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METHODOLOGY FOR OPTIMIZATION OF SHELL STRUCTURES

by

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ABSTRACT

This paper outlines the major analysis modules that could be used to optimally size shell of revolution structures. Specifications for the modules are provided. Both empirical and finite-element methods are considered. For selected optimization strategies, the modules are organized into flow diagrams indicating I/O functions and human intervention requirements. Examples of typical analysis results are presented.

INTRODUCTION

This paper describes an expert system for the computer-aided engineering and design of isogrid and waffle, integral cylinder, cone shell structures. Figure 1 shows a typical shell configuration to which this system applies.

The secondary structure in Figure 1 comprises the bosses, bolted flanges, kick ring, and split line or longitudinal member. Typical loads on the structure are body loads applied to one bolted flange while the other is fixed, and local loads on the bosses. The moment, axial, and transverse load components for both types of loading are indicated in Figure 1.

Starting with an input design specification, the function of the expert system is to perform the following tasks with a minimum of human intervention:

- Determine worst-case internal design loads.
- Select and size an optimum shell design configuration.
- Size secondary structures.
- Provide user with visibility over, and facilities for verification of, all phases of the sizing and design processes.
- Generate CAD-based detailed design drawings.

SYSTEM OVERVIEW

Figure 2 shows an overview of the expert system. The following are some of its features.

Internal shell loads are generated on the basis of a tailored or untailored shell. The untailored shell has uniform constitutive properties; the tai-

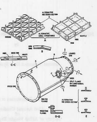


Figure 1. Typical shell configuration including secondary structure and showing typical load components.

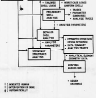


Figure 2. Overall system.

lored shell has varied properties as determined by the detailed shell analysis. As indicated, worst-case loads for a uniform (untailored) shell are used in the preliminary shell analysis.

The design specification controls all system functions, while human intervention is used to initialize detailed shell and secondary structures analyses. However, totally automatic initialization of these analyses are possible.

Trades and parameter summaries from the preliminary shell analysis are the bases for the initializing parameter passed to the detailed shell analysis. This, in turn, initializes the secondary structures analyses.

Analysis traces are user-selected routines that list consecutive lines of code and variably valued input and output for each line. The user can select initial variable values for these traces. The traces provide facilities for rapid detailed verification and checking of all significant analyses.

Design drawings are automatically generated via a data base created by the optimized structure design definition processes.

DESCRIPTIONS OF MAJOR PROGRAM SEGMENTS

Figures 3 through 10 and matching items in the Appendix describe the major program segments that comprise the expert system. Table 1 is a summary of items in the design specification that appear as inputs to major program segments.

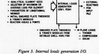


Figure 3. Internal loads generation I/O.

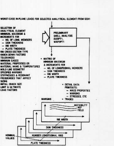


Figure 4. Preliminary shell analysis.

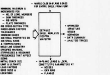


Figure 5. Detailed shell analysis.

SAMPLE OUTPUT DATA

A sense of the character of some of the expert system hard copy output is provided by the simplified examples in Figures 11 through 13.

Table 1. Design specification summary.

- WAFFLE OR ISOGRID CONSTRUCTION
- MATERIAL PROPERTIES
- EXTERNAL SHELL & BOSS LOADS
- SHELL GEOMETRY
- BOSS SIZES, LOCATIONS & HOLES
- ANALYTICAL ELEMENT PARAMETERS
- ANALYTICAL ELEMENT INTERNAL LOAD CRITERIA
- ULTIMATE LIMIT & KNOCK DOWN FACTORS
- REFERENCE RIB CROSS-SECTION
- MINIMUM GAGES & TOLERANCES
- INITIAL MINIMUM, MAXIMUM & INCREMENTAL VALUES FOR SKIN & PLATE THICKNESS, RIB WIDTH & NUMBER OF LONGITUDINAL RIBS (BOUNDS OF OPTIMIZATION)
- INITIAL KICK RING CONFIGURATION
- INITIAL CRACK SIZE FOR CRACK GROWTH ANALYSIS
- POWER SPECTRAL DENSITY OF ENVIRONMENT FOR HCF ANALYSIS
- SELECTIONS OF MARGINS, RESONANT FREQUENCIES, ETC TO BE USED IN STRUCTURAL SIZING
- BASELINES FOR TRADES & TRACES
- RING SPACING FOR WAFFLE OR POSITIONS OF FIRST NODES IN ISOGRID
- BOLTED FLANGE CONFIGURATION
- WEIGHT ESTIMATING CRITERIA
- ENGLISH OR SI UNITS

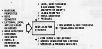


Figure 6. Boss analysis.

