GRID STIFFENED STRUCTURES: A SURVEY OF FABRICATION, ANALYSIS AND DESIGN METHODS

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SUMMARY: This paper documents the recent history of grid stiffened structures and summarizes existing successful analysis and manufacturing methods. Grid stiffened structures, shells supported by a grid lattice of stiffeners, have been researched for many decades as a possible replacement to monocoque, skin-stringer, and honeycomb sandwich structures. In the past 10 years, these structures have finally become an option to structural designers, with several successful analysis and manufacturing methods developed and demonstrated. This paper surveys the analysis and manufacturing methods that have been successfully proven. In addition, a comprehensive survey of lessons learned, manufacturing issues encountered, and existing trade studies is presented. This survey is preceded by a history of grid stiffened structures and a review of their advantages, disadvantages and potential uses.

KEYWORDS: Grid Structures, Advanced Grid Stiffened Structures, Rib Reinforcement, Isogrid, Orthogrid, Aerospace Structure Manufacturing, Composite Structures

INTRODUCTION TO GRID STIFFENED STRUCTURES

Composite Grid Stiffened Structures have long been of interest as a replacement for Honeycomb Sandwich and Aluminum Isogrid constructions but, for many decades, were unused due to the tremendous manufacturing and analysis challenges associated with their construction. During the past 10 years, remarkable progress has been made in the manufacturing of these structures at several locations around the United States. Programs at The Boeing Company, The US Air Force Research Lab, McDonnell-Douglas (now part of The Boeing Company), Alliant Tech Systems, Stanford University, and others have pushed the state of the art in grid stiffened structures, finally leading to processes and methods of interest to real-world production systems. As a result, Composite Grid Structures have found their way into several business jets, research satellites and the Minotaur Launch Vehicle. Additionally, they are currently being investigated by a number of manufacturers of aerospace structures.

Typically, Composite Grid Stiffened Structures are fabricated using a continuous fiber, organic composite material. These structures are characterized by a shell structure (or skin)

supported by a lattice pattern (or grid) of stiffeners. Typically, these stiffeners run in 2-4 directions forming a repeated pattern. Examples of these structures are shown in Figure 1. In rare cases, a second shell structure (skin) is present at the tops of the stiffener pattern, opposite the first skin. Advantages and disadvantages of the composite grid structure configuration are presented in a later section.

