagonally-shaped cell structure (hexcell) and the square cell (egg-crate). Web core construction is analogous to a group of I-beams with their flanges welded together. The U.S. Navy refers to this web core construction as "double hull" construction. Truss or triangulated core construction is being widely used for the bridge constructions discussed above. In most foam core and honeycomb core sandwich constructions, one can assume for all practical purposes that the in-plane and lateral bending loads are carried by the faces only. However in truss core and web core constructions, a portion of these loads are carried by the core.

Hexcel's latest honeycomb core is Hex Web HRH-36 Flexcore involving a phenolic resin for high strength retention at 350F/175C. Foam or solid cores are relatively inexpensive and can consist of balsa wood or an almost infinite selection of foam/plastic materials with a continuous variety of densities and shear moduli, many of which are polyvinylchloride (PVC).

As in all composite constructions, thermal and hygrothermal considerations must be taken into account. Concerning the thermal effects, with increased temperature, there are three effects: thermal expansion, degradation of elastic properties; and an increase in nonlinear creep/viscoelastic effects.

For the "hygro" part of the effects, there is moisture expansion in all polymer materials, which is mathematically analogous to the thermal expansion. The good news is that if one has the thermal effect solution then one also has the "hygro" solution and they can be superimposed. Moisture also affects the glass transition temperature. One major difference between the thermal and the moisture effects on a polymer matrix structure difference is in the time scales. It takes weeks or months to have a saturated specimen or structure. Weitsman points out that the deleterious effects of moisture continue even after the ten or more years after composites have been soaking in salt water, according to his experiments.

Most materials have significantly different mechanical properties when subjected to dynamic loads that cause high strain rates. However, most structural designs today are made using static properties. See publications of Lindholm, Daniel, La Bedz and Liber, Nicholas, Zukas, Sierakowski, and Feichtinger for discussions of high strain rate effects and test methods.

A research program was conducted at the University of Delaware under ONR sponsorship of the high strain rate effects on many materials that are used in sandwich faces up to strain rates of 1600/sec. It is clear that dynamic properties should be used rather than static properties for structures primarily subjected to dynamic and shock loads. However, there are no means by which dynamic properties can be predicted from known static material properties. Testing at high strain rates is necessary.

Most sandwich structures can be analyzed by using the laminate analysis methods of composite material structures by employing the appropriarte A, B and D stiffness matrices. Only in the case of sandwich constructions with a very flexible core must a higher order sandwich theory be used. For an easy example, consider that the lower face is lamina 1, the core is lamina 2, and the upper face is lamina 3. In this way one can also easily handle sandwich constructions of mid-plane asymmetry as well as symmetric sandwich constructions. Also by involving the 44, 45 and 55 terms in the analysis, one can include the effects of transverse shear deformation. Likewise you can include thermal, hygrothermal and piezoelectric effects.

Localized loads are one of the major causes of failure in sandwich constructions, because the faces are significantly thinner than the same material used in a monocoque construction to resist the same loads. These localized loads can cause the loaded face to deform significantly different from that of the unloaded face. The loaded face acts as a beam, plate or shell on an elastic foundation, i.e., the core. This causes the core to be subjected to significant deformations locally, which can cause high shear and normal stresses that can exceed the allowable stress for the flexible, weak core material. In addition because of the significant deformation of one face the stiffness matrix quantities shown above in equations and, can be locally reduced significantly. This can cause a weak spot in the overall structure which can precipitate a premature failure

To account for these conditions in design and analysis, a higher order sandwich theory must be employed. Since the 1990s this problem has been investigated, accounting for the soft core, differing boundary conditions and behavior for the upper and lower faces. Frostig (along with his collaborators, Baruch, Thomsen, Shenhar and Rabinovitch) has developed a consistent rigorous closed-form, higher order theory for sandwich plates, curved panels and shells. The theory is valid for any loadings (localized or distributed), accounts for discontinuities in load and geometry (ply drops) and includes transverse flexibility of the core. This theory has been used for buckling, vibrations, delaminations, tapered beam and stress concentration problems. It has also been used in comparisons with photoelasticity experiments by Thomsen and Frostig, and found to be very accurate. Most recently this higher order theory has been used by Thomsen to determine the behavior of non-circular boxy shells typical of a fuselage or truck tank, under internal pressure.

Composite sandwich construction also provides a unique opportunity to incorporate piezoelectric, optical and other materials for sensing, monitoring and advising regarding the “health” of the structure during manufacture and use. Piezoelectric effects on a structure are analogous to thermal and hygrothermal effects, analytically, and therefore can be treated analogously. Recently, J-Q Sun has studied the effects of piezoelectric (PZT) patch actuators on curved sandwich trim panels for improved acoustic control in vehicle interiors.