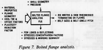


Figure 7. Bolted flange analysis.

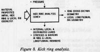


Figure 8. Kick ring analysis.

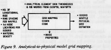


Figure 9. Analytical-to-physical model grid mapping.

Figure 10. Flat pattern layout.

Figure 11 shows the first page of the output by GENI. MX,MY are applied external body moments; VX,VY transverse shear; TE is torsion; FA axial load; NC,NE tension, compression internal line loads; V,VE shear flows.

Figure 12 shows part of a typical ISO9PT1 output for a selected analytical element. The items on the first page, WA( ), WT( ), WW( ) and WF( ), are various tolerance-dependent weight summaries. The other items in this figure are generally self descriptive. The second page contains a summary of margin data including ultimate factors and the sizing conditions and dimensions governing these factors. The shell resonant frequencies (modal analyses) are based on the entire shell having the same structural constitutive properties as the selected element.

```
GENATLAS/G     AVERAGE, CONVENTIONAL, COMBINED TYPE I LOADS SHEARING - UIATLAS/G                1/12/84

TA             C(TA)          MX             MY             VX             VY

 1              0              0             1.8E+06        30000           0
 2              57             0             2.7E+06        33750           0
 3              107            0             3.3E+06        36666           0
 4              157            0             4.05E+06       42187.5         0
 5              205            0             4.5E+06        43720.5         0

L(1)           L(2)           L(3)           L(4)           L(5)           LT
RC(1)          RC(2)          RC(3)          RC(4)          RC(5)          P              TE             FA

 57             50             50             48             16             221
 59.375         66             66             66             63             0              0             -70991.7

SECTION   1

TA             NC             NE             V              VE

 10             212            1              188            159
 20             234            1              183            155
 30             255            1              172            147
 40             275            1              157            133
 50             292            1              137            116
 60             308            1              112            95
 70             318            1              84             71
 80             324            1              54             45
 90             327            1              21             18

SECTION   2

TA             NC             NE             V              VE

 10             194            1              190            162
 20             222            1              186            158
 30             248            1              175            149
 40             272            1              159            135
 50             294            1              139            118
 60             311            1              114            97
 70             325            1              85             73
 80             333            1              56             46
 90             338            1              22             18
```

Figure 11. Internal loads, GENI.

Numerous state variables and design definition parameters generated by ISO9PT1 are output on other data sheets not shown here.

Figure 13 shows a waffle flat pattern layout including a boss. It was produced by a Computervision CADDs 3 execute file generated by CVEX7. WAF9PTN outputs initialized CVEX7.

SUMMARY AND CONCLUSIONS

The expert system described in this paper:

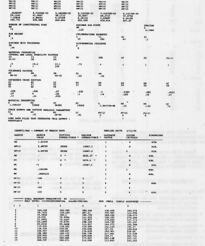
- Produces significant cost and time-to-design savings for the specialized isogrid and waffle strucures it addresses.
- Can be used as a model for development of a similar or a related expert system.
- Captures expert knowledge and significantly reduces human intervention.
- Is extremely user friendly.
- Can be readily expanded to incorporate other sizing and optimizatin routines and criteria.
- Provides a high level of user visibility, accountability, and verifiability over all of its functions.
- Outputs a complete stress analysis and mass properties report, including documentation describing all variables, algorithms, and analytical functions.

Most of the code described in this paper is fully developed and tested — some of it is in the early stage of development.

The expert system is an implementation of a design-for-CAE-and-CAD philosophy. In this case, extension of the system to design-for-CAM should also be feasible.