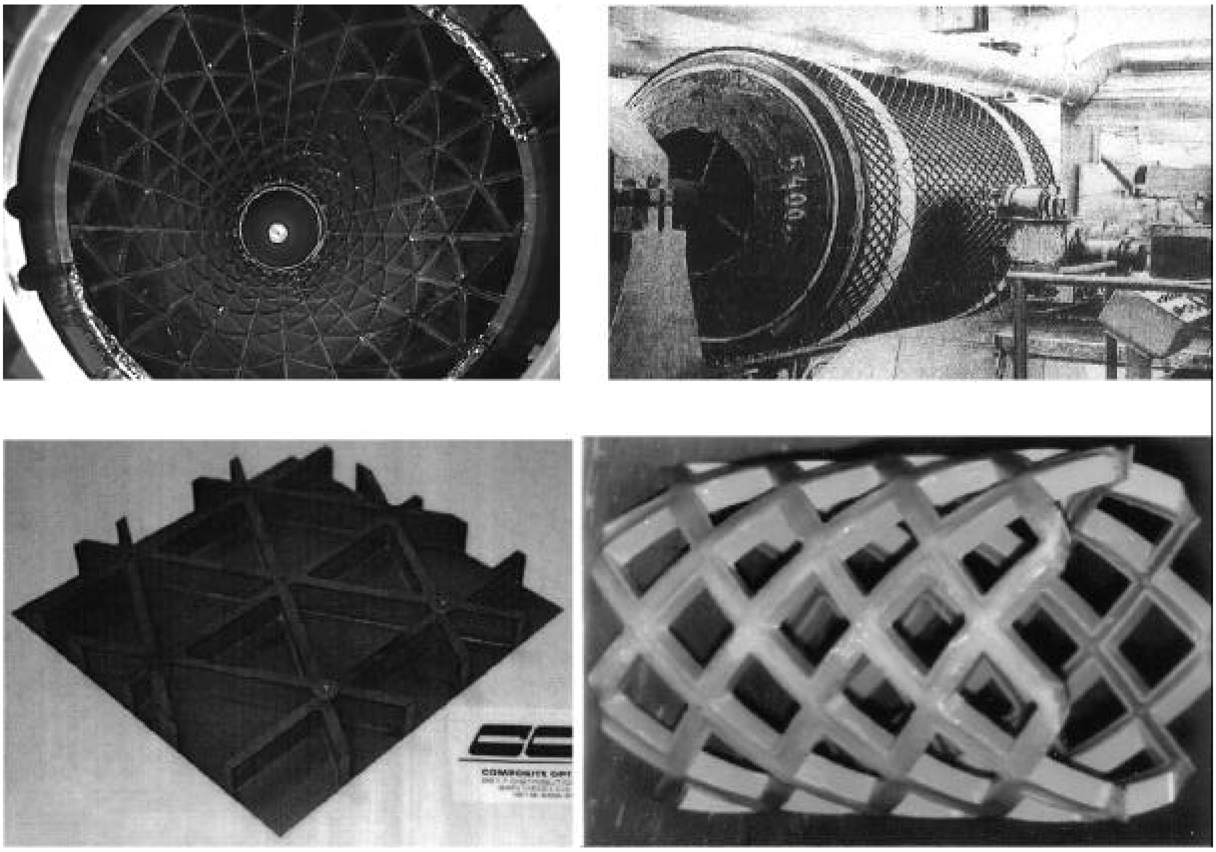

Fig 1. Examples of grid structures.

The goal of this work is to capture and detail the wide variety of work performed toward the goal of practical grid structure analysis, design, and manufacture. This work represents a collaboration of authors in key locations at the sites where major grid structure development programs have, and are still, taking place. All efforts have been taken to include authors from all major Grid Structure researchers in the United States. This work aims to document all the advancements in analysis, manufacturing, and associated theoretical predictions, in one place. This work, then, provides the basis upon which an individual or organization can become familiar with the basics of grid stiffened structures, avoiding all the pitfalls and dead-ends encountered during the past several decades.

THE HISTORY OF GRID STIFFENED STRUCTURES

The McDonnell-Douglas Corporation (now part of The Boeing Company) holds the patent rights for development of the first aluminum isogrid, the earliest precursor of the modern AGS structure. This structure is machined from a single piece of aluminum stock and consists of a skin with stiffeners that form equilateral triangles. The stiffness behavior of an isogrid is isotropic within the plane of the structure, leading to the "iso" prefix.[1] Despite being

[1] The term 'isogrid' is now commonly used to refer to any grid structure whose stiffeners form equilateral triangles. In some groups, 'isogrid' is even used to refer to all grid structures, even those that are not isotropic in any sense. Other common specializations of the grid structure concept are the 'angle grid' where stiffeners run

developed several decades ago, this structure is still used as the basis for the Titan, Atlas and Delta launch vehicle shrouds and interstages. While a very proven and reliable structure, the aluminum isogrid is heavy and expensive by today's standards. An example of an aluminum isogrid is shown in Fig 2.

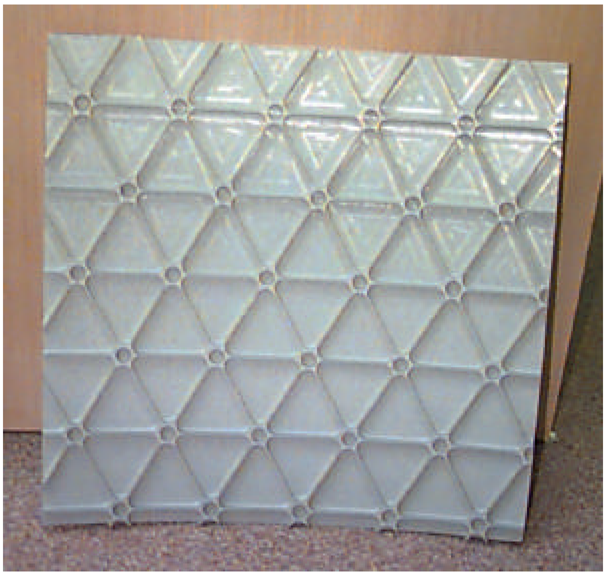

Fig 2. Aluminum isogrid curved panel.

In the late 1970s, with increasing interest in composite materials for aerospace applications, early attempts were made to fabricate composite isogrid structures. Composite materials are particularly well suited for this type of structure as the typical stresses in an isogrid structure's ribs are highly directional along the rib length. The high directionality of composite materials allows for the majority of the material's stiffness and strength to be directed along this directional state of stress, leading, in many cases, to an order of magnitude increase in stiffener strength [1].

