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Unistructure — A New Concept for Light Weight Integrally Stiffened Skin Structures

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Unistructure — A New Concept for Light Weight Integrally Stiffened Skin Structures

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UNISTRUCTURE IS THE CHEM-TRONICS' DESIGNATION given to integrally stiffened skin structures produced by a novel chemical milling process.

The process can be applied to a variety of structural shapes and is typically applied after all forming is completed so it does not complicate the forming process. This is a significant advantage since forming of honeycomb or integrally stiffened panels that have to be produced as flat products prior to forming require complex forming procedures.

Figures 1a, 1b, and 1c show typical patterns produced in cylindrical elements of jet engines. The Unistructure concept can also be applied to flat or curved panels, cones, shells, and elements with compound curvature, such as bulkheads or fairings.

A typical cross section through a primary stiffening rib is shown in Figure 1 Section A-A. In some cases, smaller uncapped secondary rib patterns are added to the skin areas to reduce resonant frequencies. The uncapped secondary rib cross section is shown in Figure 1c Section B-B.

Two chemical milling cuts are needed to produce the primary rib cross section, with each cut producing approximately half the rib height. As a consequence, the fillet radii at the intersections of ribs and at the intersection of ribs and skin are approximately half the rib height, with a gentle transition between the radial elements and the skin. There are no abrupt changes in cross-section anywhere in the structure.

Non-optimum material in the waffle nodes is less than in the isogrid nodes. However, this is generally compensated for by the larger node-to-node spacing permissable in isogrid which results in fewer nodes per unit of surface area than in the waffle. On occasion, a smaller secondary reinforcing pattern of simple standing ribs is added to the primary pattern to provide higher skin panel resonant frequencies and structural stability with less weight than would be possible if the panel size were reduced by moving the primary ribs closer together.

ABSTRACT

Unistructure is a new concept for light weight integral rib-reinforced skin structures that is readily adaptable to many configurations. The rib cross sections are a form of I beam. The rib reinforcing patterns considered here are isogrid and waffle, (i.e. triangular and rectangular constructions) but any desirable form can be produced.

This paper provides an over-view of the methods of fabrication and the structural performance features of Unistructure. Comparisons are made with honeycomb, skin/stringer, and integral-machined structures. These comparisons indicate that the combined ease-of-fabrication and performance advantages of Unistructure warrant its consideration in many applications.

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In both waffle and isogrid configurations, node weight may be reduced without undue impairment of rib structural performance by the use of tapered ribs. These ribs are widest at the midspan and reduced in width at the ends to reduce the node sizes. Through the use of nearly rectangular cross sections at the ends and capped cross sections at the mid-spans, the cross sectional area may be held constant along the length of the rib to retain the tensile strength. Also, node weight can be reduced by mechanical material removal from node centers if economically justified.

CHEMICAL MILLING OF CAPPED RIBS

Figure 2 outlines the basic steps taken to chemically mill a capped rib cross section. After the first mask is applied and trimmed into the desired pattern (a) the first chemical milling cut is made to about half the final rib height. The first mask is then removed and a second mask is applied and trimmed to protect the flanks of the first cut, with a specific relationship to the first cut. The second chemical milling cut produces the desired cross section by undercutting the first pattern and producing a section approximating an I beam.

ALTERNATIVE RIB CROSS SECTIONS

By adjusting the relative positions of the first and second masks, it is possible to produce different primary rib cross sections, as shown in Figure 3. The maximum under-cut configuration (a) has the minimum web width relative to cap width. The 50% undercut configuration (b) has a web approximately equal to half the cap width, and the no undercut (c) is essentially a rectangle. The one cut cross section (d) is the section produced by conventional chemical milling. It is simpler to produce, but is less structurally efficient than any of the two-cut shapes because of the large skin-to-rib blend radii. It is normally used only for small secondary reinforcing features associated with increasing resonant frequency of the skins. The maximum undercut is the most efficient configuration, in terms of section modulus.

