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ISOGRID DESIGN ASPECTS FOR CYLINDRICAL SHELL

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ABSTRACT: Lightweight, compression load carrying cylindrical structures form part of all space vehicle structures. Isogrid structures are effectively used in such applications with the advantage of lower weight and higher structural efficiency. An Isogrid structure is characterized by face-sheet thickness (*t*), rib thickness (*b*), rib depth (*d*) and height of triangle (*h*). Analytical methods, such as that compiled in 'NASA CR 124075' are available for sizing of the above Isogrid parameters for a given geometry, load and material of cylinder. These parameters ensure simultaneous failure of Isogrid structure by local skin buckling, rib crippling and general instability. It also ensures minimum weight structure. These parameters, however, are dependent on the machining accuracy and may not be feasible for fabrication. The examples of this machining limitation being very small face-sheet thickness or triangle height as suggested from the analytical method. In such circumstances, a deviation from these parameters is required to realize the structure. These deviations, however, make the structure non-optimum. Therefore, it is necessary to evolve a systematic iterative procedure to obtain a feasible and optimum design. It is proposed to use Finite Element Method (FEM) based software (ANSYS).

In the present study, the Isogrid structure is discretised using FEM. ANSYS Parametric Design Language (APDL) has been extensively used to analyze the structure for iterative design. For the given optimum Isogrid parameters (obtained using analytical method), the FE model is validated by comparing stresses and buckling failure modes. Assuming that these optimum Isogrid parameters are not feasible for fabrication, a detailed study of the effect of variation of these parameters on stresses, buckling failure and weight of a typical cylindrical section under compression is carried out. From this set of Isogrid parameters obtained using FEA, the one which is feasible and optimum is proposed.

A node of an Isogrid structure is a point where all six ribs intersect. In the manufacture of Isogrid, extra material is left at the node because the milling cutters cannot cut to the center of the intersection without cutting in to the ribs. The weight penalty of this extra material is reduced by drilling a hole at the centre of each node. This nodal region in Isogrid deserves special consideration because the nodes are flexible and affect local stress distribution near the nodal region. Milling cutter tool radius and drill bit radius govern the machining at nodal region. The effect of the milling cutter tool radius and drill bit radius on the node flexibility and consequently local stress distribution is also presented.

This paper outlines automated iterative design procedure with APDL macro capability for Isogrid cylindrical shell with manufacturability of component. This is expected to give a near optimal solution.

1. INTRODUCTION TO ISOGRID STRUCTURES

Isogrid consists of a lattice of intersecting ribs forming an array of equilateral triangles integral with the face sheet. This pattern takes advantage of the simple fact that triangular trusses are very efficient structure. Isogrid behaves like an isotropic material with no directions of instability or weakness and Poisson's ratio as 1/3. It is found to be most efficient in resisting compression and bending loads. It gives lower weight, less structural depth, standard pattern for attachments at nodes and better resistance to impact damage. It is also a cost effective structure. Isogrid structures are effectively used in many aerospace applications such as Delta vehicle, Skylab and Space Shuttle to name a few. The details of Isogrid construction are given in Fig.1 to Fig. 4. ISOGRID DESIGN HANDBOOK (NASA CR-124075) has been used as a guideline for initial sizing of the Isogrid in this study.