Most recently, a team involving Thomsen, Rabinovitch, Bogetti, Drysdale Arters, Weinacht, and Vinson has investigated the use of piezoelectric materials in flight projectile fins to transform a ballistic projectile into a maneuvering vehicle. Several designs evolved, analysis and structural optimization was performed, and models were constructed. Within the last year these models have been tested in wind tunnels at the University of Maryland and Texas A&M at wind speeds up to 200mph, and the piezoactuators worked as predicted.

One very important dynamic loading unique to ship hulls is wave slamming. Allen and Shenoi have performed extensive experimental research on sandwich beams involving two million cycles each lasting for one second, realistic of the loads on ship hull structures.

Ramachandra and Meyer-Piening report a significant reduction in natural frequencies when a sandwich (or any other) panel is in contact with water on one surface. Their equations should be used when designing or analyzing ship hulls.

Dobyns has provided the methods by which to calculate the natural flexural frequencies for orthotropic and isotropic sandwich plates, including the effects of transverse shear deformation. He has provided forced vibration response solutions for these panels subjected to dynamic sine loads, step function loads, triangular loads, exponential decay (blast)loads, and stepped triangular loads (nuclear blasts). The solutions are given in easy to use Duhamel Integral formulations. Solutions for many static load problems are given as well. Concerning vibration damping, the texts by Nashif, Jones and Henderson, and another by Inman are highly recommended.

For buckling, there are five major textbooks dealing primarily with elastic instability or buckling. These are authored by Bleich, Timoshenko and Gere, Brush and Almroth, Simitses, and Jones. Although these texts deal primarily with structures other than sandwich, the solutions can be applied to sandwich structures to investigate overall buckling of sandwich structures by using the appropriate flexural stiffnesses.

For the overall instability of honeycomb and solid core sandwich panels subjected to in-plane compressive loads or in-plane shear loads, for all boundary conditions, the solutions first appeared in USFPL reports and in Military Handbook 23. Also, the equations to predict core shear instability are given as well. Another local buckling that can occur is face wrinkling. There are two equations that have been given to express this type of buckling. One is by Heath and the other by Hoff and Mautner. There is still disagreement on which of these equations to use. For honeycomb sandwich structures, both hexagonally shaped cells or the rectangular (egg-crate) type, monocell buckling or face dimpling can also occur. For truss core sandwich panels, the elastic and geometric constants were first derived and presented by Libove and Hubka and by Anderson. Overall buckling was treated by Seide and given in Mil HDBK 23.

For a truss core sandwich, care must be taken to insure that the faces do not buckle locally, and that the core plates do not buckle as well, for both in-plane compressive loads and in-plane shear loads. For web core sandwich panels, the equation for overall buckling is given by Seide Again care must be taken to insure that the face plates do not buckle locally, and that the core plates do not buckle as well.

Minimum weight optimization studies have been performed for the honeycomb core, the foam or solid core, the truss core and the web core sandwich panels subjected to in-plane compressive loads, and in-plane shear loads as well. In the process figures of merit were determined that are most helpful in material selection and comparison. In addition, these methods also provide the optimum stacking sequence for the face plates if a laminated construction is used. This research has appeared in many papers.

Shell structures behave significantly different than plate and beam structures, in that under laterally distributed loads for example there exists a "bending boundary layer" in which bending stresses are superimposed upon the membrane type stresses over a small region close to any structural, load or material discontinuity. Further away from these discontinuities, the stresses are membrane only. The bending boundary layer length in shells is on the order of four times the square root of the product of the local radius of curvature times the structural wall thickness.

Regarding the buckling of shells, sandwich or not, shells buckle usually at a fraction of the load predicted by standard methods of analysis, because shells are very imperfection sensitive. This requires the use of empirical factors with the equations.

4. FUTURE

The future for sandwich construction looks bright indeed. Sandwich construction will continue to be the primary structure for satellites. In aircraft, sandwich construction will be increasingly used particularly for large aircraft. Several countries are now using composite sandwich constructions for their navy's ship hulls. However one of the largest uses will be for bridge constructions. Not only will it be used in those states whose Departments of Transportation (DOT) are or become knowledgeable, but there is a large international market in developing countries who may welcome the advantages, thus leapfrogging their bridge constructions into the 21st century without all of the conventional constructions used in the major countries today. Finally, with the growing need for alternative sources of energy, wind energy mill systems are being developed all of which rely heavily on composite sandwich constructions.

Thus the "big ticket items", the major uses of sandwich construction in the future will be ship hulls, bridge structures and wind energy systems.
These will drive the industry throughout the world.