PADS AND BOSSES

Attachment features may be designed as integral parts of the reinforcing pattern if their geometry and the starting stock thickness are compatible. There is considerable freedom of choice in the location and size of the structural elements and in the choice of panel thickness, but to facilitate the integration of supplemental features, the feature designs must be compatible with the starting stock thickness selected for the structure.

TYPICAL MANUFACTURING SEQUENCES

The manufacturing sequences typically used to produce a Unistructure fan duct are illustrated in Figure 4. The flat pattern blank (a) is produced by plasma cutting, saw cutting or chemical blanking. The detail is

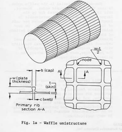


Fig. 1a - Waffle unistructure

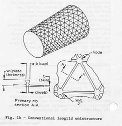


Fig. 1b - Conventional isogrid unistructure then roll formed (b) EB seam welded (c), sized and trimmed to final length. The basic structure is then chemically milled (d). elding on of flanges, resizing, stress-relieving, and final machining are indicated in (e).

APPLICATION EXAMPLES

Examples of Unistructure applications are illustrated in Figures 5 to 9.

Figure 5 illustrates a jet engine fan case. This is a Titanium 6AL 4V conical waffle Unistructure having an overall length of 45.07 inches, diameters of 40.98 and 50.04 inches and a plate thickness of .312 inch. The pocket sizes are nominally 1.70 inch by 6.00 inch, the rib cap widths are .150 inch and skin thicknesses are .030 inch. Manufacturing tolerances on cap widths are ± .030 inch, on skin thickness ± .010 and on plate thickness ± .005.

The fan case is split into two unequal halves that bolt together along axial flanges. The flanges are add on features, but a number of integral bosses and pads are included in the integral reinforcing pattern.

Figure 6. illustrates another fan duct. It has a forward conical section attached to an aft cylindrical section containing thrust reaction trunnions, and add on flange details. The manufacturing processes for producing this duct are similar to those already discussed, with the addition of building up and

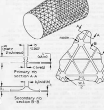


Fig. 1c - Ribbed skin isogrid unistructure

E.B. welding the cylindrical section to the conical section.

Figures 7 and 8 illustrate other jet engine ducts, with similar features in a variety of patterns.

Figure 9 illustrates a jet engine firewall and stiffener structure made from .500 inch thick Ti 6-4 plate. A Warren girder-like Unistructure configuration has been chemically milled to produce a skin thickness of .030 and a number of integral pads, bosses and through hole reinforcements. Rib lengths are 1.00 to 14.0 inches, and rib cap widths are .250 to .650 inch.

UNISTRUCTURE ADVANTAGES

Use of Unistructure offers many advantages.

Bosses and through hole reinforcements can be integral, thereby eliminating fasteners, improving structural performance, and achieving manufacturing economies through reduction of the piece part count.

Optimum structural performance can be provided because structural properties such as rib width, skin thickness, cross-section configuration and node spacing can be globally tailored in accordance with load variations over the structure.

Local features, such as bosses and through holes can be designed to have minimal effect on the stiffness and load carrying capability at a minimum weight penalty.

Corner radii in the Unistructure pattern are significantly smaller than can be practically achieved by machining. As a consequence, the non-optimum material at nodes and other local features is minimal.

Design changes in the reinforcing pattern features are readily incorporated at little cost.

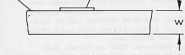
The reinforcement pattern can be applied to the final product shape, avoiding the necessity of forming parts by sophisticated procedures to avoid damage to the structure.

COMPUTERIZED STRUCTURAL ANALYSIS

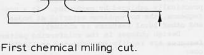
Computer programs have been developed to optimally design Unistructure plates and shells subjected to a variety of loading conditions. These programs take into account load distributions throughout the structure as determined from finite element or other elastic analysis. Using iterative analytical methods, the programs compute the minimum weight combination of Unistructure elements that will safely carry the projected loads without experiencing undesirable skin panel resonant frequencies, local rib crippling, skin buckling, or general instability. The programs include provisions of generic cross-sections for the configurations shown in Figure 3, as well as other standard and tapered rib cross sections, which can be selected for use in the various analyses. Some parameters, such as plate thickness, node-to-node spacing, minimum allowable skin gages and rib widths may be selectively fixed, as are the overall geometric parameters of the shell.