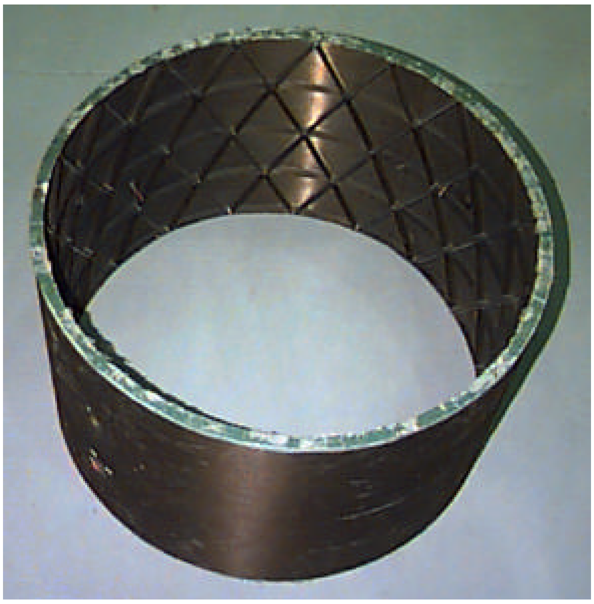

Fig 3. Early Composite Isogrid.

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in only 2 directions at some angle to each other and the 'orthogrid', an angle grid where the stiffeners run in two perpendicular directions.

Early composite isogrid structures were manufactured for aerospace applications by government research groups in both the United States of America (US) and the Union of Soviet Socialist Republics (USSR), with most early American concepts being developed at the National Aeronautics and Space Administration (NASA). Several composite isogrid launch vehicle components were flown in the USSR although the promise of light weight isogrids was never fully realized due to very low fiber volume fraction and poor part quality. Further research into composite isogrid fabrication continued sporadically in the US at a number of universities [2] and aerospace companies. Much aerospace industry work is still considered proprietary and none of the developed methods resulted in structures that were competitive with other existing composite structure types.

In the early 1990s, the Air Force Phillips Laboratory was involved in an effort that finally achieved high quality, light weight composite isogrid structures (See Figure 3). These structures were manufactured using tooling made of silicon rubber and proved to have extremely high strength-weight ratios. While successful, the manufacturing method developed was very labor intensive and was limited primarily to cylindrical structures.

Despite the challenges, continuous fiber, composite grid structures did find their way into one very large, unexpected market: floor grating. Companies such as Chemgrate, Inc were able to fabricate large quantities of low cost, low fiber volume grid structures for use as non-corrosive flooring in factories. While of little use to the aerospace community, these early production grid structures were critical to the development of effective analysis techniques for grid structures, which in turn was critical to grid structure development into a usable real-world technology. In the early 1990s, grid structure analysis was a serious impediment to their acceptance, with aerospace companies having little faith in existing composite structure analysis techniques yielding acceptable answers for structures as complex as grid structures. Significant research at Stanford University, The Ohio State University and Georgia Tech in the early 1990s led to several new analysis techniques [1, 2, and 3] that were verified using grid structure floor grating.

The breakup of the USSR in the early 1990s gave US researchers unparalleled access to Soviet composite structures technology. The US Air Force initiated several programs to transfer Soviet grid structure manufacturing and analysis technology to the US. Although helpful to the state of the art, this technology was still not practical for real-world systems.

In the past few years there has been a renewed interest in grid structures leading to an abundance of new design ideas and manufacturing concepts from industry, academia, and governments. The traditional equilateral pattern, which leads to the name isogrid, has been abandoned in favor of stiffener patterns optimized to specified loading situations. Recognizing this change, these structures are increasingly referred to as composite grid structures or advanced grid stiffened (AGS) structures. Additionally, many new and innovative manufacturing methods have been created.