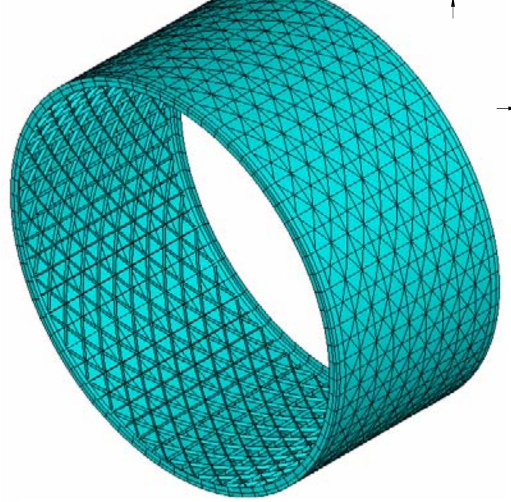

Figure 1: Typical cylinder with Isogrid construction

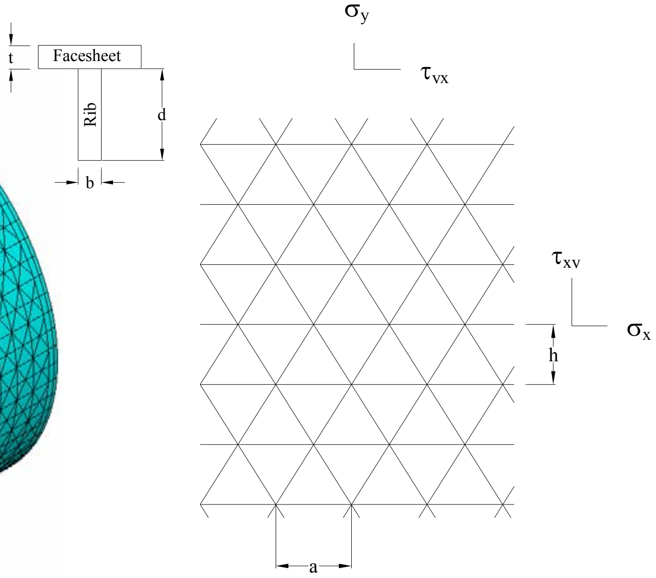

Figure 2: Isogrid design parameters

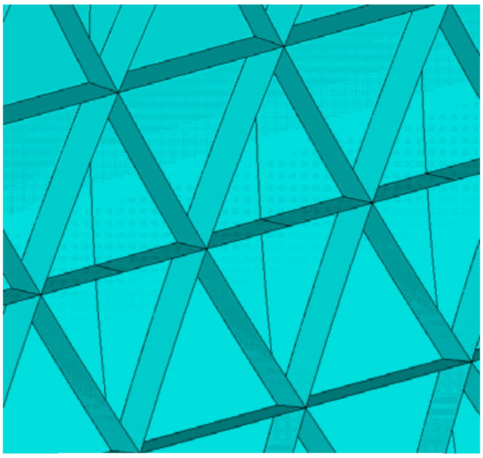

Figure 3: Shell Model of Isogrid

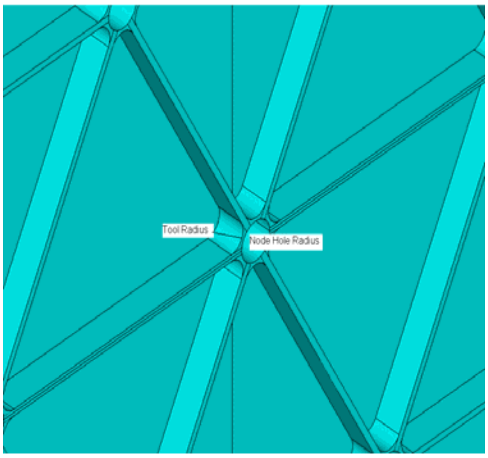

Figure 4: Isogrid Node

The Isogrid design parameters are t (skin thickness), b (rib width), d (rib depth), h (triangle height) and a (leg of triangle). The other non-dimensional parameters used in Isogrid sizing are $\delta = d / t$, $\alpha = b\, d / t\, h$ and $\beta = [3\alpha\,(1+\delta)^2 + (1+\alpha)(\,1+\alpha\delta^2)]^{1/2}$.

2. HOOKE'S LAW FOR ISOGRID RIB GRID

The Isogrid rib-grids are analyzed by smearing out such that the grid-work is considered as a solid continuous sheet of material with appropriate elastic properties. It can be shown that if one assumes a uniaxial state of stress in the ribs, the smeared out elastic constants are identical to those of an isotropic material in plane stress. When ribs and skin are combined, the composite construction is treated as an isotropic layered material, with appropriate elastic constants for each layer i.e. rib grid and skin. The internal strains in the composite construction are determined by the stress resultants and couples in the composite construction. The stress strain relation is the Hooke's law relation for isotropic materials in plane stress as given by

$$\sigma_x = (E_1 / 1\text{-}\nu_1^2)\ (e_x + \nu_1 e_y)$$
$$\sigma_y = (E_1 / 1\text{-}\nu_1^2)\ (e_x + \nu_1 e_y)$$

$$\tau_{xy} = \tau_{yx} = (E_1 / 2\,(1+\nu_1))\,\gamma_{xy} \quad \text{……………………………………..……. (1)}$$

where E_1 (= (b/h) E) and ν_1 (= 1/3) are equivalent Poisson's ratio and Young's Modulus of the grid work. The rib and skin elements are combined to produce an equivalent skin thickness t^* and equivalent modulus E^* such that the structure can be treated like an equivalent monocoque cylindrical structure. The equivalent monocoque skin thickness which will give same extensional and bending stiffness K and D is

$$t^* = t\,\beta / (1+\alpha),\ E^* = E\,(1+\alpha)^2 / \beta \quad \text{……………………………..………… (2)}$$