APPENDIX
SPECIFICATIONS FOR MAJOR PROGRAMS

1. Internal Loads Generation



```
ISO9PT1/BAS - SUMMARY            CONVENTIONAL ISOGRID ANALYSIS  NO UNDERCUT CROSS SECTION     1/31/84
2219-T851 ALUM. RM. TEMP.                   AD CRITERIA = 2                                   ENGLISH UNITS

WEIGHT SUMMARY
WA(0)        WA(1)          WA(2)          WA(3)          WA(4)          WA(5)
WT(0)        WT(1)          WT(2)          WT(3)          WT(4)          WT(5)
WW(0)        WW(1)          WW(2)          WW(3)          WW(4)          WW(5)
WP(0)        WP(1)          WP(2)          WP(3)          WP(4)          WP(5)

 .0101837    9.72054E-03    9.18506E-03    9.32859E-03    9.51655E-03    9.15178E-03
63.1444     61.5647        58.1732        59.0697        60.2727        57.9751
7.23826      6.84050        6.46389        6.56329        6.69697        6.44168
906.753     956.999        899.804        822.509        838.034        807.07

NUMBER OF LONGITUDINAL RIBS                 MINIMUM RIB WIDTH                      SPACING
NO                                          BM                                     A
 72                                          .125                                  6.3485

RIB HEIGHT                                  CYLINDER/CONE GEOMETRY
W                                           L            L1           RC           S1
 .5                                         16           221          63           .2

MINIMUM SKIN THICKNESS                      DIFFERENTIAL PRESSURE
TM                                          P
 .04                                        0

MATERIAL PROPERTIES
GENERAL AND LOCAL STABILITY FACTORS
CO           C1            CV            GA           DSN          UF           UG           UL(1)
UL(2)        UB            WS

 .5          10.2          23.1          .75          4            1            1            1
 1           1             154

TOLERANCE FACTORS
ET           ES            CW            EL           TR
 4E-03       .03           4E-03         .02          .03

REFERENCE CROSS SECTION
D1           D2            D3            D4           D5           DA           DB           DC
DD           E1            E2            E3           E4           E5           EA           EB
EC           ED            TS

 .059        .058          .07           .055         .1           .0585        .082         .0625
 .07         0             .05           .1           .14          .265         .02          .07
 .13         .21           .035

MATERIAL PROPERTIES
E            FS            FU            FY           G            NU           RH           TT
 1.05E+07    33000         56000         39000        3.94737E+06  .33          .102         70

CRACK GROWTH AND FATIGUE ANALYSIS PARAMETERS
KI           A0            AD            XI           FF(1)        FF(2)        FL(1)
 70          .01           1E-03         .01          0            0            0

LOAD DATA FILES THAT GENERATED THIS OUTPUT :
WETSTLAB/G


   ISO9PT1/BAS - SUMMARY OF MARGIN DATA                  ENGLISH UNITS   1/31/84

   MARGIN     MARGIN        CRITICAL        MAXIMUM          ULTIMATE     SIZING        DIMENSIONS
              VALUE         STRESS/FORCE *  STRESS/FORCE *   FACTOR       CRITERIA
   ==========================================================================================
   MS         1.21478                                        1              N           MIN.

   MP(1)      2.88727       39000           10047.3          1              N           MIN.

   MP(2)      4.00736       56000           10047.3          1              Y           MIN.

   MD         -             0  *            2631.17  *       1              N           NOM.

   MI         -             0  *            1874.6   *       1              N           NOM.

   ML         -1            0               10047.3          1              N           MIN.

   MG         .181058                                        1              Y           NOM.

   MW         .0083135                                       1              N           NOM.

   MF(1)      100           0               0                1              N

   MF(2)      0             0               0                1              N           NOM.

   MF(3)      100           0               0                1              N

   MF(4)      100           0               0                1              N           MIN.

   ------- SHELL RESONANT FREQUENCIES HZ ----------
   ------- HALF WAVES: I=CIRCUMFERENTIAL  J=LONGITUDINAL        FOR  SHELL  SIMPLY SUPPORTED --------

   I  J       1             2               3                4              5

    2         100.185       266.585         385.443          436.896        500.073
    3         59.7432       150.163         207.31           353.081        414.999
    4         38.3316       103.3           180.725          269.251        338.475
    5         39.578        78.8504         141.822          209.392        273.299
    6         51.5031       72.2247         115.837          170.625        227.373
    7         60.1085       79.4791         108.165          149.799        197.357
    8         88.8436       95.3606         113.817          144.273        182.588
    9         110.932       116.263         119.006          151.125        181.37
   10         136.553       140.96          150.646          167.24         190.816
   11         164.947       168.667         176.028          180.061        209.06
   12         196.066       199.733         206.709          217.901        233.838
   13         229.902       233.408         239.828          249.77         263.701
   14         266.449       269.868         275.945          285.108        297.727
   15         305.707       309.071         314.936          323.603        335.355
```

Figure 12. Isogrid shell analysis ISO9PT1 outputs.

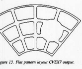


Figure 13. Flat pattern layout CVEX7 output.