The past few years have seen the first demonstration uses of composite grid structures on actual systems. With these successful demonstrations, interest in grid structures in the aerospace community has increased dramatically. On 23 February, 1997, the Ballistic Missile Defense Organization, in conjunction with the National Air Intelligence Center, flew a composite grid stiffened payload shroud built by the Air Force Research Lab on the Combined Experiments program. This grid structure was 61% lighter, 300% stronger, and 1000% stiffer than the aluminum structure it replaced. Additionally, the US Air Force MightySat I satellite, launched off the US space shuttle in December, 1998, had a grid structure for its upper payload deck, fabricated using the SnapSat™ concept developed by Composite Optics International, San Diego, CA. Scaled Composites of Mojave, CA, using a wet winding process developed internally, developed a grid structure fuselage for its V-Jet,

Boomarang, and Vantage demonstrator aircraft and plans to use this technology for several future civil aviation aircraft concepts. Additional aerospace uses of grid structures include a Delta II interstage replacement funded by the Air Force Research Lab and developed using Russian manufacturing processes (not yet tested or flown by this writing) and development work by The Boeing Company toward developing a grid stiffened fairing for the Minotaur Launch Vehicle, slated to fly in the year 2000. To date, grid structures have been successfully fabricated in flat, curved, cylindrical and conical shapes. No high quality grid structures with complex, or double, curvature have been demonstrated by this writing.

BENEFITS AND DRAWBACKS

Grid structures, as all other structures, have distinct benefits and drawbacks. As with all structure types, they are not the best choice for all solutions, but tend to fit applications that play to their strengths and down-play their weaknesses. These strengths and weaknesses are detailed below. As grid structures are fairly new, the following lists are bound to be incomplete. While there has been significant lab experience with these structures, real-world experience has been limited and true operational experience is non-existent. Therefore, some of the perceived benefits and drawbacks of these structures are unproven.

Benefits of Grid Structures

The primary benefits of grid structures can be grouped into three categories: environmental robustness, low-cost manufacturing for certain geometries, and structural efficiency to certain types of loading.

Grid structure *environmental robustness* is a perceived, if not yet proven, benefit in operational environments. Some studies have shown [4] that grid structures have significantly higher damage tolerance than their main competitor, the honeycomb sandwich. In addition to inherent damage tolerance, grid structures have shown a tendency to contain delamination, a result of impact damage, to within one cell, thereby limiting its spread and eventual catastrophic failure. In addition to delamination damage tolerance, the redundancy in load paths inherent in grid structures leads to characteristic tolerance to other types of damage, such as cracked ribs or cut skins. Additional environmental robustness is derived from the fact that grid structures are open structures. Unlike honeycomb sandwich structures, grid structures do not absorb and retain water over their lifetime. The propensity of honeycomb sandwich structures to retain water is particularly bad as this water often has a tendency to corrode the core material.

Automated, *low-cost manufacturing* is another grid structure benefit. The ability to fabricate grid structures using an automated, single cure process is potentially superior to skin stringer and sandwich construction where significant hand operations are involved. This benefit, in practice, tends to be very dependant on geometry, with grid structures often being superior for conical and cylindrical sections and loading conditions compatible with thin-to-medium rib dimensions.

Structural efficiency is another grid structure benefit that is situation dependant. Grid structures can be designed such that the ribs take the majority of the load, or so that the skin takes the load and the ribs simply suppress the global buckling mode of failure. In either case, using honeycomb sandwich construction as a baseline, for an equivalent weight, grid structures tend to be stiffer in-plane and less stiff out-of-plane. For aerospace structures, therefore, a grid structure design tends to be preferable when deflection or fundamental

frequency requirements govern the design space. Sandwich structure designs are preferable when global buckling is the driving factor.

Finally, grid structures can be the structure type of choice for specific applications that lend themselves to the grid construction. One example is solar panel substrates, where heat radiates directly off of the heated skin. This situation is obviously preferable to the case of a sandwich where the heated skin is insulated from the radiating skin by the core material. Another case is that of structures that require multiple points where point loads are transferred into the structure (such as hardware attachment points). In this case, the grid structure nodes (where ribs cross) can perform this function with little or no additional structure requirements.

Drawbacks of Grid Structures

The primary drawback of grid structures is a lack of knowledge about their behavior, particularly failure. Additionally, the complexity of a grid pattern can lead to excessive manufacturing times, especially for simple constructions such as flat plates. Finally, grid structures are by their very nature asymmetric through the thickness[2]. This asymmetry can be a serious drawback, particularly for flat plates and curved panels that must experience temperature swings[3].

Grid structure tooling requirements are another serious drawback of the structure type. Typical grid structure tooling is significantly more complex than tooling for sandwich structures. The cost of this complexity can be slight for large production runs but becomes very significant for unique aerospace parts where the tool cost must be amortized over a very small number of parts. Tooling reuse is another concern as most grid structure tooling incorporates sections that must be replaced frequently.

Finally, other concerns are worth noting in specialized applications. One example is the case of launch vehicle fairings where the cost of cleaning a grid structure pattern before payload integration can be much higher than the cost of cleaning what effectively is a flat surface on the inside of a sandwich structure fairing.