Material properties at temperatures to which the structures will be exposed are included in the programs. The programs also take into account manufacturing tolerances in computing cross sectional properties and weights. Local skin buckling and rib crippling are based on minimum skin thickness and rib width, respectively. General instability is based on nominal dimensions and weights are based on dimensions half way between nominal and maximum.

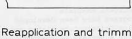
Some of the programs have been used to generate numerical data for the following discussion and illustrations, utilizing the Unistructure parameters presented in Table I.



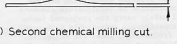
(a) Mask application and trimming



(b) First chemical milling cut.



(c) Reapplication and trimming of mask



(d) Second chemical milling cut.

Fig. 2 - Steps in two stage chemical milling of capped rib

EFFECTS OF RIB CROSS SECTION ON STRUCTURAL PERFORMANCE.

Figure 10 compares the use of maximum undercut vs. single-cut rib cross sections with 3" and 6" node spacing on structure unit area weight under various axial edge load conditions. Computed values for minimum acceptable skin thicknesses are indicated at selected points on the plot.

It is evident that the maximum undercut cross section produces significantly lower structural weights, particularly at loads of less than 1000 lbs./in. This is the feature that differentiates Unistructure from a conventionally chemically milled pattern of similar appearance.

EFFECTS OF NODE-TO-NODE SPACING IN ISOGRID PATTERN WITH SECONDARY REINFORCEMENT.

Figure 11 illustrates the effects of node-to-node spacing on the structural unit area weight vs. edge axial load for a secondary reinforced isogrid Unistructure. A primary node spacing of 6 inches provides the lowest weight structure for loads up to about 1200 lbs./in. However, beyond that load, the 6" primary node spacing causes the steepest rate of increase of weight vs. load, primarily due to column buckling of the ribs. When the design loads are relatively low, the nodes can be spaced relatively far apart, but as loads increase, the node spacing must be decreased. There is an optimum relationship for each design requirement. In a cylinder or a panel, the node-to-node spacing is generally kept constant. However, in a conical shell, spacing would increase in proportion to the shell diameter. The choice of an optimum spacing or a range of values in a particular design depends on shell geometry, plate thickness and most importantly, on the edge load distribution over the shell.

EFFECTS OF RIB SPACING IN WAFFLE PATTERN

Figure 12 illustrates the effects of rib spacing on unit area weight in a waffle pattern, having a minimum skin thickness of .018. The choices in this case are more complex since for the selected rib spacings, minimum gage considerations become more important at lower load conditions. This is particularly apparent when the circumferential spacing of the ribs is reduced to one inch in the example illustrated. In this case, the assumed minimum skin thickness, and possibly the primary rib cross section itself, are greater than they need to be for this rib spacing, with an obvious effect on weight.

The width of skin on either side of the rib that contributes to the rib cross sectional properties depends on the stress level in the skin. The lower the stress, the larger the effect of skin on rib strength. As a consequence, when both circumferential spacing and load are relatively small, all of the skin between ribs will contribute to the rib cross sectional properties. This factor influences the shapes of the curves in Figures 11 and 12.

EFFECTS OF MANUFACTURING TOLERANCES

Figure 13 illustrates representative changes in rib section modulus and unit area weight vs. tolerances for .625 inch plate, with 6 inch node spacing in isogrid Unistructure. Section modulus is chosen as a basis for assessing effects of minus tolerances because of its direct influence on general instability and indirect influence on local crippling. It is evident from Figure 13 that rib width minus tolerance has the greatest effect on reducing section modulus, but plus tolerance has close to the least effect in increasing weight. Skin thickness tolerances have the reverse effect. The curves in Figure 13 have spotted on them typical manufacturing tolerances.