GEN1 — Computes distributed loads in a cylinder-cone shell structure. Externally applied loads can be sinusoidally distributed or point loads. Shell is monocoque except for optional longitudinal members, which may be located at any angle with respect to top dead center. Computes average and maximum in-plane compression-tension line loads and associated shears for al analytical elements. It also computes:

- All external reactions.
- Load peaking factors when point loads or reactions are used on the shell.
- Axial component of internal pressure that acts on the conical part of the structure. This is in addition to hoop loads.
- Moment and axial load relief in the primary shell structure due to the presence of longitudinal members.

Inputs

- Geometry, including all section lengths and radii, analytical element sizes, longitudinal flange cross-section properties, and shell structure smeared-out-stiffness-equivalent, monocoque plate thickness and Youngs' modulus.
- For each load-case applied external body bending, axial, torsional, and transverse loads, plus all point loads.
- Internal or external pressure.
- Load reactions poits or areas.
- Overriding load symmetry: one for no load symmetry, two for two-way or diametral symmetry, and four for four-way symmetry.
- Selection of whether average or maximum analytical-element load intensities are to be passed shell analysis programs.

Outputs

- Distributed in-plane tension-compression load intensities and associated shear flow in each analytical element for all load cases.
- Worst-case distributed design loads which can be alternatively be used as input to the shell analysis programs.
- Overall axial, torsional, and bending stiffnesses of the complete shell structure, including longitudinal members.
- Reactions in mounting surfaces and point attachments.

FEM1 — A pre- and post-processor for SAP80(15). Generates a three-dimensional FEM model of the shell based on an overall shell geometry, longitudinal member parameters, stiffness-equivalent skin thickness, and Young's modulus for each shell analytical element as generated by the detailed shell analysis programs. Extracts element in-plane loads from SAP80 output for input to shell analysis.

Inputs

Same as those for GEN1 with addition of different skin thickness and Young's modulus for each analytical element.

Outputs

Same as those for GEN1.

2. Preliminary Shell Analyses

ISO9PT1 — Optimally sizes an isogrid shell structure element using user-defined or automatically selected analytical element. The shell is a cylinder-cone. Sizing is based on GEN1 loads and specified design criteria. Following are some of the features of ISO9PT1:

Automatic computation of cross-section properties of different rib types, including stress-dependent effective skin; i.e., the greater the stress, the less is the skin contributing to cross-section properties. The cross-sections can be types produced by machining or chemical milling. The chemically milled cross-sections require automatic curve fitting routines to establish closed-form solutions for cross-section properties. Reference cross-sections are also used as baselines for establishing proportions between different parts of the cross-section.

Margin computations include:

- Four alternative general instability margins based on References 1, 3, 6, 7, and 12.
- Two alternative acoustical high-cycle fatigue (HCF) margins based on Reference 8, etc.
- Material ultimate and yield strength properties.
- Rib crippling.
- Skin buckling (Reference 3) secondary rib-stiffened and unstiffened skins.
- Low-cycle fatigue (LCF).
- Resonant frequencies and mode shapes under load and no load conditions are computed per References 4, 5, and 10.
- Estimates of number of load cycles to failure due to crack growth are made on basis of Reference 13.
- Computation of total and unit area shell weights are based on nominal, maximum, and average dimension for separate and combined skin thickness, rib width, and plate thickness. The nominal weight is based on tolerances halfway between nominal and maximum. The unit area weight determined for the selected element is used to compute a total shell weight having constant rib widths, skin thickness, and plate thickness.
- ISO9PT1 will determine the minimum weight structure by: (1) meeting specified margin, resonant frequency, and stiffness requirements; and (2) iterating through the matrix of minimum, maximum, and incremental values specified for rib width, skin thickness, plate thickness, and number of longitudinal ribs. The algorithm employed for this purpose establishes a margin floor which is raised above zero by successively, incrementing either rib width or skin thickness, depending on which produces the greatest floor increment per given weight increment. The process is terminated when the floor is above zero. Newton Raphson techniques are used to speed the computation.
- Margins for rib crippling, skin buckling, LCF, and material properties are computed using minimum cross-section and skin dimensions while nominal dimensions are used to compute instability margins. Any tolerance criteria can, however, be specified to override these default conditions.
- HCF margins for skin panels are computed by ISO9PT1 for a matrix of minimum, nominal, and maximum skin thicknesses and secondary rib widths to select the critical value. The most critical values in this case are not necessarily produced at minimum gages.
- Temperature-dependent material properties can be separately specified or computed by ISO9PT1 for selected range of materials.
- A detailed data printout is provided by ISO9PT1. It includes margin, mass properties, and invariant parameter summaries.