And the stiffnesses are

$$K = E^*\,t^* / (1-\nu^2) = E\,t\,(1+\alpha) / (1-\nu^2)$$

$$D = E^*\,t^{*3} / 12(1-\nu^2) = [E\,t^3 / 12(1-\nu^2)]\,[\beta^2 / 1+\alpha] \quad \text{…………………………… (3)}$$

All established isotropic solutions from extensively developed theory of plates and shells can be used for Isogrid structures.

3. DESIGN CRITERION

The Isogrid parameters which ensures simultaneous failure of Isogrid structure by 'General Instability', 'Skin Buckling' and 'Rib Crippling' are given by [1].

3.1 General Instability

For a cylinder with L/R ratio ≤ 10 and subjected to combined bending and axial compression, the critical buckling load is given by

$N_{cr}(1) = c_0\,E\,(t^2/R)\,\beta$, where $c_0 = 0.397$ …………………………………………………(4)

3.2 Skin Buckling

The critical stress for skin buckling is given by

$N_{cr}(2) = c_1\,E\,t\,(1+\alpha)\,t^2/h^2$, where $c_1 = 10.2$ …………………………………………..(5)

3.3 Rib Crippling

The critical stress for rib crippling is given by

$N_{cr}(3) = c_2\,E\,t\,(1+\alpha)\,b^2/d^2$, where $c_2 = 0.616$ …………………………………………...(6)

For cylinder subjected to axial compression and bending loads, one of the ribs is aligned in the axial direction. It is generally found that the Isogrid design parameters obtained from the design handbook are not feasible from machining considerations. Also the initial sizing gives the Isogrid parameters for buckling load multiplier of 1.0. Generally for semi-stiffened structures, knock down factor as suggested in literature is 0.6. A minimum FOS of 1.5 also needs to be ensured for the design. Thus resizing of Isogrid parameters is required to establish a feasible and minimum weight design.

A detailed study has been carried out to establish the effect of each Isogrid parameter on the nature of instability and the results are as shown in the following Fig. 5. It can be observed that skin buckling is governed by skin thickness and cell height. As expected, higher skin thickness and lower cell height will give maximum FOS against skin buckling. Rib crippling, on the other hand, is governed by rib thickness and rib depth. Higher rib thickness with lower rib depth will give maximum FOS against rib crippling.

A similar study was carried out to see the effect of each Isogrid parameter on the weight of structure. It was observed that with increase in face sheet thickness, rib thickness and rib depth, the weight of structure increases. However, for increase in cell height, the weight of structure decreased. These results were further used for the design.