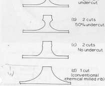


Fig. 3 - Typical rib cross sections

Fig. 4 - Fan case manufacturing sequences

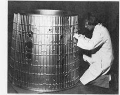


Fig. 5 - Jet engine fan case

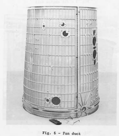


Fig. 6 - Fan duct

Fig. 7 - Jet engine duct

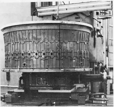


Fig. 8 - Jet engine duct

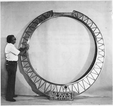
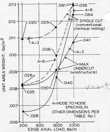


Fig. 9 - Jet engine firewall and stiffener



conventional chemical milling.

Fig. 10 - Weight savings of unistructure versus conventional chemical milling

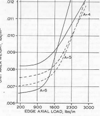
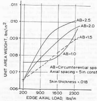


Fig. 11 - Effects of changing node to node spacing in secondary reinforced unistructure



unistructure

Fig. 12 - Effects of rib spacing in waffle unistructure

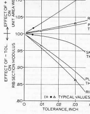


Fig. 13 - Effects of rib, skin and plate tolerances on section modulus and unit area weight

TABLE I. Parameters Used to Generate Data in Figures 10 to 12.

Plate thickness	.250 in.
Minimum Rib Width	.110 in.
Tolerances	
plate thickness	± .005
rib width	± .030
skin thickness	± .010
Cylinder Radius	19 in.
Cylinder Length	50 in.
Edge Shear	200 lbs./in.
Material	6AL 4V
Temperature	520°F
F_{cy} (Yield Strength)	63440 psi
F_u (Ultimate Strength)	81640 psi
E (Modulus of Elasticity)	1.39×10^7 psi
G (Shear Modulus)	5.226×10^6 psi
u (Poissons Ratio)	.399
Minimum allowable skin panel resonant frequency	650 Hz

STRUCTURAL EVALUATION FACTORS

Comparisons between Unistructure, honeycomb, and skin/stringer structures for shell and panel applications depend on a number of factors which include:

Size and geometry, i.e. diameter, length shell thickness and shape.

Loads, i.e. axial, body bending, shear and torsion.

Minimum allowable dimensions, i.e. in skin thickness, rib width, web thickness, and plate thickness.

Manufacturing tolerances.

Construction materials.

Operating temperatures.

Design margins and safety factors.

Overall shell stiffness requirements.

Resonant frequency requirements.

Configuration of bolted flanges, bosses, access holes and other attachment hardware.

Cost, weight, and maintainability considerations.

Ease of making design changes or creating derivative configurations.

One of the more significant features of Unistructure is the ease with which bosses, through holes, hardware and attachments and other local features can be incorporated. Figure 14 illustrates a representative fitting as applied to each concept. Compared to honeycomb, and skin/stringer structures, in Unistructure the local features can be included with a relatively small increase in non-optimum structural material and with no increase in manufacturing piece part count. If structural continuity is required across the local feature, then in the honeycomb and skin/stringer structures, both the local cross section and attachment means (i.e. rivets or braze joints) must be designed for this purpose. However, in Unistructure, only the local cross section must be designed since the feature is integral with the structure.

Figure 15 illustrates comparative methods for attaching flanges to Unistructure, honeycomb and skin/stringer structures. As in the case of the local features, it is evident that Unistructure offers the advantages of simplicity and lighter weight, at least when compared to skin/stringer construction.

COMPARATIVE EVALUATION OF STRUCTURE TYPES

A qualitive comparison of the three basic structural concepts discussed is made in Table 2. The following comments pertain to items (a) to (i) in this Table.