Inputs

- Shell mold line geometry.
- Manufacturing tolerances.
- Minimum and maximum values; increments for rib width, skin thickness, and plate thickness; and number of longitudinal ribs.
- Limit, ultimate, knock-down, and margin factors.
- Margins, resonant frequencies, and/or stiffness requirements to be used as sizing criteria.
- Initial crack size and life cycle requirements.
- Rib cross-section type and reference cross-section.
- Material properties or material name and temperature.
- Analytical element to be optimized and worst-case design loads for uniform shell.

Outputs

- Detail data printout, including mass properties, margin summary, modal analysis, invariant parameters, stress, stiffnesses, etc.
- Trades: A matrix or plots of margins, weights, and resonant frequencies vs rib width, skin thickness, plate thickness, and number of longitudinal ribs.

- User-selected traces of computations of significant margins, stresses, stiffness, and/or resonant frequencies. These can be used by the analyst to perform direct numerical checks referencing source material.

WAF9PT1 — Optimally sizes a waffle shell structure element using user, or automatically selected, analytical element. The shell is a cylinder-cone. Sizing is based on GEN1 loads and specified design criteria.

The features of WAF9PT1 are similar to those of ISO9PT1 except for the following changes:

- One of the general instability computations from Reference 3 is replaced by a computation based on Reference 2.
- Inputs must include ring spacing.
- General instability is skin-buckling dependent; consequently, positive skin buckling margins must be specified with general instability margins.

3. Detailed Shell Analyses

ISO9PTN — This code is similar to ISO9PT1 with the folowing exceptions:

- All analytical elements of the shell are optimally sized and overall weights are based on a sum of element weights. Individual elements do not, therefore, have to be selected. The element sizing involves selection of optimum skin thickness and rib width while holding the plate thickness and number of longitudinal ribs constant for each run.
- Element data printout is limited to margin and cross-section parameter values.
- Inputs from GEN1 are replaced by inputs from FEM1. Also ISO9PTN creates an output file of stiffness-equivalent element thicknesses and Young's modulii for input to FEM1. This output is used recursively to update FEM1 internal loads.
- Outputs include optimized structure design definition and inplane design loads and shell constitutive parameters at bosses, kick rings, and flanges. A three-dimensional SAP80 finite-element is also a by-product.

WAF9PTN — This is similar to ISO9PTN, with the differences described under WAF9PT1.

4. Secondary Structures Analyses

4A. Boss Analysis

STRUBOSS — This program performs the following functions:

- Automatically models a planar FEM multisided ring truss frame structural equivalent of a boss or cut out in a cylinder-cone shell. The FEM model includes influence of surrounding shell as well as tension/compression and shear flow loads derived from the local in-plane load environment (i.e., from FEM1).
- Performs a mini FEM analysis using the above model and computes stresses and stress margins for all (at least 48) critical points on the model. Mini FEM is incorporated in STRUBOSS.
- Computes stress concentration factors (Reference 14) for clearance/bolt holes in boss and at fillets on attachment ribs. These are used in stress margin computations for these points.
- Stresses and stress margins are computed for external local loads applied to the boss. This computation is based on Reference 9 which is fully implemented in STRUBOSS. Superposition is used to add these Wickman-analysis results to those from Mini FEM.

  On the current STRUBOSS version the bosses must be circular or square in plan layout and must be (or assumed to be) located in a shell area free from the influences of other bosses, the kick ring and bolted flanges.

Inputs

- Material properties.
- Boss geometry: rim ID, OD, width, thicknesses; mounting flange ID thickness: flange holes, locations, etc.
- Loads from FEM1, local applied loads, and pressure.
- Boss location on shell plus local in-plane load environment from FEM1 and local skin thickness and rib widths from ISO9PTN or WAF9PTN.

- Number of skin rib widths contributing to boss rim effective cross-section.
- Initial rib width and type plus skin thickness terminating on boss. Default values for these taken from ISO9PTN or WAF9PTN. At least two diametrically aligned ribs are assumed to intersect the boss in both the longitudinal and circumferential directions.
- Rib width increments.