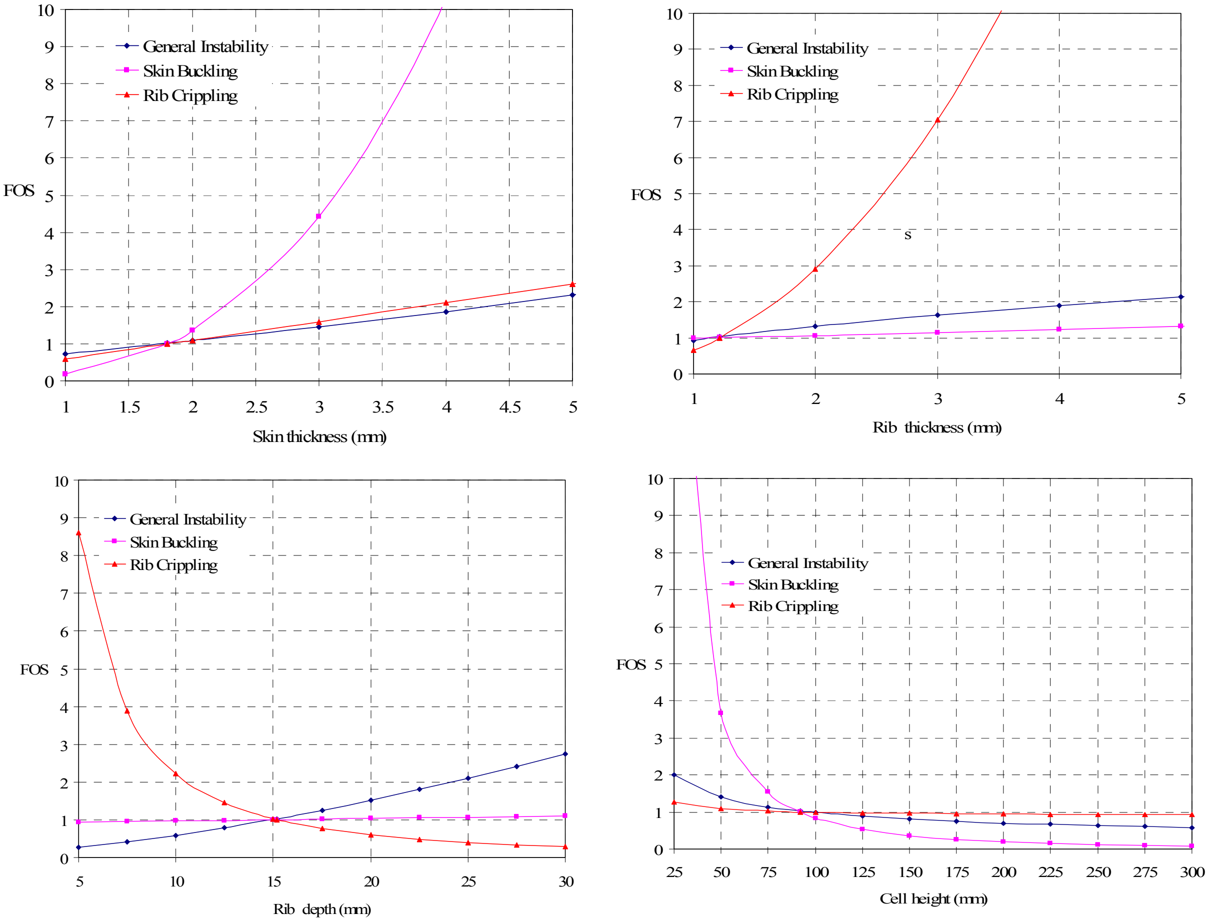

Figure 5: Effect of Isogrid Parameters on Mode of Buckling

4. MACHINING CONSTRAINTS

Isogrid structures, unless they are very shallow and used with parts with compound curvature, are machined in the flat and subsequently formed. Machining limitations are, therefore, of prime importance in the design of Isogrid structures. Isogrid is pocket milled where an end mill traces the inside contour of the pocket and cleans out all the material in the centre. Six abutting triangular pockets, with corners appropriately rounded by the cutter dimensions, define the geometry of the Isogrid node. Holes are drilled in the nodes to reduce weight. For different components, geometric standardization of machining parameters needs to be done, keeping in mind the machining limitations. For example, if the height of the cell as 90 mm is possible with the existing machining facilities, the same height will be maintained for all the components. The other Isogrid parameters such as t, b and d should also be feasible from machining considerations e.g. the minimum weight Isogrid configuration with t=1.57 mm, b= 0.86 mm and d=7.3 mm, may or may not be possible to machine. These dimensions will also vary for different components. In such circumstances, it is always convenient to choose near optimal configuration which will be easier to machine. An automated iterative design procedure with APDL macro capability for design of Isogrid cylindrical shell has been developed here keeping in mind manufacturability of component. Firstly, FE model is validated with the analytical results and then used for design.

5. VALIDATION OF ISOGRID THEORY USING FINITE ELEMENTS

Finite Element Analysis (FEA) was carried out for Isogrid parameters obtained using [1]. An excellent match was observed between the predicted [1] and FEA results as can be seen from Fig. 6. The deformed plot clearly shows simultaneous failure of the structure by local skin buckling and rib crippling. Also, the load multiplier as obtained from the FE Analysis closely matched with that given by analytical model. The same FE model was used for further design.