Comparisons, Paper & Physical, Between Grid and Other Structures

Several trade studies and direct comparisons between grid and other structure types have been performed over the past several years. These comparisons are listed below.

1. Troy Meink, while at the Ohio State University, performed a paper study comparing a complete grid structure design to an existing honeycomb sandwich design for Boeing's SeaLaunch Launch Vehicle Fairing. The SeaLaunch fairing is a medium class fairing of approximately 4m in diameter. This study concluded that to the design requirements of this fairing[4], the grid and sandwich structure fairings would be approximately of equivalent weight. The grid structure fairing was 28% stiffer, though, leading to a larger payload envelope. In contrast, the grid structure fairing had a buckling load 55% lower than the sandwich structure fairing, leading to decreased stability failure margin. Finally, the grid structure fairing first frequency was 39% higher, leading to better acoustic attenuation properties. More details on this study can be found in [5].
2. As stated above, the Air Force Research Lab flew a grid stiffened shroud on the Combined Experiments program in early 1997. This program had two flights with identical shroud

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[2] An obvious exception is the case of a grid structure with two facesheets, one on each side of the ribs. This case is very rarely encountered, though, and very difficult to manufacture in practice.

[3] This asymmetry is a mitigating factor when considering the thermal radiation benefits that grid structures provide for solar panel substrates.

[4] Considering as criteria only stiffness (payload envelope impingement), material failure and stability failure.

requirements, one of which flew an aluminum shroud, the other the grid stiffened shroud. Providing a good one-on-one comparison between the technologies, the grid stiffened shroud was 61% lighter, 300% stronger, and 1000% stiffer than the aluminum shroud on the other flight. Cost of the two shrouds was estimated to be roughly equivalent. More information on this program can be found in [6], the November 1997 issues of *Aerospace America*, the ? issue of *Defense News* and the ? issue of *Space News*.

3. Steven Huybrechts, while at Stanford University, performed a study comparing grid structures to a number of other structures. This work is documented in [8].
4. The Air Force Research Lab, in conjunction with Marshall Space Flight Center conducted a study to determine the suitability for the use of grid structures in large vehicle applications. This study is available from the authors.

MODERN ANALYSIS AND DESIGN

Composite grid structure analysis and design has progressed significantly in the past decade. At the start of the 1990s, no reliable grid structure analysis methods were available other than analytical models developed in the Soviet Union that were so generalized as to be of little use to design engineers. At the close of the decade, many analytical analysis techniques have been developed at various universities that achieve fairly good results over a wide range of grid structure geometry. While useful for design purposes, these techniques are still somewhat generalized and don't take into account irregularities. Finite Element techniques have been successfully applied to analyze grid structures, taking into account irregularities, but are still of little use for overall design due to model complexity and the inability to easily changes stiffener geometry (angle, spacing, etc). In short, the state of grid structure analysis capability at the end of the 20th century can be summarized with the following bullets:

- Closed form, analytical solutions (typically smeared approaches) are available to solve the general grid structure problem disregarding irregularities. These solutions are valuable for parametric studies and initial grid pattern acceptance/rejection activities. These solutions are not acceptable for calculating final structure margins or characteristics.
- The Finite Element Method (FEM) has been shown to work reasonably well for calculating final structure margins and characteristics. Typically, FEM model geometry is highly dependant on rib stiffener spacing and angle making these models very difficult to modify to accommodate small changes in rib pattern. This drawback limits the usefulness of this method for design activities.
- Areas of grid structure analysis that are not well understood analytically and are not typically captured by FEM models are the effect of nodal offset, rib-skin attachment, and rib behavior at & near nodes.
- Areas of grid structure analysis that are not well understood analytically but are typically captured by FEM models are local rib buckling, local skin 'pocket buckling', rib termination effects and the effects of grid pattern irregularities.
- The final poorly understood variable in grid structure analysis is the impact of manufacturing. Grid structure detailed geometry is heavily dependant on the manufacturing method used. Very little data is available on the effects of various manufacturing processes on grid structure behavior. Some examples are skin print-through (markoff) near ribs where rubber tooling deforms the skin, wavy fibers in ribs due to lateral compaction, resin rich/dry areas at or near nodes, and non-uniform fiber volume fraction from rib top to rib bottom.

Following is a list of major analytical techniques that have shown reasonable agreement with real world grid structure behavior. Due to paper size limitations, only a brief description of each is given.