Outputs

- Lengths and orientations of all ring truss members comprising the boss or cutout model.
- Loads on all truss members including start and end moments, axial forces, and shears.
- Linear and angular deflections at each node of model.
- Stress concentration factors.
- Stresses and margins in boss (ID and OD) at mounting holes and in four ribs terminating on boss.
- Rib widths of four terminating ribs that produce positive stress margins in rib attachments.

4B. Bolted Flange Analysis

FLG — The flange analysis is based on a series of self-chaining codes which perform the following functions:

- Two mini FEM models are automatically created: one with a rib in line with a bolt and one with the bolt centerline midway between ribs. The models include a default offset of one-eighth of the bolt diameter for the location of the reaction point between the bolt head and the flange. Heel-to-toe action is also assumed on the flange face.
- The mini FEM analysis is run to produce internal loads and deflections for both models.
- After the bending moments in the bolt are reduced by a 1.5 plasticity reduction factor, combined stresses and their margins are computed at nine critical points in the bolt, flange, and shell structure for both models.
- Negative margins are corrected by human interaction in the current software version. These can include increasing rib width, local skin thickness, or bolt diameter, or decreasing bolt spacing.

Inputs

- Flange geometry, including bolt circle diameter, bolt sizes, bolt hole diameter, bolt length, flange thickness, and flange ID and OD.
- Initial shell local rib width and skin thickness from ISO9PTN or WAF9PTN.
- Worst local in-plane shell loads from FEM1.
- Material properties for bolt and flange. Note: Default properties for flange are the same as those of the shell.
- Bolthead reaction point offset and heel-toe reaction point offset, if other than default value.
- Plasticity reduction factor, if not 1.5.

Outputs

- Models: geometry, cross-section properties, internal load, deflections, and invariant factors.
- Summary of stresses and margins at nine critical locations for both FEM models.

4C. Kick Ring Analysis

CONE4 — This program is used to size the kick ring at the cone-cylinder intersection. A classical analysis is used to compute induced-moment axial and transverse loads in the kick ring from which rib cap stresses and margins are computed for both the ring and longitudinal ribs that terminate on it. A monocoque shell has to be assumed in this analysis. Numerical accuracy of computations must be increased with decreasing cone angle below 15°.

Inputs

- Material properties.
- Local shell rib width and skin thickness from ISO9PTN or WAF9PTN.
- External body bending, transverse, axial, and torsional loads from input specification.
- Initial kick ring cross-section properties, including offset of its centroidal axis from centroidal plane of shell.
- Internal pressure.

Outputs

- Induced moments, torsional, shear, and axial loads in ring and local longitudinal skin and ribs.
- Induced effective radial load components on ring.
- Stress and stress margins in ring caps and local longitudinal rib caps.

5. Graphics Generation

5A. Analytical-to-Physical Model Grid Mapping

CXWIN — This program maps the analytical element rib widths and skin thicknesses from WAF9PTN into arrays defining physical model rib widths and skin thicknesses. The number of longitudinal ribs and ring spacing in the physical model are also derived from WAF9PTN. The algorithm used in this program includes the following features:

- When a physical pocket is intersected by more than one analytical element, the selected rib width and skin thickness is taken from the analytical element having the greatest smeared-out bending stiffness.
- Discontinuities between conical or conical and cylindrical sections are detected and the initial ring of the succeeding section is located at the discontinuity.
- The material volume of the physical model is computed, from which weights are determined. These calculations can be at nominal dimensions or any combination of off-nominal dimensions for different parts of the rib-skin cross-section. The mass properties should corroborate those from ISO9PTN and WAF9PTN.

CXIIN — This is the isogrid version of CXWIN. Its inputs come from ISO9PTN. Ring spacing input is not needed; however, the user must specify the locations of the first circumferential set of nodes in each conic section of the physical model.

5B. Automated Flat Pattern Layout

CVEX7 — This is an expert system (Reference 16) for the automatic layout of the flat pattern of an integral cylindrical or conical waffle structure, including its bosses. Boss blending fillets are automatically inserted to integrate bosses into the waffle structure (as, for example, they would normally be by end mill machining operations). Procedures for boss installation include pattern recognition to determine which graphic entities are to be deleted and which are to be added. Extensive geometric analysis and testing are required to implement these and related procedures.

Inputs

- Half-rib widths, skin thicknesses, corner fillet radii, and all pocket coordinate data from WAF9PTN (These are used for the layout of the basic grid of waffle pockets).

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