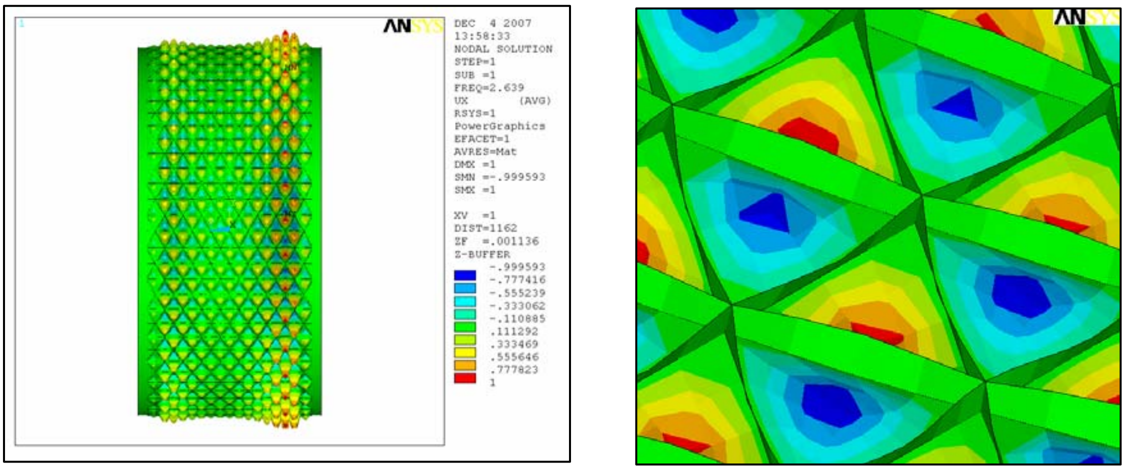

Figure 6: Simultaneous failure of cylinder by General Instability, Skin Buckling & Rib Crippling

6. EFFECT OF NODE FLEXIBILITY

The point where the Isogrid ribs intersect is called a node. In the manufacture of Isogrid, extra material is left at the node because the milling cutters cannot cut to the centre of the intersection without cutting in to the ribs. The weight penalty of this extra material is reduced by drilling a hole in the centre of each node. These node holes are ideal points of attachment for other structures or for fittings carrying concentrated loads. The nodal region in Isogrid deserves special consideration because the nodes are flexible and cause a local redistribution of stresses in the area. A detailed study has been carried out to see the effect of node flexibility on the local stress distribution using FEM. Milling cutter tool radius and the drill bit radius at the node were considered as the design parameters and local stresses were obtained for the same. Typical results are as shown in Fig.7.

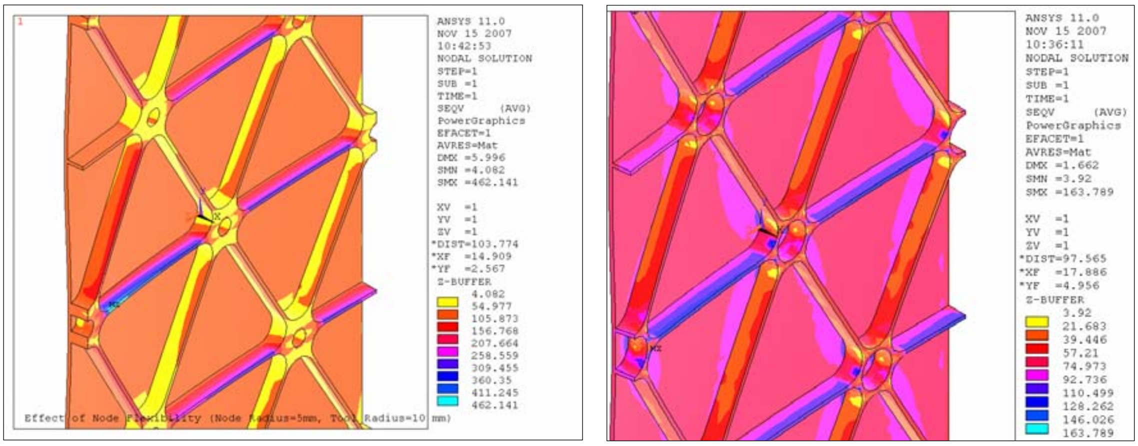

Figure 7: von-Mises Stress distribution at Isogrid Node

7. CONCLUSION

The main aim of this study was to achieve near optimal and fabrication feasible Isogrid structure. A systematic analysis was carried out to study effect of each Isogrid parameter on mode of buckling and weight of the structure. APDL was used extensively to automate the design. It was also established that a significant weight saving can be achieved with Isogrid structure.

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[3] Danoka DK, Jensen DW. Advanced Space Structure Concepts and their Development