(a) The use of non-optimum material as described in connection with local features and flanges applies in varying degrees to all three basic shell structures. Fasteners are needed to assemble stringers and frames in the skin/stringer structure and brazing material must be added to attach honeycomb core and face plates. The weight of the fasteners and brazing material is non-optimum since they are not normally as fully stressed as the rest of the structure. Fillets at Unistructure waffle and isogrid rib intersections contribute to rib end and fixity and hence to load carrying capability, however, the excess material in the node centers is non-optimum. However, we believe the relative non-optimum material is lowest in Unistructure.

(b) The effects of normal manufacturing tolerance on structural performance tend to be more significant in Unistructure since the chemical milling process introduces more variability than would be expected in a typical sheet metal structure. However, while control of rib cross section requires special attention, the overall shell geometry is easily controlled by sizing operations. This can tend to offset local tolerance effects, especially when general instability is a driving design consideration. Therefore, depending on design considerations, effects of tolerances on performance can be low to moderate.

(c) The piece part count of Unistructure is uniquely low. Reduced parts handling and reduced inventories result in manufacturing economies.

(d) There have been few opportunities for valid comparison of fatigue characteristics of the various structural concepts in similar applications; however, from what has been observed, Unistructure performs exceptionally well. The absence of discrete attaching devices and the fairing of all changes in cross section (every juncture has a fillet radius) make the structure more durable.

(e) The inspectability of Unistructure is excellent because there are no hidden surfaces. Honeycomb is particularly poor in this respect because of lack of direct accessibility to the core-to-face plate brazed joints.

(f) Repairability of Unistructure is good because a damaged area can be cut out and replaced by a welded inlay that is a replica of the removed area. A field repair with compatible solid plate stock is also possible at some weight penalty.

(g) Material costs tend to be moderately higher in Unistructure because of the need to chemically mill away a significant portion of the basic plate stock used in its manufacture. However, because of the lower prices paid for plate stock used in Unistructure as compared to sheet stock used in honeycomb and skin/stringer and the significantly lower number of details involved, the material cost differential is less than the differential in the weights of the initial raw stock.

(h) Because there are no rivets to pull out or braze joints to peel, Unistructure tends to have better post-buckling load carrying capabilities than either honeycomb or skin/stringer structures. The redundant load paths available in isogrid Unistructure are of particular significance in enhancing post buckling strength. This is due to the ability of the normally lightly loaded diagonal isogrid ribs to pick up load when in-line highly-loaded ribs fail. While substantial load carrying capability is lost in the post buckled state, in many cases, it can still provide sufficient

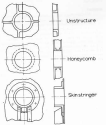


Fig. 14 - Comparison of local features inclusion

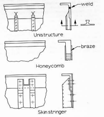


Fig. 15 - Comparison of flange attachments

TABLE 2. Comparison of Structures

	Unistructure	Honeycomb	Skin/ Stringer
a. % Non-optimum Material Used in structure	low	high	high
b. Effects of tolerance on performance	low to moderate	low	low
c. Piece Part Count	low	high	high
d. Fatigue Characteristics (Life)	excellent	poor	good
e. Inspectability	excellent	poor	good
f. Repairability	good	poor	poor
g. Material Costs	moderate	low	low
h. Post Buckling Strength	excellent	poor	good
i. Ease with which changes in the reinforcing pattern may be made.	excellent	poor	poor

structural integrity to prevent other forms of catastrophic failure. For example, when used in a jet engine fan containment case, the local failure of the containment case structure due to a blade penetration, is followed by a cut off of engine thrust. The axial load on the structure is thereby greatly reduced; however, there must still be sufficient strength in the structure to survive other aero-dynamic loads.

(i) Tooling needed to generate specific grid patterns in Unistructure is relatively simple and flexible compared to the other tooling used in its manufacture. It is relatively easy to incorporate changes that effect only the rib and pattern features. Fortunately this is the area where most changes have occurred.

SUMMARY

Unistructure is an outstanding advancement in the field of rib and skin structures. It has already found many applications in which it excells in both performance and life cycle cost. Such advantages should improve with time as more advanced methods of manufacture are applied and as further understanding is gained about its structural properties. Its excellent performance warrants consideration when various stiffened skin structures are being evaluated.

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