- **Closed Form Equations for Isogrids Developed at Georgia Tech.** Early US analytical analysis for grid structures was developed by Dr Rayfield at Georgia Tech and the Air Force Phillips Lab. Grid structures being fabricated at the time had tall, thin ribs. As a result, rib buckling was the limiting factor on most of these structures. Therefore, a simple equation was developed to predict rib buckling for grid structure ribs [2].
- **Analytical Methods Developed in the Soviet Union.** Significant analytical work was done for grid structures in the former Soviet Union. Several equations were developed for predicting grid structure behavior by 'smearing' stiffeners. Most of this work can be found in the works of Tarnapolski.
- **Development of Point Analysis Suitable for Optimization at Stanford University.** In 1995, Dr Chen and Dr Tsai at Stanford University published a point analysis method for grid stiffened structures [7]. This method 'smears' grid stiffeners to a solid plate of equivalent properties[5] for stiffness calculations.
- **Failure Envelope Analysis and Conclusions Developed at Stanford University.** In 1995, Dr Huybrechts and Dr Tsai at Stanford University published a series of finite element derivations and failure theories for grid structures [8].
- **Rib Buckling Predictions Developed at Ohio State and the Air Force Research Lab.** Several rib buckling predictions were developed by Ohio State University and the Air Force Research Laboratory. This work is published in [10].

SUCCESSFUL MANUFACTURING METHODS

Significant progress has been made towards viable grid structure manufacturing processes in the past decade. While many shapes remain unmanufacturable, many standard grid structure geometries are now easily fabricated. the state of grid structure manufacturing at the end of the 20th century can be summarized with the following bullets:

- Grid structures for stiffness controlled applications (such as solar panel substrates, spacecraft structure, and optical benches) are now easily fabricated so long as they are built up of flat or only slightly curved sections.
- Grid structures for strength controlled applications can now be manufactured fairly easily for most applications (cylinders, conic sections, bi-conic sections, domes) with low rib fiber volume fractions (less than 40%). These grid structures with low rib fiber volume fractions can often be too heavy to be practical.
- Grid structures for strength controlled applications can be fabricated with high rib fiber volume fractions successfully for limited rib-skin dimensions. Typically, there is a maximum rib width for these processes as well as a minimum skin thickness.

Following is a list of proven viable manufacturing methods that have shown reasonable agreement with real world grid structure behavior. Due to paper size limitations, a description of each of these methods is not feasible but will be included in an upcoming work.

- Wet Winding Around Pins (A Russian Manufacturing Method)
- Wet Winding In Hard Tooling With E-Beam Cure (Developed At Boeing)
- Nodal Spreading (Developed At Stanford University)
- Winding Into Solid Rubber Tooling (Developed at Phillips Lab)
- The Hybrid Tooling Method (Developed at Air Force Research Laboratory (AFRL)) [11]

[5] The 'A', 'B', & 'D' matrices, the standard matrices of composite laminate plate theory, determine equivalence.

- Fiber Placement with Hybrid Tooling (Developed at AFRL & Boeing)
- Fiber Placement with Expansion Inserts (Developed at Alliant Tech Systems)
- The Located Expansion Tooling Method (Developed at AFRL & Boeing)
- Wet Winding: The Brute Force Approach
- The SnapSat™ Method (Developed at Composite Optics, Inc)
- The TRIG Method (Developed at Stanford University)

OTHER ISSUES

While great progress has been made toward the goal of usable composite grid structures in the past 10 years, there are still several outstanding questions. A brief list is follows.

- What is the true effect of nodal offset?
- How do we best terminate rib patterns?
- In cylindrical structures should we include axial ribs, circumferential ribs, or both?
- How do we best repair of grid structures?
- How do we deal with grid structure cutouts?
- How well does FEM model grid structures?
- Can we fabricate a grid structure with a zero B-matrix [9] that will, therefore, not warp under a temperature change?

CONCLUSIONS

This paper documents the recent history of grid stiffened structures and summarizes existing successful analysis and manufacturing methods. At the end of the 20th century, multiple grid structure analysis and fabrication methods have been developed and proven, making this construction a viable alternative for many various applications. The availability of these methods has led to the successful integration of grid structures into several aerospace structures that have successfully flown. Grid structures are now being surveyed for use in a wide variety of applications, primarily in the aerospace and civil engineering fields. The next decade will undoubtedly see these structures become a viable alternative for structural designers & engineers in many fields.

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